Part 9 / Strand 9

Science Education For Sustainability, Agency And Futures Literacy

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Theories, methods, and practices of science education for sustainability, agency, and futures literacy. Includes future-oriented proposals for framing science education research agenda into contemporary debates on agency, sustainable development and sustainability education as well as analysis, discussion and reflection about both contemporary and foundational competence frameworks, reports and agendas at the European and international level.

Sub-themes:

1) Theories, methods, and practices of science education for sustainability
2) Theories, methods, and practices to Foster Agency and Empowerment
3) Futures Literacy and Future Thinking in Science Education
4) Policy and Practice in Science Education for Sustainability

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Strand 9: Science Education for Sustainability, Agency and Futures Literacy

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Strand 9 brings together research concerned with the role of science education in addressing sustainability challenges, socio-scientific complexity, civic participation and futures-oriented science education. The strand focuses on how learners, teachers and educational communities can engage with environmental, technological and social issues that are uncertain, contested and ethically charged. Across the contributions, science education is not framed simply as the transmission of scientific knowledge, but as a space for developing responsibility, agency, critical reflection, communicative rationality, future literacy and democratic participation.

The papers included in this section cover a wide range of sustainability-related themes. Scientific literacy continues to be a strong theme particularly in relation to political and structural issues associated with the energy transitions. Several contributions go in depth about the significance and necessity of bringing together disciplines across the natural sciences to address social and environmental challenges, including biodiversity loss, green infrastructures, ecosystem services, wind energy, critical raw materials, bio-based plastics, vegan diets and green and sustainable chemistry. These papers explore how science education can make complex environmental issues meaningful for students and teachers by connecting scientific concepts with ethical, emotional, political and everyday dimensions of sustainability. In this sense, the strand strongly reflects the conference theme of sustainability, showing how environmental issues are increasingly approached through interdisciplinary, participatory and action-oriented pedagogies.

A second important group of contributions focuses on Education for Sustainable Development, Global Citizenship Education. These papers examine teachers' competences, willingness and pedagogical preparation for integrating ESD into school and university contexts, including technical and higher education. Ongoing attention is given to the importance of teacher preparation learning through professional development courses, exploratory seminars, interdisciplinary teaching and design-based approaches which supports students in assessing sustainability controversies from environmental, economic and social perspectives. Together, these contributions highlight that sustainability-oriented science education requires not only new topics, but also new forms of curriculum design, teacher learning and institutional support.

A third set of papers foregrounds responsibility, agency and civic engagement. Contributions examine a wide range of assessment tools for measuring students' sense of responsibility in chemistry-related STSE contexts, which emphasise wider civic competencies with practical applications in climate assemblies, opportunities for youth participation, placemaking, and collective and political agency in the Anthropocene. These studies point to a shared concern: students need opportunities to participate in decision-making, imagine alternative futures, engage with uncertainty and act in relation to complex global challenges such as climate change, biodiversity loss and social inequalities. Approaches such as serious games, imagining futures are offerings which are multi-modal and participatory. These contributions also resonate with the conference theme of digital advances suggesting that digital and game-based environments can support imagination, systems thinking, collaboration and engagement with complex sustainability issues when they are embedded in critical and pedagogically meaningful designs.

Positioned within the wider field of science education research, Strand 9 contributes to ongoing debates on scientific literacy, STSE education, socio-scientific inquiry, ESD, climate change education, and democratic approaches to science education. The contributions collectively challenge narrow technocratic views of science education and call for pedagogies that are more relational, critical, participatory and future-oriented. They portray science education as a key site for preparing learners and educators to understand complexity, to deliberate about values, to imagine desirable futures and participate responsibly in the transformation of society towards more just and sustainable worlds.

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Trade-Offs In ESD Related To Using Wind Energy – A Study Conception

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The use of wind energy is highlighted in the interests of sustainability. At the same time, wind turbines harm the environment due to their demand for raw materials and their purification processes. A trade-off is required. For education for sustainable development (ESD), this expresses the need to promote evaluation skills in addition to the transfer of knowledge about raw materials. Research is already being carried out on the contents of raw materials, evaluation skills, and dealing with trade-offs within ESD. This project aims to expand the discussion of raw materials in the context of wind turbines while incorporating new evaluation perspectives, including emotional interaction. This is considered particularly relevant in the emotionalised context of ESD trade-offs. Therefore, an intervention study monitors the interaction of school students with different presentations of the trade-offs related to wind turbines. The article shows the structure of the project, the methodological approach as well as initial findings from the first study.

