sustainability

MDPI

Article

An Action Research Teacher's Journey while Integrating Green Chemistry into the High School Chemistry Curriculum

Michael Linkwitz [1,2] and Ingo Eilks [2,*]

[1] Otto-Hahn-Gymnasium Bensberg, Saaler Mühle 8, 51429 Bergisch Gladbach, Germany
[2] Department of Biology and Chemistry, Institute of Science Education, University of Bremen, Leobener Str. NW2, 28359 Bremen, Germany
* Correspondence: ingo.eilks@uni-bremen.de

Abstract: In recent years, a growing number of publications have emerged discussing how to integrate education for sustainable development (ESD) and systems thinking into science education in general, and chemistry education in particular. However, when it comes to more specific fields of chemistry education, most studies focus almost exclusively on higher education. Examples of ESD units in secondary chemistry teaching are mostly limited to single topics. They often do not explicitly deal with the theoretical concepts behind green or sustainable chemistry. This paper reports on a long-term initiative to develop secondary chemistry education. This effort attempts to thoroughly integrate ESD based on the concept of green chemistry into high school programs. The project is based on teacher-centered action research, a cyclical development and research approach within authentic classroom practice. The process was supported by an academic chemistry education research group and a network of experienced action research teachers. The current paper describes the development of a teaching sequence for first-year upper secondary chemistry education. Elements of the development and selected findings from the accompanying feedback processes are reported.

Keywords: chemistry education; education for sustainable development; green chemistry; curriculum; high school; action research

check for updates

Citation: Linkwitz, M.; Eilks, I. An Action Research Teacher's Journey while Integrating Green Chemistry into the High School Chemistry Curriculum. *Sustainability* **2022**, *14*, 10621. https://doi.org/10.3390/su141710621

Academic Editors: Edwin Charles Constable, Colin Michael Hall, Idiano D'Adamo, Maxim A. Dulebenets and Mihajlo (Michael) Jakovljevic

Received: 20 July 2022
Accepted: 22 August 2022
Published: 25 August 2022

1. Introduction

In 2015, the United Nations (UN) issued the Agenda 2030, in which it defined seventeen Sustainable Development Goals (SDGs) to be achieved by 2030, among them SDG 4 "Quality Education" in general, and education for sustainable development in particular [1]. An analysis of the United Nations Environment Program (UNEP), namely the Global Chemical Outlook II (GCO II), was also published recently with a focus—among others—on chemistry education [2]. The GCO II generally suggests that chemistry is central to many of the challenges laid down in the SDGs and is connected to almost all of them. Because chemistry is central to many sustainability challenges today, education for sustainable development (ESD) needs to become a central focus of chemistry education at all educational levels, and the ideas of green and sustainable chemistry should be part thereof [2,3]. This has to include secondary school chemistry teaching [4].

ESD can be understood as a regulatory idea within 21st-century education [5], to which all teaching and learning domains need to contribute. Curriculum action is necessary to provide learners with a contemporary, balanced view of how chemistry is carried out today—and should be in the future. It is also important to learn how changes in chemistry and its associated applications affect the environment and society [6]. This balanced view is important for students planning to embark on a career in chemistry-related fields. It is also needed for those who are not scientifically inclined but still need to act as responsible citizens in an ever-changing world [7].

The Agenda 2030 states in goal 4.7 of the SDGs, " ... by 2030 ensure all learners acquire knowledge and skills needed to promote sustainable development, including among others through ESD and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship, and appreciation of cultural diversity and of culture's contribution to sustainable development" [1]. The aim of ESD is supported by international policy from chemistry's point of view [2]. Such a view has also been acknowledged in several newer national regulations for high school chemistry education. For example, the newly issued federal German standards for upper secondary chemistry teaching state that "Chemistry offers society enormous opportunities for development in all areas of life and the environment. This is accompanied to a large extent by the social call to critically engage with the developments and products of chemistry, to discuss the opportunities, limits, and risks, and to promote sustainable development" [8].

One potential answer to equip chemistry for the growing challenges of a more sustainable future was suggested in the 1990s by Paul Anastas and John Warner. This was the concept of green chemistry (GC) [9]. According to Anastas and Warner, GC provides a set of twelve principles that were drawn up to spearhead different practices in chemistry research and industry (Table 1). The aim was to make chemistry safer and more environmentally benign. Around the same time, the OECD introduced the concept of sustainable chemistry (SC), which was differently structured but generally had the same goals as GC [10]. Since then, the term GC has come to be associated with more holistic approaches which go beyond the original, technical side of the twelve principles presented by Anastas and Warner. Both concepts (GC and SC) developed further and grew closer to one another [11], although some differences still exist [3]. The transition between GC and SC became more fluid. Internationally, for example in the GCO II, there is increasing interchangeability in the use of the terms green and sustainable chemistry (GSC) and green and sustainable chemistry education (GSCE) [2].

Table 1. The twelve principles of green chemistry suggested by Anastas and Warner [9].

1. Prevention: it is better to prevent waste than to treat or clean up waste after it has been created.
2. Atom economy: synthetic methods should be designed to maximise the incorporation of all materials used in the process into the final product.
3. Less hazardous chemical syntheses: wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. Designing safer chemicals: chemical products should be designed to affect their desired function while minimising their toxicity.
5. Safer solvents and auxiliaries: the use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.
6. Design for energy efficiency: energy requirements of chemical processes should be recognised for their environmental and economic impacts and should be minimised. if possible, synthetic methods should be conducted at ambient temperature and pressure.
7. Use of renewable feedstocks: a raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. Reduce derivatives: unnecessary derivatisation (use of blocking groups, protection/deprotection, temporary modification of physical/chemical processes) should be minimised or avoided, if possible, because such steps require additional reagents and can generate waste.

