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A Systematic Review Research Article on Education for Sustainable Development (ESD) Integration in Chemistry Learning

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Abstract. This article explores the potential integration of Education for Sustainable Development (ESD) in chemistry learning through a systematic literature review of identification, screening, eligibility, and inclusion stages. A total of 13 articles that met the criteria were analyzed with a focus on research design, topic or theme, form of intervention, and outcomes of ESD integration in chemistry learning. The results showed that Research and Development (RnD) dominated the research design. ESD integration topics include chemistry and environment, social and economic issues, natural cycles, the role of innovation and technology, and traditional products. Interventions in learning emphasize the linkage of chemistry concepts with sustainable development issues, involving students in problem-based projects, practical experiments, or discussions with a holistic and contextual approach. Positive impacts include increased environmental protection awareness and motivation, experimental skills development, concept understanding, problem-solving, formulating system maps, and linking chemistry content with sustainable development from social, economic, ethical, and environmental aspects.

Introduction

The consensus of 193 countries united under the United Nations has agreed upon 17 Sustainable Development Goals (SDGs) aimed at enhancing sustainable quality of life in economic, social, and environmental development [1]. To achieve these goals, UNESCO has formulated a vision for education towards empowering students to make informed and responsible decisions for environmental integrity, economic viability, and a just society for both the current and future generations [2]. The fundamental elements of education, including institutions, teachers, students, and society, collectively build an education system capable of shaping and nurturing sustainable awareness within the community and preparing it to face global challenges related to Sustainable Development [3].

Education for Sustainable Development (ESD) can be realized by equipping individuals with knowledge, skills, attitudes, and values to make informed and responsible decisions and actions when addressing issues related to Sustainable Development [4]. Critical thinking skills are essential in identifying issues, analyzing crucial information, assessing the effectiveness of problem-solving, drawing conclusions from thoughts and actions, and evaluating thinking and acting concerning emerging issues in society [5]. Creativity in ESD is required for seeking and generating new ideas, applying technology, or modifying technology that is useful in addressing emerging issues in society [6]. Attitudes and values are needed as the foundation of behavior and actions in their role as responsible individuals in realizing Sustainable Development [7], [8].

Chemistry education plays a crucial role in the development of ESD. Integrating chemical reactions, energy, and the use of chemicals that can lead to climate change, global warming, or environmental pollution can encourage learners to evaluate their use and provide alternative processing solutions based on green chemistry principles [9], [10]. Critical concepts of green chemistry include avoiding persistent, bio-accumulative, toxic, hazardous substances, focusing on the use of renewable resources, resource and energy efficiency, minimizing negative production impacts on the environment, and safety and workplace accident prevention [11]. The ultimate goal of green chemistry is how the field of chemistry can serve as a step and guide in developing the economy through the chemical industry while maintaining environmental sustainability and creating social stability [12].

In addition, applying concepts and technology in chemistry has an important role in developing ESD. Applying concepts and technology can encourage students to reject, accept, develop, or modify by considering the environmental, socio-cultural, and economic impact [13], [14]. For example, the concept of osmosis and the application of reverse osmosis technology can be considered and applied to coastal communities facing freshwater challenges, serving as a guideline for sustainable development research [15]. Another example is the technology for making aromatherapy candles by utilizing the abundance of existing raw materials, which can increase the selling value of a product so that it can be considered for sustainable economic development [16].

Efforts to incorporate ESD into chemistry classes take work. The study of chemistry at the educational level focuses on understanding structure, the nature of changes in matter, and chemical energy [17]. Various ideas emerged as an effort to integrate ESD in chemistry subjects, including adapting green chemistry principles in school laboratory work, adding SDGs content as study material in chemistry subjects, using sustainable issues based on socio-scientific issues in chemistry learning, and developing school projects ESD based [18]. Another thought is to coordinate information of substance, apply information in particular settings, and create chemical techniques in research facility work and innovation [9]. Therefore, this paper aims to provide a systematic literature review of the forms and research designs related to integrating ESD into chemistry education. The second objective is to propose ESD topics that can be applied in chemistry education, along with supporting concepts and ESD dimensions. The third objective is to present various forms of interventions and the resulting impacts on the development of student competencies supporting Sustainable Development.