Keywords: Education for Sustainable Development, Raw Materials, Emotion

Introduction

Global warming increasingly poses a threat to the environment. To reduce the impact of energy supply on the climate, efforts are being made to expand renewable energies such as wind energy, as set out in SDG 7.2. No greenhouse gases are released when wind energy is converted into electrical energy. Nevertheless, the energy supply with wind energy is not 'neutral' in terms of climate and environment. Raw materials such as iron, copper, rare earth elements, aluminium and carbon fibre are required for the construction of wind turbines (Rueda-Bayona et al., 2022).

With its demand for raw materials and the associated purification processes, the technology declared sustainable in SDG 7.2 counteracts the efforts of SDG 15 to a certain extent; making a trade-off necessary. Such trade-offs over raw materials are represented more transparent in the media, most recently concerning lithium mining (e.g. Santos, 2024). This can be overwhelming for school students. ESD aims to support students develop the skills they need to help shape sustainable development despite trade-offs. The ability to allow ambiguity and to learn balancing different goals are central to these skills (UNESCO, 2020). Therefore, when dealing with trade-offs in ESD, it is necessary to analyse the content of raw materials but also train evaluation skills and create a framework that allows for ambiguity. In doing so, the emotional impact of the content needs to be considered in addition to the content itself.

In the following, the context of wind turbines presents the content level. While fossil-fuelled energy plants place a heavy burden on the environment during the operational phase, wind energy has almost no impact on these factors during operation. But what about the phases before and after operation? Life cycle assessments include these steps in their endpoint categories of ecosystem, human health, and resource depletion (Rueda-Bayona et al., 2022). They show that wind energy plants have the greatest impact on the environment in their production including the mining, beneficiation and purification of raw materials (Xu et al., 2018). These processes require energy and chemicals and release emissions into soil, water, and air. This can be exemplified by the purification of the rare earth element neodymium. Neodymium is used in permanent magnets in the generators of some wind turbine types. Usually, concentrated sulphuric acid is used for leaching of neodymium-containing ores, e.g. fluorocarbonates. This produces harmful by-products such as hydrogen fluoride. In addition, radioactive thorium is released, and acidic wastewater remains due to incomplete reactions (Schreiber et al., 2021).

Even though life cycle assessments identify different environmental impacts of wind turbines, the primarily impact is the abiotic resource depletion potential of chemical elements (Atilgan & Azapagic, 2016). The impacts can be varied depending on decisions in three areas: the energy plant itself (Atilgan & Azapagic, 2016), the raw materials used (Schreiber et al., 2019), and the processing of the raw materials (Li et al., 2019).

Although the trade-off is dealt with, scientifically, in life cycle assessments, it is hardly ever recognised in society and schools. So far, school students have made an undifferentiated distinction between renewable and non-renewable energy use with the descriptions clean and dirty (Hüfner, 2020). A differentiated evaluation allowing ambiguity must be aimed, for example with the process-oriented framework PAAWD^R (Langlet et al., 2022). It allows to focus on ambiguity, criteria determination, and balancing more closely, which are of particular interest in these complex trade-offs in ESD. PAAWD^R divides the process into the steps of perceiving, analysing, arguing, weighting, deciding, and reflecting (Langlet et al., 2022).

Regarding the perception, it requires an openness to engage with the trade-off and to allow nuances between the clean-dirty distinction. In ESD contexts, the emotional preload and reaction should not be overlooked, especially due to the nature of the challenge in trade-offs. Studies show that learning in the context of climate change can evoke worries, hopelessness, and helplessness. Half of young people are very worried about climate change (Hickman et al., 2021) and disillusioned about a sustainable future (Grund & Brock, 2019). The sometimes resulting helplessness (Kuthe et al., 2020) runs counter to the aim of ESD to promote the ability to shape the future.

In addition to their impact on society, emotions such as fear and hopelessness can be harmful to the learning success. In achievement emotions, positive activating emotions such as joy were found out to be the most promising, and negative deactivating emotions such as hopelessness the least promising (Pekrun et al., 2007). The feeling of hope can counteract paralysing fear or hopelessness (Kleres & Wettergren, 2017). Grund and Brock (2019) therefore encourage emotionally sensitive ESD with the promotion of constructive hope. This in mind, solution-oriented approaches are developed along the sustainability strategies of sufficiency, efficiency, and consistency (e.g. Applis et al., 2022). In this research project, aspects of these solution-oriented approaches will serve as inspiration for the design of the intervention and learning content.

Aim And Research Questions

The aim of the whole project is to design a learning unit for chemistry. Using the example of the raw material demand for wind turbines, the unit should introduce school students to an emotionally charged ESD trade-off in a sensitive manner and support them in making differentiated evaluations.

To this end, two key questions with sub questions will be investigated and categorised according to the PAAWD^R model. The first question focusses on perception. The second question covers weighting, deciding, and reflecting.