Table 1. *Cont.*

9.	Catalysis: catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10.	Design for degradation: chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
11.	Real-time analysis for pollution prevention: analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12.	Inherently safer chemistry for accident prevention: substances and the form of a substance used in a chemical process should be chosen to minimise the potential for chemical accidents, including releases, explosions, and fires.

More and more, it is suggested that secondary school lessons should be updated to a chemistry curriculum for ESD [4,12]. Lessons have to add a focus on how chemistry is handling the issue of sustainability, for example, by fostering understanding of GSC [3]. Changed teaching goals include reflecting on students' views of and attitudes toward chemistry and asking how to better them. It is suggested to make GSC a more prominent topic in chemistry lessons [3,4,13]. It is also suggested to call for reflection upon the consequences of human activities on the environment. This can occur through changes in the content of teaching, the related pedagogy, and any associated laboratory practices [4]. In the end, integrating ESD with chemistry education is seen as a path to increasing the relevance of chemistry education [12]. It also has the potential to foster systems thinking skills among learners, one of the central competencies for the 21st century [14–16].

A growing number of publications for integrating ESD with chemistry education have emerged [3]. However, most of these efforts focus on higher education. Examples covering secondary school chemistry remain limited. Most of this focus neither on a broader view on GSC nor on a goal of changing school curricula throughout. Because of this, a teacher-driven initiative was started a few years ago in Germany [17]. It seeks to develop lesson plans thoroughly integrating sustainability into secondary school chemistry education in Germany based on the ideas found in GC. The initiative is a project of teacher-driven action research. Action research, for many years, has been suggested as a promising strategy for classroom change and professional development of teachers in general [18], or for science education in particular [19,20].

The teacher-driven action research in this project is supported by an academic science education research group and a network of experienced action research teachers, such as the method described by Laudonia and Eilks for a project on vocational chemistry education in Switzerland [21]. Action research (AR) as carried out here follows a cyclical model of development and action [22]. It is operated within authentic classroom practice and based on the collaborative work of a teacher within a group of other teachers accompanied by science education researchers. The group involved has been working on curriculum innovation in chemistry education for more than 20 years now. While systematically involving a group of other teachers, the action research model implemented can be seen as a hybrid model between teacher-centered and participatory action research [21].

The current paper describes a five-year, teacher-centered, participatory action research process involving a teaching concept for GC called "From sugar beet to bioplastics". It is created for the first term of upper secondary chemistry education in Germany and uses GC as a guiding principle of the upper secondary chemistry curriculum. The teaching series was systematically tested in several upper secondary school courses and evaluated via feedback from the action research group and the students (mainly through questionnaires and focus group discussions). This article describes the teacher's action research journey, starting from the idea to the realization and finalization of the project within a group of other teachers. It provides reflections from a personal point of view including the perspectives of the students and colleagues involved.

2. Project Aims

The aim of this ongoing curriculum development project is to thoroughly implement aspects of GC into secondary chemistry education. It was carried out in North Rhine-Westphalia, the largest of the German states. With respect to the mandatory governmental standards, the project works in a cyclical, evidence-based development to create a series of lessons in organic chemistry fitting the official syllabus. The lesson plan should provide students with insights into the different ways of thinking employed in GC. The project develops individual teaching sequences along with associated suggestions for practical work, which might also be relevant for other secondary and undergraduate chemistry education programs. Lesson changes include covering all twelve principles of GC, introducing methods for the sustainability assessment of chemical processes, products, and developments, e.g., inspired by [23], and altering laboratory practices based on enzymatic catalysis or microwave-induced chemical reaction, e.g., inspired by [24,25]. The lesson plan and the associated experiments intend to show how a GC focus can expand chemistry teaching practices, introduce a changed chemistry curriculum, and possibly change students' attitudes toward chemistry. The project seeks to better understand whether such a changed teaching approach and curriculum can potentially provide students with a better understanding of the basic ideas of GC. It also looks at whether such changes can improve the often-negative perception of chemistry and the chemical industry among learners.

3. Method

3.1. Action Research to Develop Chemistry Education

A large variety of strategies and focal points exist when it comes to applying action research in science education [26]. One interpretation is the model of participatory action research (PAR) as suggested by Eilks and Ralle [22]. The operated model of PAR in science education is a collaborative process. It combines a group of in-service teachers with external supporters from academic science education research to drive classroom-based research and development [21]. It differs from other types of networked action research which tend to be based on individualized research activities by single teachers [27]. In the case of this suggested PAR model [22], the whole group works on the same area of interest over longer periods of time, in this case, led and guided by one teacher of the group (M.L.).

In the case described here, one teacher began the initiative and steered the group's work. Other teachers and external supporters from academia helped during the joint development of the teaching and learning materials, as was described recently in a similar study on vocational chemistry education in Switzerland [21]. The aim of collaborative PAR work is to reach a consensus about the goals of the intervention and to identify the most feasible and promising teaching strategies to be implemented and cyclically improved in class. With the agreed-upon strategies, cycles of testing, evaluation, reflection, and revision are then conducted until the group of teachers agrees that a sufficient level of development has been achieved [22].

The lesson series "From sugar beet to bioplastics" has been developed cyclically over five years in several courses of first-year upper secondary school chemistry teaching. The basic idea for the lesson plan, however, was developed well in advance of this action research initiative, as were single materials and experiments. The systematic development of the lesson plan was then carried out from 2016 onwards. To date, the complete lesson plan has been applied with variations in four consecutive schooling years from 2016 to 2020. Each course consisted of about 20 students, so a total of about 120 students took part.