Research Methods

This research aims to map the forms of research, objectives, and integration results within the ESD integration framework in chemistry learning. A systematic literature review was chosen in this research because it provides a frame of reference for synthesizing academic articles comprehensively, systematically, and transparently by considering the specified eligibility criteria [19]. The steps taken refer to with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach, namely an approach accompanied by selection guidelines from the selected literature [20].

Search Terms

Article searches were carried out using the Scopus and ERIC databases. The first stage of the search is carried out by entering keywords that must be contained in the title or abstract. The inclusion criteria are only journal articles that go through a review process and have complete documents available. The keywords and inclusion criteria used in the ERIC database are (education for sustainable development OR ESD OR Green Chemistry) AND (Chemistry education)) with additional criteria include: peer review only; full text available; journal article; since 2015 and obtained the total document: 1,413. The keywords and inclusion criteria used in the Scopus database are TITLE-ABS-KEY ((education AND for AND sustainable AND development OR ESD OR green AND chemistry) AND (chemistry AND education)) AND PUBYEAR > 2009 AND PUBYEAR < 2024 AND (LIMIT -TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) and obtained a total of 208 documents.

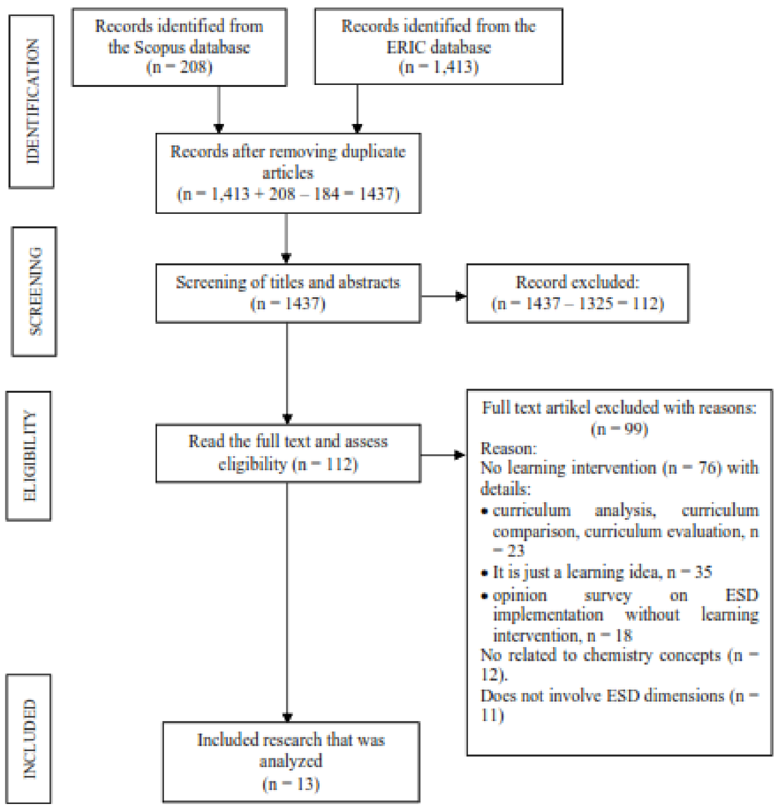
Selection criteria

A number of criteria were determined from English language articles. The selection criteria are:

- Articles that focus on forms of intervention implemented in ESD-integrated chemistry learning.
- The impact of ESD-integrated chemistry learning interventions (e.g., knowledge, skills, attitudes, motivation, and response) on sustainable development is clearly stated qualitatively and quantitatively.
- Involve intervention participants at the minimum secondary school level (including junior and senior high school).
- ESD-integrated chemistry learning interventions have at least one of three ESD dimensions (environmental, social, or economically sustainable).

PRISMA Stages

The stages of systematic literature review carried out consists of four stages, namely the identification, screening, eligibility, and included stages [21]. The identification stage is carried out by entering keywords, including criteria described in the search item section, and excluding duplicate articles. The screening stage is carried out to exclude irrelevant articles through abstract analysis. The eligibility stage is carried out by carefully reading the complete article and adjusting it to the selection criteria that have been formulated. The final stage is included, which is to select, analyze, and synthesize articles that match the theme. The steps, along with the results of the prism stages, can be seen in Figure 1.