1. How do school students perceive different facets of the trade-offs on wind turbines?
   1.1 Which area would they like to deepen?
   1.2 Which emotions occur while being confronted by the trade-offs?

2 What information is relevant for school students in their decision-making process of the trade-offs regarding wind turbines?
   2.1 Which criteria are important to them?
   2.2 How does their evaluation change?
   2.3 Why does their evaluation (not) change?

Method

Within this project, the research questions are investigated through two studies using a mixed-methods design. The study presented here focuses quantitively on students' perception of the trade-offs (RQ1, $N = 129$). It was conducted in 2025 with 10th and 11th grade students. The second research question (RQ2) will be addressed qualitatively in a separate forthcoming study.

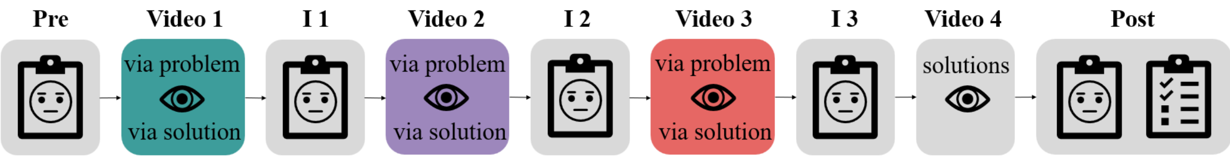
The trade-offs addressed in the study cover the three areas mentioned: energy plants (contrasting wind energy and natural gas plants), raw materials (contrasting the use of a higher amount of copper to rare earth elements in the generator of an energy plant), processing (contrasting pyrometallurgical and hydrometallurgical methods). The trade-off interventions are presented as videos with a duration of two to three minutes. Moreover, the subject of solution perspectives is addressed, using examples from the sustainability strategies sufficiency, efficiency and consistency (see table 1).

Table 1. Content of the intervention.

	Energy plant	**Raw materials**	**Processing**
Problem-oriented trade-off	Wind energy vs. natural gas	Copper vs. rare earth elements	Pyrometallurgical vs. hydrometallurgical
Added solution approach	Sufficiency	Efficiency	Consistency

The study was conducted with an online questionnaire (duration: 30 min) including a pre-test, video interventions on the trade-offs, a post test, and a video on solution approaches. In addition, there were brief intermediate measurements after each video (see Figure 1). The trade-off interventions were carried out in two groups. Group A was introduced to the trade-off directly via the problem. Group B was introduced to the trade-off via a solution approach that reduces the extent of the trade-off beforehand.

Figure 1. Structure of intervention (I: intermediate measurement, face: emotion measurement, eye: video intervention, list: selection of topics).



The intermediate measurements assess the emotions dimensionally using the Self-Assessment Manikin (Bradley & Lang, 1994). The emotions were further assessed categorically pre and post using a 5-point Likert-scale (adapted from Duffy et al., 2020). Moreover, students' attitudes towards wind turbines were assessed, and in the post-test, they selected the trade-off topic and solution approach they would like to explore further as well as whether they would like to study one of the two selected topics in greater depth than the other.

Data with more than 30% missing values or unusually fast processing times (RSI > 2; < 25 s on intervention pages) were excluded, leaving n = 99. Analyses were conducted in *IBM SPSS*

Statistics 29.0.0.0. The topic selection is described via frequency distributions (RQ1.1). Since the emotion variables are not normally distributed (Shapiro-Wilk-test: $p < 0.001$), Wilcoxon test will be applied for the categorical emotions and Friedman test for the dimensional emotion assessment (RQ1.2).

Initial Results And Discussion

The analysis for RQ1 is still ongoing. However, the initial results of the analysis of the frequency distribution of the topic selection (RQ1.2) have already been obtained. These results show a clear tendency within the trade-off-topics to deepen the trade-off concerning energy plants, as well as a desire for solution approaches to be discussed.

The majority of students (62,6%) want to expand the trade-off between wind energy vs. natural gas use. The trade-offs in the areas of raw materials and processing are similarly chosen (see figure 2).

Figure 2. Initial results of the selection of a problem-oriented trade-off topic.