3.2. Resources and Aims

Action research is characterized by the juxtaposition of data and sources from different perspectives. In the suggested model of action research, resources from science and educational research and teacher experiences and intuition are compared and contrasted for the development of new teaching practices. Within the cyclical process of development, new teaching practices are reflected, and evidence is collected from different points of view. In the action research project presented here, the method of triangulation was used by collecting and analyzing data from the teacher's perspective on the series of lessons (e.g., through observations, diaries, and documentation), the students' views (e.g., through questionnaires), and the perceptions of the action research group and research team (e.g., focus group discussions) [28]. Figure 1 is intended to illustrate the process, its fundament, and intended outcomes.

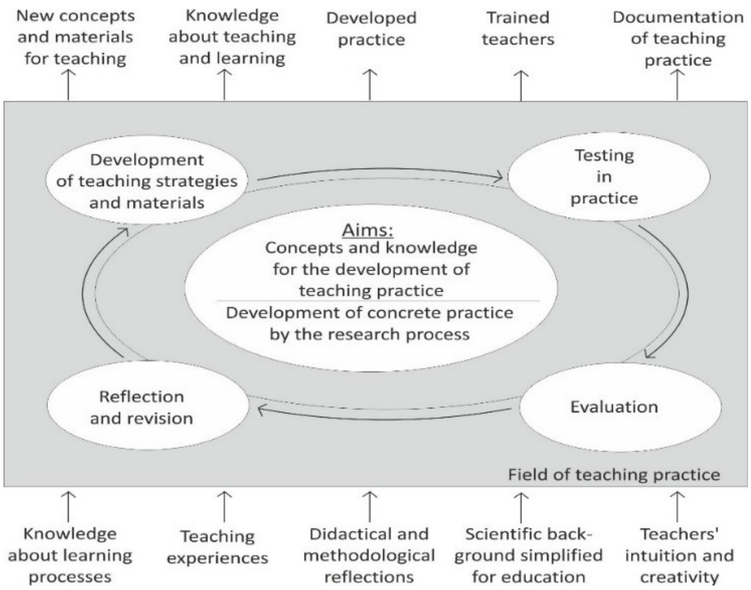

Figure 1. A model for action research in chemistry education [22].

3.3. Collecting Evidence

An appropriate understanding of research needs to be applied in action research [29,30]. Teachers work with the students they have at the time. The groups are neither large nor representative regarding sample size. Methods need to be selected which do not interfere with normal teaching practices. They must also be feasible for teachers' everyday work. Therefore, many varying methodological approaches are suggested for classroom-based action research [28], which allow for the triangulation of different perspectives and methods to create understanding. In this project, three perspectives were used, namely the perspective of the students, of the teacher, and of an external expert group of action research teachers. Different methods were also selected [31,32]. These included oral and written feedback from the students, focus group discussions with students and expert teachers, and the acting teacher's self-reflections based on his lesson documentation after each action cycle (Table 2).

The students were informed that their feedback is collected for a study done by the teacher. All students provided feedback anonymously and on a voluntary base. Formal approval of the study was not required, the headmaster of the school was informed and agreed to the project.

Table 2. Overview of the course of the project and the associated action and research.

School Years(s)	Number of Courses	Teaching/Action	Reflection/Research
2012-16		Literature review; implementation of single GSC experiments.	Individual teacher's reflection on single teaching elements; informal exchange with colleagues; informal discussions with students.
2016-17	2	Applying a first complete design of the lesson plan; creating a better understanding of students' prior knowledge about GSC and their perception of chemistry and the chemical industry.	Monthly focus group discussions within the PAR network; questionnaire study of students' understanding and perception of chemistry and the chemical industry after the lesson plan (N = 19) and creating an external reference (N = 326).
2017-18	1	Applying a revised design of the lesson plan, which now additionally includes experiments on biocatalysis and tools for sustainability evaluations.	Monthly focus group discussions within the PAR network; focus group discussion with students.
2018-19	1	Applying a revised design of the lesson plan, now including additional experiments with microwave and ultrasound-assisted syntheses.	Monthly focus group discussions within the PAR network; focus group discussion with students.
2019-20	2	Applying the provisionally ready design of the lesson plan.	Monthly focus group discussions within the PAR network; focus group discussion with students; questionnaire study on students' perception and understanding of chemistry and chemical industry one year after the lesson plan (N = 18).

3.4. The Provisional Ready Lesson Plan

The GC lesson plan "From sugar beet to bioplastics" is comprised of 24–28 lessons. Each lesson lasts 45 min over a time frame of about 8–12 weeks. The lesson plan is split into seven smaller modules, in which all twelve of the principles of GC are addressed (Table 3). The plan begins with an introduction to the basic ideas of GC and the corresponding twelve principles. Modules 2 and 3 emphasize the role of biotechnological processes and the role of renewable raw materials (carbohydrates and lactic acid) for synthetic organic chemistry. Modules 4 and 5 deal with different green syntheses using immobilized enzymes as biocatalysts or employing microwave and ultrasound support. Modules 5 and 6 bring together all acquired knowledge in the synthesis of polylactic acid (PLA) as an example of a bioplastic from renewable raw materials. The product is then evaluated in terms of sustainability, which introduces the students to aspects of sustainability evaluation metrics. Module 7 concludes the series, by bringing all the findings together once again and critically reflecting upon the students' own perceptions and attitudes.

Table 3. Overview of the lesson plan "From sugar beet to bioplastics".

Module	Teaching Content	Principles of GC
1	Introduction to GC—the 12 principles and the importance of sustainability	
2	Renewable raw materials and their importance for GC	7, 1, 10
3	Importance of biotechnological processes for GC	9, 1, 3, 4
4	Importance of enzymatic catalysis for GC	3, 5, 8, 9, 12
5	Applications of various principles of GC (energy, enzymes, microwave synthesis, ultrasound, etc.)	6, 8, 12
6	Synthesis and use of PLA and other bioplastics	1, 2, 3, 4, 9, 11, 12
7	Conclusion of the series	

The focal points of the modules are:

- Importance of sustainable development and the 12 principles of GC;
- Renewable raw materials (e.g., starch, glucose, lactic acid);
- Synthesis and importance of esters using the example of lactate esters;
- Importance of biocatalysis in synthetic chemistry; comparison of conventional ester synthesis with enzymatic ester synthesis;
- Importance of microwave technics and sonochemistry for sustainable synthetic chemistry;
- Synthesis and properties of polyesters using PLA as an example;
- Evaluation of bioplastics in comparison to petrochemically produced ones by life cycle assessment (LCA).