GAMBAR 1. Diagram alir prosedur systematic literature review yang dilakukan

Results

The Systematic Literature Review in this research is divided into three parts. The first section examines the research design on integrating ESD in chemistry learning. The second part examines the topics, supporting concepts and dimensions of ESD used in learning. The third section examines forms of chemistry learning interventions integrated with ESD.

Research Design for ESD Integration in Chemistry Learning

This section analyzes 13 selected articles based on the themes of research objectives, research form, and design and intervention subjects (Appendix 1). Based on the form and research design is divided into three, namely Research and Development (RnD) with a total of 9 articles (68%), Practice-Based Action Research with a total of 2 articles (16%), Model of Educational Reconstruction (MER) with a total of 1 article (8%) and Interpretive Case Study Research (8%). The results of the research "Research and Development (RnD)" analysis show development activities or modification of learning materials, modules, experiments, and learning strategies to improve the quality of chemistry learning. In the form of research, "Action Research and Practice-Based Action Research", the subject teachers work collaboratively to develop learning materials and plan the implementation of learning and involve a cycle of action, evaluation, and reflection, thus creating an environment that supports continuous improvement in teaching and learning in the classroom. The research form "Model of Educational Reconstruction (MER)" provides an overview of the insertion or reconstruction of commonly used learning materials with additional research results that have relevance to the subject matter and contribute to the development of learning materials that are dynamic, relevant, and by the latest developments in the field of research. The form of research, "Interpretive Case Study Research, " provides an overview of theoretical concepts and practical aspects that can improve chemistry learning.

The research objective themes can be grouped into seven categories. The first category is Green Chemistry and Environmental Impact, with the main focus on the principles of green chemistry and its impact on the environment [22], [23], [24]. The second category is Context-Based Chemistry Education, with the main focus centred on the environmental context by presenting real problems [25]. The third category is Inquiry-Based Learning, with the main focus on the process of inquiry and exploration, the development of problem-solving skills and promoting contextualization and relevance in life [26], [27], [28]. The fourth category is Conceptual Understanding and Attitudes, with the main focus on exploring students' conceptual understanding of chemistry materials and measuring students' attitudes towards the environment and sustainable development [29], [30], [31]. The fifth category is Sustainable Development Education, with the main focus on the integration of sustainable development concepts and principles in chemistry learning and its influence on students' understanding and attitudes [32]. The sixth category is Socio-Scientific Inquiry and Literacy, with the main focus on integrating socio-scientific issues in chemistry learning and evaluating students' science literacy and responsible attitudes as citizens [33]. The seventh category is Cultural Responsiveness in Chemistry Education, with the main focus on responsiveness to students' culture in the context of chemistry learning, as well as its influence on students' cultural identity and cultural sustainability [34].

ESD Topics Studied in Chemistry Learning

This section analyzes 13 selected articles on ESD topics, supporting concepts and ESD dimensions. Based on (Appendix 2), the reviewed ESD topics in chemistry learning illustrate the close relationship between chemistry, sustainability, and education. Within this framework, the emphasis on environmental sustainability is strong through waste management, renewable energy, and green chemistry themes. Themes such as the degradation of acridine orange with H_2O_2 and UV radiation under various conditions [22], utilization of waste as raw material for production and recycling as an effort in waste treatment [26], selection of environmentally friendly fuel types [33], and the use and consequences that can arise from chemical processes in local communities show the various efforts that can be made to protect the environment from chemical waste [32]. The integration of social and economic issues, such as the production of biodiesel from palm oil [35], the use of natural pesticides [30], and designing environmentally friendly micro-scale power plants [28]. The examples show that chemistry education considers not only scientific aspects but also its impact on society and the economy. Thus, learning chemistry in the context of sustainability can provide opportunities to create individuals who have a deep awareness of chemistry's impact and how to develop sustainable solutions.