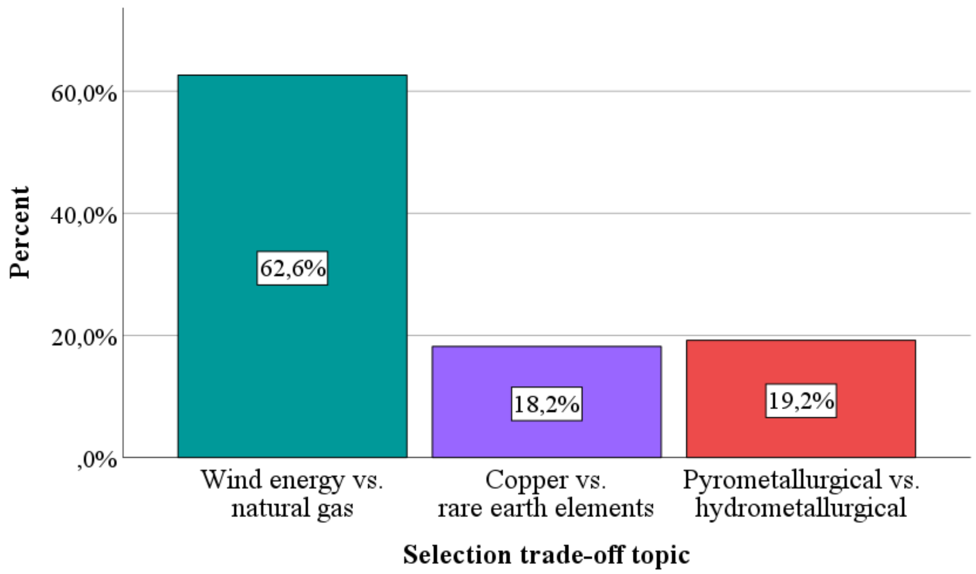
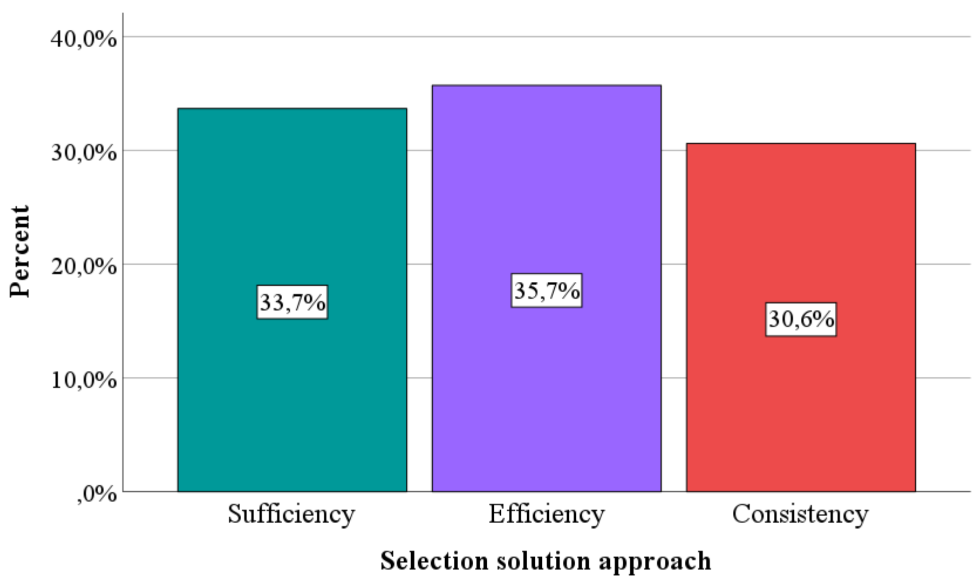


Figure 3. Initial results of the selection of a solution approach



The solution choice is more evenly balanced with a slight preference for the efficient use of raw materials (35,7%, see Figure 3). Comparing the selected trade-off topic and solution approach, only nearly a fourth of the students want to focus on their problem-oriented choice (24,2%) in further lessons. More students want to concentrate on the solution approach (35,4%) or equally both (39,4%).

Based on the results of life cycle assessments and the objectives of ESD, this article emphasises the importance of addressing trade-offs related to the use of raw materials. It presents potential topics in three areas as well as school students' preferences within these topics. Both trade-off topics and corresponding solution approaches were considered. The surveyed preferences for the areas are topic-specific and cannot be generalised. Nevertheless, for the chosen topics the initial results of this study show that the implementation of solution approaches to promote constructive hope, as proposed by Grund and Brock (2019) and Ojala (2012), is also demanded by the students.

The analysis on the topic emotions and their changes alongside the (different) interventions still needs to be carried out. Furthermore, in order to answer RQ2, data from a second study will be obtained and analysed.