Unfortunately, due to the scope of this paper, we cannot describe the series of modules in detail. More details are provided in [17].

4. Reflecting on the Action Research Process

4.1. Reflecting the Design Process

4.1.1. Intervention with the Initial Design: The First Cycle of Action Research (2016-17)

The first complete run of a lesson plan took place in the school year 2016-17. The materials and experiments from the preparatory phase were put in a coherent sequence. Available worksheets were revised regarding coherence in scope, terminology, and layout. The general structure and the associated pedagogy for each module were discussed and decided within the PAR group.

Parallel to this action phase of planning and teaching, a questionnaire was developed to reveal any changes in the pupils' understanding of and attitudes toward selected aspects of GC. The questionnaire focused on student attitudes, knowledge, and interest in the chemical industry, sustainability, and GC. The questionnaire contained thirty-six four-step Likert items (from strongly disagree to strongly agree) and six open-ended questions. The sections in the questionnaire covered (a) a definition and understanding of the terms sustainability and GC, (b) student attitudes toward the chemistry industry, (c) participant attitudes toward inclusion of the topics sustainability and GC in school chemistry education, and (d) rating the relevance of the topic. The questionnaire was applied to randomly selected chemistry classes in northern and western Germany at the beginning of upper secondary education. A total of 326 students took part in the study, which was viewed as an external reference point to see any differences to the intervention groups [22].

The reference sample showed that most students at this stage of their education (age range 15–16) generally have a limited understanding of sustainability, which is mostly restricted to environmental sustainability (approx. 70%). Only a few students were able to provide a sound definition of sustainability that also included economic and societal sustainability. Regarding GC, a larger segment of the students (approx. 40%) associated the term with chemistry carried out in an environmentally friendly fashion. For example: "By green chemistry I can imagine that chemical production processes are optimized in such a way that they are more environmentally friendly, i.e., they emit no or only little CO_2 into the air and only renewable raw materials are used". There was, however, no theory-based knowledge that could be identified. Additionally, some students understood the term GC in the sense of greenwashing: "Green chemistry is something that is supposed to sound good, but in reality, is nothing more than chemistry." Some students associated GC with terms like "good", "environmentally benign", or "environmentally friendly". However, none of the students was able to refer explicitly to any of the 12 principles of green chemistry. In the reference sample, about 60% of the students agreed that the topic of sustainability should be integrated into chemistry education. Asked about the importance of learning about topics such as climate change, environmental protection, and sustainability on a scale of 1–10 (1 = unimportant; 10 = very important), the students rated education in general with an average of 8. However, for chemistry education, the rating was only 6.5. We can interpret this as students generally recognizing the importance of sustainability, but not really comprehending what chemistry or chemistry education must contribute to this area. Figure 2 shows a selection of responses from the reference group.

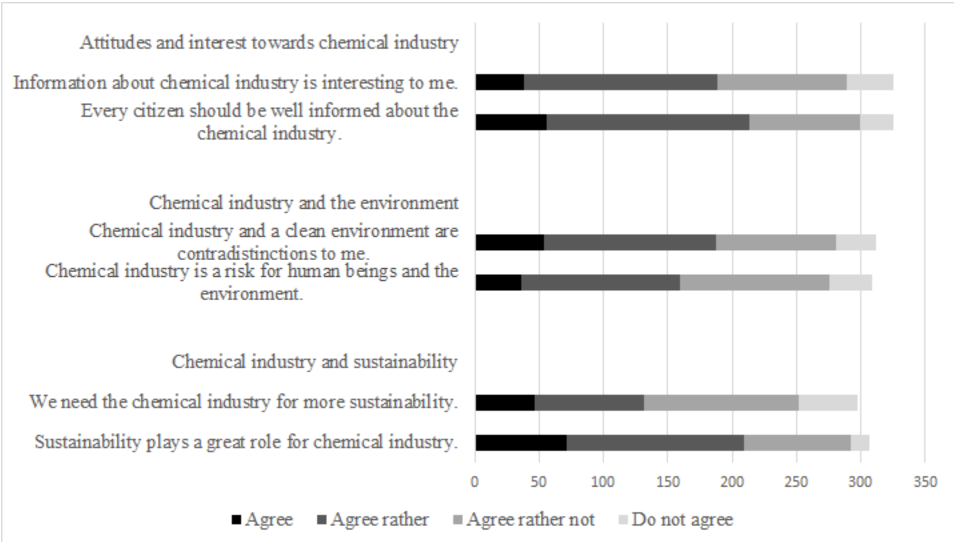

Figure 2. Student agreement from the representative sample (age range 15–16) to selected items on the Likert questionnaire (N = 326).

After the lessons were over, the students from one of the two intervention classes were asked to fill out the same questionnaire. A total of 19 out of the 21 students decided to participate on a voluntary basis. All of them showed a sound understanding of sustainability in relation to chemistry: "I think sustainability is the conservation of fossil fuels and the use of regenerative raw materials. During production and mining, the production of harmful substances is prevented." All students were able to explain the term GC and refer to the 12 principles based on Anastas and Warner. In their own view of themselves, the students felt that they had gained some knowledge about GC. The measured values for the questionnaire items "I can describe what green chemistry is" and "I know an example of the concept of green chemistry" averaged 3.8 and 3.7 (overall range 1–4), as compared to 1.6 and 1.5 in the reference sample. After the intervention, all the students agreed that sustainability should be integrated more strongly into chemistry lessons in the future. "Yes, I think it [the topic of sustainability] should be more integrated because at an early age you should know what is best for the environment." "Sustainability is a key aspect of chemistry, so it needs to be covered in depth in chemistry lessons." Regarding the perceived importance in chemistry education of topics such as climate change, environmental protection, and sustainability, a remarkable change was noticeable after the intervention. The general importance of ESD was rated 8.8 on average (reference sample 8). The importance of these topics for chemistry lessons after the intervention was given an 8.6. This is nearly as high as the consensus and much higher than the reference sample, which only averaged a value of 6.5. Figure 3 shows a selection of responses from the intervention group.