Themes addressing natural cycles, climate change and eutrophication highlight the importance of understanding natural cycles in the context of sustainability. Themes such as the carbon cycle and its relationship to water quality and global warming are associated with students' attitudes, relevance and awareness of environmental issues [25]. Hydrological and biogeochemical cycles with real-world phenomena and conditions (climate change, ocean acidification, eutrophication) are linked to sustainable development issues related to sustainable food and energy availability [31]. In addition, the theme of Volcanic Ash Derived Soils (VADS) can be used as a sustainable solution to prevent the risk of groundwater pollution from herbicides [29]. The role of innovation and technology in achieving sustainable development is illustrated through themes that examine the production of biodiesel from palm oil [35], environmentally friendly micro-scale power generation [28], sugar beet processing technology into environmentally friendly bioplastic [36] and utilization of green chemistry concepts in organic synthesis experiments from a sustainable development perspective [24]. In addition, themes related to traditional food and beverage ingredients [34] highlight the relevance of chemistry learning to cultural sustainability, making chemistry a tool for understanding and overcoming sustainability challenges in the real world.

Supporting concepts in chemistry, such as chemical kinetics, green chemistry concepts, analytical chemistry, organic chemistry, and chemical energetics, are closely related to the previously described ESD topics. For example, the concepts of chemical kinetics and oxy radicals support understanding chemical reactions in pollutant degradation. At the same time, analytical chemistry, particularly in concentration analysis of water properties, is relevant to understanding water quality in the context of the hydrological cycle. Organic chemistry, such as the carbon cycle, is directly related to the theme of the carbon cycle and greenhouse effect in environmental sustainability. The concepts of chemical energetics, combustion reactions and average bond energy provide a foundation for understanding energy use and its impact on sustainability. Site-specific biological and geological data support a localized understanding of sustainability challenges in the region. Chemical (C, N, P, S) and hydrological cycles are closely related to sustainable development and environmental impact. The concepts of oxidation and reduction aid the understanding of chemical processes in pollutant degradation and environmental pollution. Introduction to GC and application of GC principles support the theme of green chemistry, particularly in the context of renewable raw materials and biotechnological processes. The synthesis and use of PLA and bioplastics support the theme of using environmentally friendly materials. In addition, concepts such as water composition, water quality and pollution contribute to understanding the sustainability of water resources. A deep understanding of these concepts embraces the integration of sustainability principles in chemistry learning, promotes awareness of the impact of chemistry on the environment, and stimulates future sustainable practices.

Chemistry concepts studied, such as green chemistry, organic chemistry (carbon cycle), and chemical cycles (C, N, P, S), can be linked to the social dimension through understanding local communities' sustainability challenges. Biological and geological data for a place, as well as data on energy use and carbon footprint, can provide social insights into the impact of the surrounding environment. The concept of chemical energy and applying GC principles can also be linked to the economic dimension, enabling thinking about the economic aspects of chemical processes and sustainable practices. Meanwhile, these concepts, along with analytical chemistry and materials/energy, support the environmental dimension by providing an understanding of the interaction of chemistry and the environment and how to support sustainability principles. The integration of these concepts in chemistry learning allows students to explore the social, environmental, and economic impacts of chemistry, encouraging critical thinking about the role of chemistry in sustainable development.

Types and Outcomes of ESD-Integrated Chemistry Learning Interventions

This section analyzes 13 articles on the types of intervention and the results achieved. The learning intervention (Appendix 3) shows that the ESD-integrated approach in chemistry learning has several characteristics. First, there is an in-depth effort to link chemistry concepts with sustainability issues, such as photolytic oxidation in dealing with pollutants, the impact of biodiesel on economic, environmental, and social aspects, and the use of sustainable pesticides. Second, students are involved in practical experiments, discussions, and problem-based projects to understand and apply these concepts in real life. Third, a PBL (Problem-Based Learning) approach, an inquiry model, and the use of web platforms are used to enhance student engagement and develop problem-solving skills, critical thinking, and digital literacy. Fourth, using modules, multimedia materials, and field activities support holistic and integrated learning experiences. Fifth, learning is designed to encompass social, environmental, and economic dimensions, ensuring students can connect chemistry concepts to the overarching context of sustainability. In addition, the learning intervention reflects a holistic and contextual approach to integrating chemistry learning with ESD principles, preparing students to understand and face the challenges of sustainable development.