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Exploring Students' Conceptions Of Critical Raw Materials And Their Availability

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Critical Raw Materials (CRMs) are essential for clean-energy technologies, yet their supply is often vulnerable due to import dependencies, geopolitical conflicts, and socio-environmental constraints. Although policy initiatives such as the EU Critical Raw Materials Act address these challenges, public awareness remains limited, highlighting the need for education. While existing science education projects provide valuable learning environments addressing CRMs, less is known about how students conceptualize the availability of CRMs prior to instruction. This study is embedded in the educational research of the Collaborative Research Center (CRC) "Iron, upgraded!" and follows the Model of Educational Reconstruction (MER). Focusing solely on the learner perspective in this article, we investigate students' conceptions of the availability of CRMs. A preliminary survey (N = 295) on associations with the term "critical raw material" indicated that students primarily approach the topic in a problem-oriented way, while also referencing dimensions of criticality such as scarcity and importance. Subsequently, guideline-supported interviews with 12 upper secondary school students were conducted and analysed using qualitative content analysis. Five conceptions regarding the availability of CRMs emerged: supply constraints due to (i) low geological availability, (ii) geopolitical instability, (iii) low ecological and social acceptance, (iv) demand growth, and (v) limited technological accessibility. Results suggest that students predominantly interpret availability through a finite-stock mental model, while geopolitical, socio-ecological, technological, and demand-related dimensions are less spontaneously integrated and may require contextual prompts. These insights provide starting points for MER-based instructional design and point to opportunities for linking criticality to mitigation strategies such as substitution.

Keywords: Conceptual Understanding, Sustainability, Critical Raw Materials

Introduction

Critical Raw Materials In The Energy Transition

In response to the global climate crisis, a shift towards a post-fossil society with a sustainable energy system is essential. However, this transition requires substantial amounts of raw materials needed for deploying clean energy technologies. For instance, EU demand for lithium is expected to increase twelve-fold by 2030 and twenty-fold by 2050 (European Commission, 2024). Yet, many of these raw materials are either not found in Europe or are not mined in sufficient quantities. Consequently, the EU relies heavily on imports, often from geopolitically unstable regions or single-source suppliers (European Commission, 2023). Without coordinated action, the European climate goals are at risk (European Commission, 2024).

To address these challenges, the concept of Critical Raw Materials (CRMs) has gained prominence (European Commission, 2011; Graedel et al., 2012; NRC, 2008). CRMs lack a universally agreed definition because criticality varies by time, country, and context. However, it is broadly understood as the likelihood and potential consequences of a supply disruption (Schrijvers et al., 2020). Accordingly, the EU describes CRMs as materials of high economic importance while also being highly vulnerable to supply disruptions (European Commission, 2011). Initiatives such as the EU's Critical Raw Materials Act aim to secure these materials to meet the 2030 climate and digitalization targets (European Commission, 2024). Nevertheless, public awareness of CRMs and their role in the energy transition remains limited, making education and communication essential (Kot-Niewiadomska, 2022).

Critical Raw Materials In Science Education

Several EU-funded projects address the educational gap around raw materials and sustainability. For example, the "Young Raw Material Ambassadors" program equips students aged 10 to 18 with knowledge about raw materials through interactive tools such as digital serious games (Torreggiani et al., 2021). Gullón Corral et al. (2023) developed the "Briefcase Project", a hands-on teaching kit highlighting mineral properties, societal impacts, and the role of raw materials in everyday life. Beyond these EU projects, Huwer et al. (2022) created digital learning environments for chemistry education incorporating augmented reality to explore elements in everyday devices and their recyclability. Bütow and Eilks (2023) developed a digital learning environment designed to integrate CRMs into chemistry curricula and subsequently evaluated its implementation by comparing German high school students with U.S. undergraduate chemistry students (Bütow et al., 2025).

While these projects provide valuable resources, a research gap remains concerning students' conceptions of critical raw materials, especially regarding what "availability" means and what learners intuitively consider as causes of scarcity. Such insights could be beneficial for designing learning environments that connect to learners' existing ideas and support conceptual development.

Motivation And Theoretical Framework

This study is embedded in the educational research subproject WIKO (German abbreviation for *Wissenschaftskommunikation*, i.e., science communication) of the Collaborative Research Center (CRC) "Iron, upgraded!" (www.chemie.tu-darmstadt.de/iron-upgraded/index.en.jsp), which investigates how iron's reactivity and selectivity can be controlled so that iron-based compounds can substitute rare, toxic, expensive, or critical metals in key technological applications, such as fuel cells and magnets. A key aim of the WIKO project is to support learners in understanding the relevance of CRMs and the idea of material substitution (e.g., iron-based solutions as potential alternatives to scarce or geopolitically sensitive materials in specific applications).