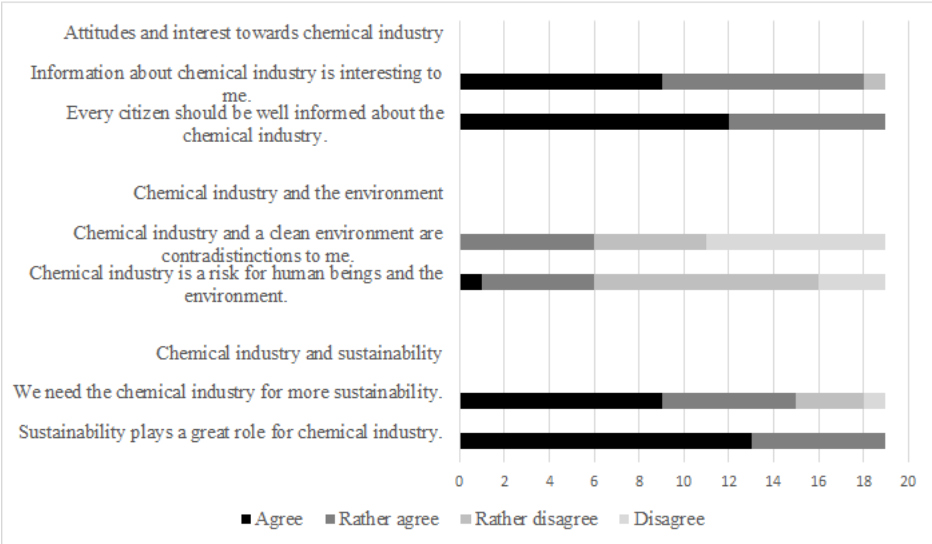

Figure 3. Agreement among the students to selected items on the Likert questionnaire (N = 19).

4.1.2. Revising the Initial Design: The Second and Third Cycle of Action Research (2017-19)

In the school years 2017-18 and 2018-19, each individual course was taught using revised versions of the initial designs. The focus in these two years was finalizing the material. All worksheets were further refined. Further aspects of GSC and associated experiments were also developed and added to the curriculum. New school-type experiments were developed and tested within the PAR network. In the school year 2017-18, experiments highlighting biocatalysis with immobilized enzymes were developed and tested with students in the classroom. In the school year 2018-19, further experiments were generated, tested, and reflected upon. These used a laboratory microwave oven. They were later optimized for broader applicability in schools by substituting the lab microwave oven with a kitchen microwave as a low-cost option. Focus group discussions with teachers in the PAR network and students in the class were actively applied. This allowed the action research group to understand the feasibility of the experiments in terms of educational value and practical applicability.

4.1.3. Applying the Provisionally Completed Design: The Fourth Cycle of Action Research (2019-20)

In the school year 2019–2020, a provisionally completed design was prepared by the teacher and the action research group. Two more classes were taught using the lesson plan. One of the courses was taught by the action research teacher. The other was instructed by a colleague in the same school. There was a total of 34 students. The students' views prior to the intervention generally fell in line with the previous results of the reference sample. In this test run, too, most of the students provided only an environmental or resource-based explanation of the term sustainability: "protecting nature" or "careful use of resources". The term GC could also only be defined in very diffuse terms. Most of the students associated GC either with the sustainable production of substances or with the use of "environmentally friendly and resource-saving substances".

After the course, all students referred to the 12 principles of GC in one way or another. All the participants agreed that the topic of sustainability needed to be integrated into chemistry lessons. Here, too, several student statements should be cited: "The topic is becoming more and more important and especially in chemistry you can do a lot for environmental protection." "Sustainability is more important nowadays than ever before." "The topic should be dealt with in detail, as it is directly related to chemistry and the topic is becoming more and more relevant." This emphasis might also be due to the parallel development of the "Fridays for Future" movement, which began contemporaneously with the curriculum development project. Fridays for Future brought sustainability more into the spotlight of the public, especially among today's impressionable younger generation. Regarding the weight given to topics such as climate change, environmental protection, and sustainability in general, there was a significant upward shift as compared to the reference cohort. The average importance of ESD rose to 9.4 and the average score for chemistry education climbed to a value of 7.8.

Unfortunately, the test school was closed directly after the lessons were completed due to the COVID-19 pandemic. The originally planned post-survey had to be skipped since no digital possibilities were available. Distance learning and evaluation had just been implemented in the school in question and were unfortunately not up to the task. Further organizational factors led to a teacher change in the class previously instructed by M.L. For this reason, the new instructor decided to postpone a direct post-survey until nearly a year after the intervention had been finished. Since this follow-up survey had to be conducted online, a shorter feedback tool was used with only four open-ended questions. Of the original 34 students, 18 students participated in the online survey via the online tool Forms. Most of the other students had left the school, in the meantime, or decided not to continue chemistry in their final two years before their university entry exam. Due to the low response rate of the questionnaires, we decided not to code the answers and subject them to qualitative content analysis, but only to conduct a descriptive analysis. Overall, the students' responses were very positive regarding the integration of GC into chemistry lessons; we could not record a single negative comment. In this respect, the statements at this point can only be interpreted as indications and we are working on being able to collect further meaningful data in the future.