The results of ESD-integrated chemistry learning show that college and high school students have experienced positive changes in various aspects. They have increased awareness of environmental issues and the relevance of chemistry in protecting the environment and personal life. In addition, they have developed better experimental skills, understanding of basic kinetics concepts and problem-solving abilities. Pre-service teachers and high school students also play an essential role in providing relevant chemistry concepts, positive attitudes, motivation, and values that support environmental protection. Students have also mastered the knowledge of sustainable development and the ability to analyze chemical processes with green chemistry principles. They can formulate system maps, connect chemistry content with socio-economic, ethical, and ecological aspects, and relate chemistry learning to everyday life. In addition, students' motivation to address sustainable environmental issues has also increased, making chemistry learning more meaningful in the context of environmental protection and sustainable development.

Discussion

Systematic literature review shows that there are variations of research on ESD integration in chemistry learning (e.g. Research and Development, Action Research Model of Educational Reconstruction and Interpretive Case Study Research). The tendency of variations in research forms and designs shows that integrating ESD in chemistry learning allows researchers to design and develop contexts and issues of sustainable development from local, regional and world [9]. In addition, the emphasis on evaluating ESD integration results allows it to be revised by considering the obstacles and constraints encountered during the learning intervention to realize the practice in the field by the objectives of ESD [37]. Involving various parties, such as teachers, students, chemists, and curriculum experts, in developing ESD-integrated learning is also essential. It contributes to the framework of long-standing learning practices, static material content, and awareness of collaboration to change learning habits [38].

From the systematic literature review conducted, it was found that the topic or theme of learning varies greatly. The results of this analysis reflect the complexity and uniqueness of ESD integration in learning, which depends on the context of sustainable development. Flexibility in selecting ESD topics enables education that effectively addresses social, economic and environmental changes and engages students in understanding and participating in addressing the complexities of sustainable development according to the context or theme presented [39]. In addition, the variety in ESD topics allows for more effective integration according to the level of education, supporting concepts contained in the education curriculum so that ESD topics are highly relevant and efficiently support the achievement of competencies guided by the subjects in the curriculum [40], [41].

The forms of intervention in the systematic literature review show the potential to achieve the competencies individuals need to realize sustainable development. Through holistic and structured learning approaches, models and strategies can help students understand sustainable issues in depth. The use of active learning methods helps students understand sustainable issues in depth. The importance of local context also allows students to relate learning to sustainable issues around them. Developing critical, social and reflective skills is also essential in this approach. In addition, reflecting students' attitudes and views towards sustainable development is vital, encouraging a deep understanding of how individual actions can affect the sustainability of the environment and society. With stakeholder engagement and ongoing evaluation, ESD interventions can help shape positive attitudes and outlooks that support efforts towards sustainable development, creating a caring and responsible generation towards pressing global and local issues.

CONCLUSION

In conclusion, we state that the systematic literature review conducted on the study of the integration of ESD concepts in chemistry learning can clarify the description of the form and design of research, the breadth of ESD topics that can raised in chemistry learning as well as the forms of intervention in chemistry learning at the secondary and tertiary education levels and the positive ESD competency outcomes obtained. Thus, integrating ESD concepts into chemistry learning has the potential to develop.

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APPENDIX 1. Research Design in ESD Integration Research in Chemistry Learning