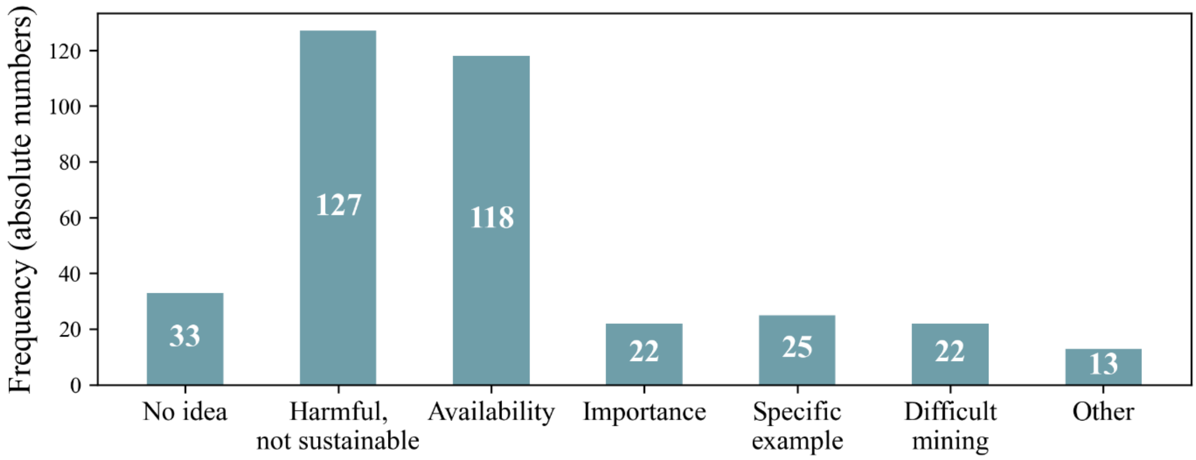
The study follows the theoretical framework of the Model of Educational Reconstruction (MER), which emphasizes the interconnection of reconstructed scientific content and students' pre-instructional conceptions to foster meaningful learning (Bliesmer & Komorek, 2023; Duit et al., 2012). MER highlights the importance of acknowledging students' perspectives and aligning them with scientifically accurate concepts (Komorek & Kattmann, 2008). This approach, rooted in conceptual change theory, is particularly effective when students' fragmented and context-dependent knowledge is incorporated into instructional design (diSessa & Sherin, 1998; Treagust & Duit, 2008).

MER comprises three perspectives: (i) the investigation of scientists' conceptions, including the analysis and structuring of scientific content, (ii) the investigation of learners' conceptions, and (iii) the design or evaluation of a learning environment. **The present contribution focuses only on the learner perspective.** It therefore provides a targeted overview of how learners think about the availability of critical raw materials, rather than reporting a complete MER cycle. We address the following research question: What conceptions do upper secondary school students hold about the availability of critical raw materials?

Preliminary Study: Students' Associations

Starting the investigation into learners' perspectives, we first explored whether the term "critical raw material" is sufficiently present in students' thinking to justify in-depth qualitative exploration. Accordingly, we conducted a preliminary quantitative survey asking: "What do you associate with the term 'critical raw material'?" (Prechtl et al., 2025). To ensure data quality, we excluded responses that were incomplete or showed signs of insufficient engagement, specifically those where the processing time fell below the threshold of 10 seconds per survey page. After this, a final sample of N = 295 responses remained. We then coded and grouped the open responses thematically and visualized their absolute frequencies to identify the most common associations (see Figure 1).

Figure 1. Frequency of thematically coded open-ended responses to the question "What do you associate with the term 'critical raw material'?" (Prechtl et al., 2025).



In Figure 1, two observations stood out. First, students approached the topic in a strongly problem-oriented way. A large share of responses related to environmental harm and non-sustainability, indicating that students tend to frame CRMs primarily through consequences and risks. Second, many responses also referenced aspects that align with the formal notion of criticality, such as availability/scarcity and the importance of raw materials. Overall, the framing and the low number of the "no idea" category suggested that the concept is present enough in students' thinking to justify a deeper exploration of how they interpret the term.

Methods

We conducted guideline-supported interviews with open-ended questions and clarifying interventions. The study included 12 upper secondary school students (mean age: 17.75 years; 7 females, 5 males) from three schools in Hesse, Germany, who participated voluntarily in summer 2023. To support an open atmosphere, interviews were conducted in a conversational setting. The average interview duration was 64.2 minutes. The content validity of the interview questions was supported using the collect, check, sort, and subsume approach, complemented by a pilot test with two students to improve clarity and understandability. Interviews included opportunities for clarifying interventions when students' meanings required further elaboration or when relevant dimensions of availability did not emerge spontaneously. Data were analysed using adapted methods of qualitative content analysis (Gropengießer, 2008) to identify and categorize students' conceptions. Audio recordings were transcribed verbatim. Relevant statements addressing the research question were systematically coded and similar statements were grouped to form categories. To support the quality and consistency of the analysis, category definitions, anchor examples, and coding rules were reviewed iteratively (Mayring, 2022). The validity of results was further supported by comparing emerging conceptions with published studies on related topics. Initially, the German interview transcripts were analysed, and relevant statements were then translated to illustrate students' conceptions.