Nearly a year after the intervention, all students who had provided feedback were still able to meaningfully explain the concept of GC and refer to its basic principles. Two short quotes can illustrate this: "... 12 principles. Sustainable chemistry, reducing toxic substances and energy, using renewable raw materials and enzymes", or "One of the principles of green chemistry is to avoid pollution. In addition, substances that are produced should be as non-hazardous as possible. As some processes require new technology, this issue is particularly important for the future."

Particularly noteworthy were the answers demonstrating very clearly that students saw topics such as sustainability and GC as an enrichment of chemistry lessons, which increased their level of motivation. All the participants suggested that schools include the topic of GC in chemistry lessons. The majority also stated that sustainability topics increase pupils' intrinsic motivation and can potentially change students' attitudes toward chemistry and chemistry education:

> "Absolutely!!! Green chemistry is very important and forward-looking. Therefore, we must start teaching the basics at school to be able to find solutions to problems more easily, since young people can also have innovative ideas..."

> "Yes, the topic should be included more often in chemistry lessons. Because the topic of sustainability is particularly important for our generation as well as for all those who come after us. Students should be taught that chemistry is not just about making things explode. Chemistry can contribute to a sustainable and environmentally friendly world. Green chemistry offers many opportunities to our generation, which we should learn about in class."

> "For many students, chemistry is a subject where it is difficult to find a comprehensible context. However, sustainability is a tangible topic and could certainly increase motivation for chemistry lessons, as there is often also personal interest in it."

The topics of sustainability and GC maintained a clear weighting trend nearly one year after teaching the lesson plan. The importance of ESD in general was rated on average with a score of 8, a slight reduction as compared to the pre-test. This might have been caused by the decline of the sustainability debate. By 2020, the COVID-19 pandemic had replaced sustainability as the dominant issue in the public media and the political discourse. At the same time, the Fridays for Future movement had faded somewhat from the public eye due to COVID-19 restrictions limiting public demonstrations. The importance of these topics for chemistry lessons was, nevertheless, still rated quite highly by the participants even after nearly a year. The average score was 8.8, which represented a value about one point higher than in the earlier intervention.

4.2. Reflecting on the Action Research Process—The Teacher's Perspective

Another aim of any action research is the increasing professionalization of the participating teachers. Through the interactions between the teacher, the accompanying chemistry education research group, and the action research teacher group, the leading teacher in this project felt a growing awareness of the students' knowledge, needs, and attitudes toward GC. The numerous discussions and reflections contributed significantly to the further development and optimization of the teaching modules, but also the teachers' self-reflection abilities as documented in his research notes.

The other teachers, more experienced in action research, supported the teacher's improvement of the skills of structuring and sequencing the learning material, the integration, and the reflective and targeted use of experiments. Regarding the pedagogical actions of the action research teacher, it can be stated that the action research contributed to supporting and strengthening the teacher's own ideas, prior knowledge of the subject matter, openness to alternative teaching and learning methods, interaction skills, and classroom-based research methodologies, as suggested in [29], e.g.,:

- Structured dialogue and focus group interviews;
- Structured classroom observations;
- Documentation by research diaries;
- Triangulating views and methods.

4.3. Reflecting on the Action Research Process—Perspectives of the Action Research Group

The GC lesson series is modular, as described above. The development of the independence of the modules is the result of discussions within the action research group, in which it was stated that implementation of the complete teaching unit is rather unlikely for most teachers due to the curricular demands, the complexity, and the scope of the series, but rather that only individual modules are taken up and used in the lessons. Over the five years of testing, the modules have therefore been repeatedly checked for independence and optimized.

Numerous worksheets, experiments, media, and social forms were reflected upon and subsequently optimized in the first phase of the project (and later in the following cycles) through group discussions with the action research group with regard to the following aspects:

- Scope;
- Layout;
- Text comprehension;
- Experimental designs;
- Subject and content requirements;
- Tasks (operators, requirement areas, internal differentiation, social forms')
- Balance between text and images;
- Motivational design.

Furthermore, during the first cycle of the action research project, participatory observations by the action research teacher and group discussions with the students, as well as with the action research group, revealed that the experimental approach of high school GC should be expanded.

5. Discussion

This case of applying action research for curriculum innovation shows both the benefits and limitations of action research. The limitations of long-term, classroom-based curriculum development often lie in small, non-representative samples, organizational limitations for data generation, and unpredictable effects such as teacher changes or students leaving the classes. This is suggested as acceptable because of clear benefits on the other hand [30]. These benefits include quick implementation speeds, a development that is carried out and effective in authentic learning environments, feasible solutions, and actions that directly influence teaching and learning practices [22,27,28].

Action research has various goals. Among them are both the development of authentic practices and contributing to the continuous professional development of teachers [28]. Such research can, however, also have the goal of contributing to the general knowledge in a certain field, in this case, chemistry education [22]. The current case shows for the first time that thorough curriculum innovation based on GC is possible already starting at the secondary schooling level. Innovations focus on the basic principles underlying GC for promoting ESD. Several indications also emerged during the study. The indications suggest that GC integrated into high school lessons can potentially increase student motivation and better students' perception of chemistry education.

Although no definitive proof could be obtained from the current study, the larger part of the participants hinted at such a positive outcome in their own personal experiences. Students at the high school level were able to learn and understand what GC is and how chemistry actively seeks paths toward sustainability. Students confronted with GC stated a demand for the thorough integration of modern chemistry practices into their curriculum. Aside from these indications, the experiments developed for the lessons, e.g., [33], can also be viewed as a positive contribution to the knowledge base in chemistry education. Knowledge of available instructional approaches including suggestions for practical work is considered part of the pedagogical content knowledge (PCK) of chemistry teachers and thus necessary for any reform in teaching [34,35].