Author	Aim	Research forms	Research design	Subject of Intervention
Ashraf et al. (2012)	To Investigate the impact of green chemistry-based experiments on the oxidative, photolytic effects in the degradation of organic pollutants on environmental awareness, data analysis, experimental skills, and fundamental kinetics concept understanding.	Research And Development (RnD)	Develop a simple green chemistry-based experiment on the oxidative, photolytic effects in the degradation of organic pollutants and implement it in chemistry classroom learning.	Second-year chemistry student
Mandler et al. (2012)	To investigate the impact of environmental context-based chemistry learning on students' attitudes, relevance and awareness of environmental issues.	Research And Development (RnD)	Develop a green chemistry-based experiment module in the context of the environment, conducting workshops with teachers and students to obtain suggestions and feedback for improvement, revising the module, and concluding with its implementation in chemistry education.	12th-grade students
Karpudewan et al. (2012)	To Investigate the impact of green chemistry laboratory guidelines adapted to the environmental context of Malaysia on achievement, pro-environmental attitudes, values, and motivation.	Research And Development (RnD)	Develop a green chemistry-based experiment module in the context of the environment, conducting workshops with teachers and students to obtain suggestions and feedback for improvement, revising the module, and concluding with its implementation in chemistry education.	pre-service teachers and secondary school students
Juntunen & Aksela (2013)	To investigate the impact of an inquiry-based life-cycle thinking project on students' attitudes about chemistry and environmental literacy in the classroom	Research And Development (RnD)	Develop learning content accompanied by an inquiry-based assignment related to life cycle thinking and research and conclude with chemistry learning implementation.	Ninth-year secondary school students
Overton & Randles, (2015)	To investigate the impact of dynamic PBL module on problem-solving skills, Sustainable development, communication of results, collaboration, and motivation.	Practise-based action research	Implement the learning scenario plan with the dynamic PBL model and evaluate the implementation results based on the action's targeted impact and practicality.	first-year chemistry undergraduates
Koutalidi et al. (2016)	To investigate students' understanding and misconceptions of the concepts of hydrological and biogeochemical cycles and attitudes towards the environment and sustainable development.	Research And Development (RnD)	It develops learning materials by considering knowledge gaps, reviewing relevant literature, considering the needs of educators and their relationship with ESD, and implementing the learning materials into chemistry learning in the classroom.	secondary schools
Timmer et al. (2018)	To investigate the impact of modifying organic chemistry experiments integrated with green chemistry on the ability to analyze and evaluate chemical reactions	Research And Development (RnD)	Modifying conventional experimental laboratory work instructions by incorporating green chemistry principles. Furthermore, the modified results	chemistry undergraduates

	and processes from a sustainable development perspective.		are applied in the implementation of laboratory work.	
Eaton et al. (2019)	To investigate a system thinking approach to sustainability knowledge in the context of procurement, use and other consequences of chemical processes and impacts on the global community.	Research And Development (RnD)	Develop a context for use in learning deep thinking systems, and the context is organized into a learning module with additional information or supporting concepts through the digital platform. Furthermore, the platform is implemented in chemistry learning in the classroom.	12 chemistry students
Zidny et al. (2021	To investigate the impact of providing socio-scientific issues on students' ability to deliver chemical arguments and concepts with real-world problems in context.	Model of Educational Reconstruction (MER)	It is inserting or reconstructing commonly used learning materials with additional research results relevant to the subject matter in the learning materials (pesticide learning materials inserted with relevant bio-pesticide research results). Furthermore, the reconstruction results of learning materials are implemented in learning.	first-year university chemistry student teachers and secondary school students
Ca´ceres-Jensen et al, (2021)	To investigate the impact of socio-scientific environmental chemistry module design on contextualized chemical knowledge and scientific skills	Research And Development (RnD)	Designing an environmental chemistry module with socio-scientific issues that has PBL stages and then implemented in learning.	Preservice Chemistry Teachers
Linkwitz & Eilks (2022)	To investigate the impact of implementing an organic chemistry learning module themed "from sugar beet to bioplastic" on students' perceptions and attitudes of sustainable development.	Action research	The group of subject teachers collaboratively developed materials and implementation plans to obtain feasible results. Furthermore, the results of learning materials and implementation plans are implemented in the classroom, forming several cycles of action, evaluating results, reflection and revision.	secondary school students
Georgiou & Kyza (2023)	To investigate the impact of socio-scientific inquiry-based learning (SSIBL) on science literacy and civic responsibility attitudes.	Research And Development (RnD)	The group of teachers compiled and developed a learning program. Furthermore, the program is applied in experimental research by comparing the results of students taught using the program and the control group without using the developed program. The results obtained are then compared so that the effectiveness of the developed program is known.	Chemistry high school
Rahmawati et al, (2023)	To investigate culturally responsive transformative teaching (CRTT) and its influence in building students' cultural identity towards cultural sustainability while learning chemistry concepts.	interpretive case study research	Implementing CRTT learning and naturally observing the learning process, reducing, coding data, analyzing, interpreting, and drawing conclusions about student engagement in cultural	high school chemistry

		sustainability through applying CRTT in chemistry learning.	