Selected Results

The analysis revealed five distinct conceptions regarding the availability of critical raw materials (Table 1).

Table 1. Students' conceptions of CRM availability.

	Students' conceptions	Example statements
1	Supply constraints due to GEOLOGICAL AVAILABILITY	"By scarce, I mean that the raw materials do not occur in sufficient quantities." (Amira)
2	Supply constraints due to GEOPOLITICAL INSTABILITY	"The countries where the raw materials come from are not necessarily always politically stable countries. This means that conflicts can arise there that can spill over into the economy." (Amira)
3	Supply constraints due to ECOLOGICAL AND SOCIAL ACCEPTANCE	"The mines are harmful to the environment and I can imagine that people don't want them in their neighborhood." (Sarah)
4	Supply constraints due to DEMAND GROWTH	"Population growth is connected to the raw material consumption. […] the global demand is rising, which means that there isn't enough for each individual country." (Chiara)
5	Supply constraints due to TECHNOLOGICAL ACCESSIBILITY	"Other deposits may then be very difficult to mine." (Chris)

Nearly all students associated scarcity primarily with geological availability. In their explanations, terms such as "rare", "scarce", and "available" referred to whether sufficient reserves of specific raw materials exist. Conception 1 (GEOLOGICAL AVAILABILITY) captures the view, that scarcity primarily reflects limited geological occurrence, i.e., insufficient quantities of raw materials being available in the nature. Accordingly, students often conceptualized availability as a largely fixed physical quantity and assumed that limited occurrence directly translates into limited supply. Some even described a depletion narrative, suggesting that continued extraction could ultimately lead to absolute exhaustion of resources. For example, one student stated: "There will simply be no more raw materials" (Mia).

Conception 2 (GEOPOLITICAL INSTABILITY) addressed geopolitical conflicts as a cause of supply constraints. For many participants, this perspective became more explicit after interventions concerning Europe's import dependency. Students argued that European countries such as Germany rely strongly on political and economic relations with supplying countries, which can be problematic when these relations deteriorate. Moreover, students highlighted that these dependencies are not only a passive vulnerability but can be used deliberately as a source of leverage. One student, for example, described the risk of supply being intentionally restricted in the context of geopolitical conflicts:

> "If China ends up in a major conflict with the EU and decides to say, 'No, you won't get any rare earths from us anymore,' that poses a significant risk because they hold nearly 100 percent of the market share" (Chris).

All students addressed environmental and social consequences of mining and frequently framed these impacts as a possible dimension of critical raw materials. However, only about half of the participants explicitly linked these concerns to availability constraints. Conception 3 (ECOLOGICAL AND SOCIAL ACCEPTANCE) describes the idea that supply limitations may result from low ecological and social acceptance of mining activities. Students argued that mining can cause severe environmental harm and social conflict, which may lead to public resistance, stricter regulation, or even the closure of mining sites. In this view, raw materials may be geologically present, yet effectively "unavailable" because extraction is contested or considered unacceptable.

Many students described scarcity as a function of rising demand. Conception 4 (DEMAND GROWTH) captures the ideas that a continuously increasing demand will eventually surpass an already limited geological supply. Students explained demand growth through drivers such as population growth and technological developments. In particular, some learners referred to the energy transition and the expansion of modern technologies as increasing the need for specific raw materials. One student exemplified this by linking battery technologies to future supply challenges: "For instance, lithium, which is essential for batteries, is relatively scarce. Expanding its use on a global scale will make the supply problematic" (Sebastian).

Some students additionally mentioned the technological accessibility of raw materials. Conception 5 (TECHNOLOGICAL ACCESSIBILITY) describes the idea that raw materials may become scarce because certain deposits are increasingly difficult to exploit. However, students' ideas were inclined to focus on the assumption that easily accessible deposits will eventually be exhausted. As a result, extraction would require more complex technologies or become less feasible.

Discussion

The prevalence of Conception 1 (GEOLOGICAL AVAILABILITY) indicates that students predominantly frame raw materials criticality as a problem of "how much exists". This perspective resembles an intuitive "running-out" narrative: resources are treated as a fixed stock that steadily declines with use. In contrast, scientific discussions of raw material availability emphasize that absolute geological scarcity is unlikely to constrain access to most materials in the foreseeable future, because what is considered as economically recoverable reserves changes with exploration, technology, and market conditions (Coulomb et al., 2015). From this standpoint, students' focus on depletion may obscure more relevant drivers of criticality such as supply concentration or geopolitical and socio-ecological constraints (Schrijvers et al., 2020). For instructional design, this suggests a need to explicitly differentiate the terms "resources" and "reserves", and show that both are not fixed but dynamic socio-technical concepts.