6. Conclusions

Our classroom experience shows very clearly that students are very receptive to the new approaches based in GC and even demand that they be integrated into chemistry classes across the board in the future. The statements documented above reinforce the approach and the concern to successively link GC (or SC) with other content areas as well and to design a continuous green curriculum for high school chemistry education.

The action research project described in this article was based on the foundations of a hybrid action research model of teacher centeredness and participation. The support provided to the action research teacher by the academic chemistry education research group and the action research teachers took place at the content level as well as at the process and interaction level. The results of the group discussions and the questionnaire studies suggest that GC can generate a significant shift in awareness and changes in the perception (evaluation) of chemistry education in the classroom through engaging materials, numerous experiments, and references to student ownership.

Furthermore, we were able to show that the following perspectives can be brought into focus through the action in this project:

- The positive perception among students and promotion of motivation and interest in chemistry as a subject can take place via GC in high school chemistry education.
- Integration of GC into chemistry curricula offers the possibility to integrate further perspectives (social, economic sustainability, e.g., through contention with LCA).
- Partnerships to achieve curriculum change in chemistry education for ESD make sense and are promising.
- Extension to other content areas of the curriculum seems to be possible and auspicious.

The teaching series on GC has now been presented several times at various conferences and professional development courses and has also received awards. Both reluctance and enthusiasm for the lesson plan were evident among the many other teachers. Most of the reluctance stemmed from teachers' lacking confidence in teaching chemistry differently, in a fashion separate from traditional curricula. In addition to the skepticism of teachers regarding the feasibility of implementing the full series within the curriculum requirements, however, there is also enthusiasm for the topic. Numerous conversations with colleagues show that many of them are very open-minded and very interested in the possibilities of integrating GC into their lessons. Other teachers recognized the need for change. They were acknowledging the motivational potential of combining chemistry education with ESD and GC. In the meantime, individual modules were also being tested and evaluated at other schools and by other chemistry teachers with very good feedback. This reveals a need to better incorporate GC education into teacher education programs and into continuous professional development.

Further research is needed on this topic. Other fields in the chemistry curriculum need to be reflected upon and researched to see if a similar inclusion of sustainability topics in general and GC examples is possible. Additionally, researchers need to answer questions about when to start such lessons. Is it perhaps possible for students to learn about the ideas of GC at the lower secondary science level? First, not yet published trials from grades 8 and 9 (ages 14–15) indicate that it seems to be possible. A corresponding lesson plan is, however, as of yet only tested once and will be subject to further cycles of development. Time and further research will tell. In terms of action research, further projects might be initiated and reflected what action research can do and where it has its limitation, for instance, one case of vocational teaching chemical bonding is described in [21]. The strategy might be open to many fields in education emerging these days, such as a demand for more student-oriented pedagogies, more effective use of ICT in education, or coming up with the growing challenges to education by increasing migration rates in certain countries.

However, what we also learned from the study is that performing action research this way is a very time-consuming demand for a full-time working teacher. Keeping a project of this length running also needs a lot of power of endurance that sometimes also asks for family support because it causes more work and less free time. A teacher going this way needs first to be deeply convinced that change is needed otherwise there is a risk that the initiative peters out. It is helpful to have the approval and support of the school headmaster, an open atmosphere among colleagues, and academic support in case of questions on the content as well as to offer support in strategies of dissemination and publication.

Author Contributions: Methodology, M.L. and I.E.; design and intervention, M.L.; data collection and analysis, M.L.; writing—review and editing, M.L. and I.E.; scientific supervision, I.E.; project administration, I.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. United Nations: Transforming Our World: The 2030 Agenda for Sustainable Development. Available online: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E (accessed on 20 July 2022).
2. United Nations Environment Program (UNEP). 2019. Global Chemicals Outlook II. Available online: www.unenvironment.org/explore-topics/chemicals-waste/what-we-do/policy-and-governance/global-chemicals-outlook (accessed on 20 July 2022).
3. Zuin, V.; Eilks, I.; Elschami, M.; Kümmerer, K. Education in green chemistry and in sustainable chemistry: Perspectives towards sustainability. *Green Chem.* **2021**, *23*, 1594–1608. [CrossRef]
4. Burmeister, M.; Rauch, F.; Eilks, I. Education for Sustainable Development (ESD) and secondary chemistry education. *Chem. Educ. Res. Pract.* **2012**, *13*, 59–68. [CrossRef]
5. Rauch, F.; Pfaffenwimmer, G. Education for Sustainable Development in Austria Networks for Development and Research. In *Schooling for Sustainable Development in Europe*; Jucker, R., Mathar, R., Eds.; Springer: Cham, Switzerland, 2010; pp. 157–176.
6. Mammino, L. A Great Challenge of Green Chemistry Education: The Interface between Provision of Information and Behavior Patterns. In *Worldwide Trends in Green Chemistry Education*; Zuin, V.G., Mammino, L., Eds.; RSC: Cambridge, UK, 2015; pp. 1–15.