APPENDIX 2. ESD topics studied in the ESD Integration in Chemistry Learning Research

Author	Topic ESD	Supporting Concept	ESD Dimensions
Ashraf et al. (2012)	Degradation of Acridine Orange with H_2O_2 and UV radiation under various conditions.	Basic chemical kinetics, oxy radicals, environmental pollution, green chemistry concept.	Environment
Mandler et al. (2012)	Water quality. Carbon cycle and the greenhouse effect.	Analytical chemistry (water properties concentration, purification). Organic chemistry (carbon cycles, chemical equilibrium, electromagnetic radiation: absorbance, emission, and transmission)	Environment
Karpudewan et al. (2012)	Biodiesel production from palm oil (topic of particular interest in the laboratory manual)	Chemical energetics (combustion reactions, average bond energy), hydrocarbons, and organic chemistry	Economy Environment Society
Juntunen & Aksela (2013)	Raw materials, manufacturing processes, and utilization, as well as recycling and waste management	Materials and energy, pollution, environmental sustainability	Environment
Overton & Randles, (2015)	Designing a microgeneration village. Energy-producing and waste-treatment universities. Biodiesel and bioethanol production. Designing the most environmentally friendly university.	Biological and geological data particular to the place, data on energy use and carbon footprint, employment densities, and a budget spreadsheet	Economy Environment Society
Koutalidi et al. (2016)	Design hydrological and biogeochemical cycle materials with real-world phenomena and conditions (climate change, ocean acidification, eutrophication) and their relationship to sustainable development issues (sustainable consumption and production, renewable energy).	Carbon, nitrogen, phosphorus, sulfur and hydrological cycles	Economy Environment Society
Timmer et al. (2018)	Green chemistry in organic synthesis experiment	Oxidation and reduction Electrophilic aromatic substitutions. Grignard reactions. Carbonyl chemistry	Environment
Eaton et al. (2019)	Chemical processes, planetary boundaries and sustainable development	Chemical equilibrium and Organic chemistry	Economy Environment Society
Zidny et al. (2021	Bio-pesticide use from different worldview perspectives	structure of matter, chemical bonding, organic chemistry, chemical reaction and chemical analysis.	Socio-economic. Ethical. Ecological.
Ca´ceres-Jensen et al, (2021)	Volcanic Ash Derived Soils (VADS) and prevention of groundwater pollution risk from herbicides	Qualitative Analytical Chemistry: Soil Sampel. Sorption Kinetics of Pollutants in Soils.	Environment
Linkwitz & Eilks (2022)	Green Chemistry "from Sugar Beets to Bioplastics"	Introduction to GC. Renewable raw materials Biotechnological processes. Enzymatic catalysis. Applications of various principles of GC.	Economy Environment Society

		Synthesis and use of PLA and other bioplastics	
Georgiou & Kyza (2023)	What type of fuel will you choose?	Air composition, quality and pollution. combustion of energy. chemical structure of diesel/biodiesel.	Economy Environment Society
Rahmawati et al, (2023)	Chemistry of Dodol, pempek (tradisional food) and chemistry of Lahang (tradisional drink)	System and colloid preparation, electrolyte and non-electrolyte solutions, acid-base properties and functional alcohol groups.	Socio-Cultural

APPENDIX 3. Forms and Results of ESD-Integrated Chemistry Learning Interventions

Author	Form of Intervention	Results achieved
Ashraf et al. (2012)	Pre-lab: discussion on issues, as well as the role of chemistry, including photolytic oxidation in tackling environmental pollutants, Lab activity: experiments to degrade organic pollutants with photolytic oxidation. Post-lab: class discussion of the results obtained and the pros and cons of using photolysis in the degradation of organic pollutants.	Students give a positive response to the rudeness of the issue and the rudeness of environmentally friendly chemistry, develop experimental skills, analyze data and understand basic kinetics concepts.
Mandler et al. (2012)	Reconstructing prior knowledge in real life, further exploration of identified principles, extension of knowledge from experimentation and data analysis, synthesis of knowledge from initial understanding and extension and ending with application of understanding to new situations.	Students experienced significant changes in their awareness of environmental issues, positive perceptions, and the relevance of chemistry in protecting the environment and personal life.
Karpudewan et al. (2012)	Pre-lab: discussion of relevant literature review on the discovery of diesel and the impact of its use. Lab activity: experiment to make biodiesel from palm oil. Post-lab: analyze the advantages and disadvantages of biodiesel and the economic, environmental, and social impacts.	Pre-service teachers and secondary school students provide relevant chemistry concepts, attitudes, motivation actions, and values to protect the environment.
Juntunen & Aksela (2013)	Students in small groups create a product recycling project by considering the raw materials, product utility, manufacturing and use process, lifetime, footprint, and responsibility for the health effects and environmental impacts of the product created.	Students provide a positive attitude towards learning chemistry where the learning atmosphere is independent and collaborative. There is a change in environmental literacy that forms awareness about the importance of environmental protection and recycling.
Overton & Randles, (2015)	Students choose a topic, solve problems using the PBL model steps, present the results and make a final report.	Students handle problems effectively, problem-solving skills, communication, and collaboration have improved and are positively motivated towards learning.
Koutalidi et al. (2016)	The developed biogeochemical teaching materials are implemented in learning through brainstorming, concept maps, experiments, simulations and models, and field activities in urban environments and memorable eras.	Students have good knowledge of biogeochemical cycles and sustainable development and form a positive attitude towards the environment and sustainable development.
Timmer et al. (2018)	Students are given a practical problem-solving project of synthesizing 4-methylumbelliferone drug via condensation of Dowex 50WX4 immobilized by choosing one of the four most environmentally friendly protocols concerning hazards, waste handling, practicality in industry and energy consumption.	Students show excellent analysis and evaluation skills of chemical reactions and processes from the perspective of green chemistry principles and sustainable development, as seen from the project report results.

Eaton et al. (2019)	Students are introduced to the topics of equilibrium and organic chemistry, explore the relationship between chemical processes, examine the impact of chemical processes on sustainable development, explore multimedia-based learning resources, and make connections into thinking systems through mind maps or concept maps.	Students can formulate a system map and evaluate the positive and negative impacts of the system map based on the principles of sustainable development.
Zidny et al. (2021	Students are given the social isue of synthetic and natural pesticides used by traditional communities, analyze the risks and benefits of using natural pesticides, and present the information in class. In the final stage, students apply chemistry concepts to strengthen their argument about the sustainable use of pesticides.	The group of university and high school students could make connections between content and concepts at specific boundaries. They were able to provide relevant arguments related to the context studied with socio-economic, ethical, and ecological aspects.
Ca´ceres-Jensen et al, (2021)	Students are given a real environmental problem (REP) related to the absorption kinetics of glyphosate (GPS), metsulfuron-methyl (MSM), and diuron (DI) herbicides in VADS, their differences in absorption rates, transportation, and potential groundwater pollution and solve these problems through the stages designed in the developed environmental chemistry module.	Students gain knowledge and skill development in contextualizing chemistry knowledge using digital resources and spreadsheets in a scientific context. They are primarily motivated by a learning environment that helps them solve real problems and develop research interests in environmental chemistry.
Linkwitz & Eilks (2022)	Students study seven learning sequences, namely Introduction to Green Chemistry (module 1), application of Biotechnology and Renewable Raw Materials (modules 2 and 3), synthesis with Biocatalysts and Microwaves (modules 4 and 5), synthesis of PLA as a renewable bioplastic (modules 5 and 6) and critical product evaluation (module 7).	Students positively perceive the application of chemistry, the development of innovative ideas, and high interest in and motivation to overcome problems related to environmentally friendly sustainable development.
Georgiou & Kyza (2023)	Students follow three phases of learning. The first phase debates scientific controversies about the use of diesel and biodiesel. The second phase is an inquiry-based scientific investigation on a web-based platform. The third phase disseminates the inquiry results to fellow citizens (parents, siblings, teachers, and other students).	Students demonstrate good science literacy skills, a sense of personal responsibility and a willingness to take action to maintain a sustainable environment.
Rahmawati et al, (2023)	Students follow four learning phases, starting from exploring cultural identity, contextualising culture and chemical concepts, exploring cultural and chemical concepts through collaborative work, critical reflective thinking through class debates, and transforming understanding and cultural values based on learning experiences.	Students believe learning chemistry is more meaningful by linking curriculum content, local cultural practices, applications and chemistry in everyday life.