7. Holbrook, J.; Rannikmae, M. The nature of science education for enhancing scientific literacy. *Int. J. Sci. Educ.* **2007**, *29*, 1347–1362. [CrossRef]
8. KMK Ländergemeinsame Inhaltliche Anforderungen für die Fachwissenschaften und Fachdidaktiken in der Lehrerbildung, [German for Education Common Agreement on Requirements for Scientific Content and Pedagogical Content Knowledge in Teacher Education]. Available online: https://www.kmk.org/fileadmin/veroeffentlichungen_beschluesse/2008/2008_10_16-Fachprofile-Lehrerbildung.pdf (accessed on 20 July 2022).
9. Anastas, P.; Warner, J.C. *Green Chemistry: Theory and Practice*; Oxford University Press: New York, NY, USA, 1998.
10. OECD. Proceedings of the OECD Workshop on Sustainable Chemistry. Available online: https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=env/jm/mono(99)19/PART1 (accessed on 20 July 2022).
11. Centi, G.; Perathoner, S. From Green to Sustainable Industrial Chemistry. In *Sustainable Industrial Processes*; Cavani, F., Centi, G., Perathoner, S., Trifiró, F.F., Eds.; Wiley-VCH: Weinheim, Germany, 2009; pp. 1–72.
12. Eilks, I.; Hofstein, A. Combining the Question of the Relevance of Science Education with the Idea of Education for Sustainable Development. In *Science Education Research and Education for Sustainable Development*; Eilks, I., Markic, S., Ralle, B., Eds.; Shaker: Aachen, Germany, 2012; pp. 3–14.
13. Obare, S.; Peterman, K.; Middlecamp, C. (Eds.) *Chemistry Education for a Sustainable Society, Volume 1: High School, Outreach, & Global Perspectives*; ACS: Washington, DC, USA, 2021.
14. Mahaffy, P.G.; Krief, A.; Hopf, H.; Mehta, G.; Matlin, S.A. Reorienting chemistry education through systems thinking. *Nat. Rev. Chem.* **2018**, *2*, 0126.
15. Orgill, M.; York, S.; MacKellar, J. Introduction to systems thinking for the chemistry education community. *J. Chem. Educ.* **2019**, *96*, 2720–2729. [CrossRef]
16. Mahaffy, P.G.; Matlin, S.A.; Whalen, J.M.; Holme, T.A. Integrating the molecular basis of sustainability into general chemistry through systems thinking. *J. Chem. Ed.* **2019**, *96*, 2730–2741. [CrossRef]
17. Linkwitz, M.; Eilks, I. Greening the Senior High School Chemistry Curriculum: An Action Research Initiative. In *Chemistry Education for a Sustainable Society*; Obare, S., Peterman, K., Middlecamp, C., Eds.; ACS: Washington, DC, USA, 2021; Volume 1, pp. 55–68.
18. Noffke, S. Action Research: Towards the next generation. *Educ. Action Res.* **1994**, *2*, 9–21. [CrossRef]
19. Feldman, A. Enhancing the practice of physics teachers: Mechanisms for the generation and sharing of knowledge and understanding in collaborative action research. *J. Res. Sci. Teach.* **1996**, *33*, 513–540. [CrossRef]
20. Scott, P.H.; Driver, R. Learning About Science Teaching: Perspectives from an Action Research Project. In *International Handbook of Science Education*; Fraser, B.J., Tobin, K.G., Eds.; Kluwer: Dordrecht, The Netherlands, 2003; pp. 67–80.
21. Laudonia, I.; Eilks, I. Reflections on a three years long teacher-centered, participatory action research experience on teaching chemical bonding in a Swiss vocational school. *Educ. Sci.* **2018**, *8*, 141. [CrossRef]
22. Eilks, I.; Ralle, B. Participatory Action Research in Chemical Education. In *Research in Chemical Education—What does it Mean?* Ralle, B., Eilks, I., Eds.; Shaker: Aachen, Germany, 2002; pp. 87–98.
23. Machado, A.A.S.C. Holistic Green Metrics for Use in Teaching Laboratories. In *Worldwide Trends in Green Chemistry Education*; Zuin, V.G., Mammino, L., Eds.; RSC: Cambridge, UK, 2015; pp. 111–136.
24. Duangpummet, P.; Chaiyen, P.; Chenprakhon, P. Lipase-catalyzed esterification: An inquiry-based laboratory activity to promote high school students' understanding and positive perceptions of green chemistry. *J. Chem. Educ.* **2019**, *96*, 1205–1211. [CrossRef]
25. Leadbeater, N.E. *Microwave Heating as a Tool for Sustainable Chemistry*; CRC: Boca Raton, FL, USA, 2010.
26. Laudonia, I.; Mamlok-Naaman, R.; Abels, S.; Eilks, I. Action research in science education—An analytical review of the literature. *Educ. Action Res.* **2018**, *26*, 480–495. [CrossRef]
27. Mamlok-Naaman, R.; Eilks, I. Different types of action research to promote chemistry teachers' professional development—A joined theoretical reflection on two cases from Israel and Germany. *Int. J. Sci. Math. Educ.* **2012**, *10*, 581–610. [CrossRef]
28. Feldman, A.; Altrichter, A.; Posch, P.; Somekh, B. *Teachers Investigate Their Work. An Introduction to Action Research across the Professions*; Routledge: London, UK, 2018.
29. Bodner, G.; MacIsaac, D.M.; Whyte, S. Action research: Overcoming the sports mentality approach to assessment/evaluation. *Univ. Chem. Educ.* **1999**, *3*, 31–36.
30. Efron, S.A.; Ravid, R. *Action Research in Education*; Guilford Publications: New York, NY, USA, 2019.
31. Norton, L. *Action Research in Teaching and Learning*; Routledge: London, UK, 2018.
32. Mayring, P. *Qualitative Content Analysis*; Sage: Los Angeles, CA, USA, 2021.
33. Linkwitz, M.; Eilks, I. Simple experiments with immobilized enzymes as a contribution to green and sustainable chemistry education in the high school laboratory. *Chem. Teacher Int.* **2022**, *4*, 121–126. [CrossRef]
34. Magnusson, S.; Krajcik, J.; Borko, H. Nature, Source, and Development of Pedagogical Content Knowledge. In *Examining Pedagogical Content Knowledge*; Gess-Newsome, J., Lederman, N.G., Eds.; Dordrecht: Kluwer, The Netherlands, 1999; pp. 95–132.
35. De Jong, O.; Van Driel, J.H.; Verloop, N. Preservice teachers' pedagogical content knowledge of using particle models in teaching chemistry. *J. Res. Sci. Teach.* **2005**, *42*, 947–964. [CrossRef]