The students' ideas regarding Conception 2 (GEOPOLITICAL INSTABILITY) are broadly aligned with established CRM logic: import dependency can create vulnerability, and exporting countries may use supply restrictions as political leverage (Nuss et al., 2016). However, the fact that this conception often became salient only after interventions suggests that geopolitical supply risk is not an everyday idea for many learners and requires contextual cues (e.g., a map of Europe's import structure of raw materials) to be activated. This pattern fits well with a "knowledge-in-pieces" interpretation (diSessa, 2018): students may possess relevant fragments (e.g., "conflicts disrupt trade"), but these pieces are not reliably triggered without situational prompts. For teaching, this implies that geopolitical considerations need structured support such as supply-chain mapping or scenarios that make dependencies visible.

Conception 3 (ECOLOGICAL AND SOCIAL ACCEPTANCE) reflects a shift from purely physical understandings of availability toward socio-environmental conditions that shape whether extraction can occur. Students' arguments resemble a "not in my backyard" logic: mining might be technically possible, yet effectively blocked by regulations or concerns. Notably, while these sustainability impacts were widely recognized, only about half of the students explicitly connected them to availability constraints. This suggests that learners often treat ecological/social harm as a separate "problem of mining", rather than as a factor that can restrict supply. In instructional terms, this indicates a learning need to explicitly link these ideas to the notion of availability.

Students' reasoning regarding Conception 4 (DEMAND GROWTH) resembles a scaling heuristic: more people and broader deployment of technologies imply more consumption, which eventually overwhelms supply. This is a plausible everyday schema and can serve as a productive starting point. At the same time, students' accounts were inclined to model supply as essentially static and demand as continuously rising, often without considering counteracting dynamics (e.g., efficiency gains, substitution, recycling). In this sense, Conception 4 parallels Conception 1: scarcity is again framed as a largely inevitable trajectory toward shortage, rather than as a system shaped by technological, economic, and political choices. From a reconstruction perspective, instruction could build on this intuitive logic but broaden it with mitigation strategies.

Conception 5 (TECHNOLOGICAL ACCESSIBILITY) expands availability beyond geology by introducing technological accessibility. However, students' ideas often remained tied to a simplified narrative: high-grade or near-surface deposits are exhausted, therefore extraction becomes more difficult. This captures an important aspect of accessibility but remains underspecified. Moreover, scientific criticality assessments highlight additional mechanisms that were not present in the students' accounts, such as by-product dependency, where production depends on the mining of the host metal (Nassar et al., 2015). For instructional design, this suggests expanding the ideas of "harder mining" with aspects of refining, co-production, by-product dependency, and processing bottlenecks.

Limitations

This study is based on a small qualitative sample from three German high schools and thus does not aim at statistical generalization. At the same time, the qualitative findings are complemented by the preceding survey (N = 295; Prechtl et al., 2025). Across both datasets, students' responses consistently foreground scarcity-related reasoning, providing converging indications of the prominence of a "running-out" narrative and a primary focus on scarcity and depletion. Therefore, these results should serve to identify possible starting points and to derive instructional guidelines for teaching the concept of CRMs. However, the learning environment developed later should be evaluated for its suitability to foster an adequate understanding of the availability of CRMs.

Conclusion

This paper provides an overview of learners' perspectives on CRM availability. Overall, the results suggest that students primarily interpret the availability of critical raw materials through a finite-stock mental model: scarcity is understood as a direct consequence of limited geological occurrence and ongoing extraction. While students are able to articulate dimensions of supply risk, these additional dimensions appear less spontaneously integrated into their initial reasoning and, in some cases, required contextual interventions. From a MER perspective, this points to fragmented, context-dependent knowledge rather than a consolidated, multidimensional understanding of criticality. Building on these entry points, the MER framework can guide the development of learning pathways that explicitly frame availability as a multidimensional concept and address common intuitive ideas such as the "running-out" narrative.

Outlook

In subsequent MER steps, the instructional guidelines derived from the present findings will be translated into an experimental learning environment in the CRC "Iron, upgraded!" context. It will utilize the case of substituting a critical platinum catalyst by an iron-based alternative in fuel cells to connect raw materials criticality to concrete mitigation strategies and their trade-offs.

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EUROPEAN SCIENCE EDUCATION RESEARCH ASSOCIATION ESERA 2025 Copenhagen

Sustainable Competencies In Education: Building Curricula And Advancing Teacher Training Together

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Sustainable development offers a pathway to address humanity's greatest challenges such as climate change and biodiversity loss. However, current science curricula often fall short in adequately preparing students to address these complex issues. At ESERA 2025, we held an exploratory seminar addressing this gap by focusing on the interdisciplinary nature of Education for Sustainable Development (ESD) and developing ideas for effective curricula and empirical studies. We discussed two key questions: 1) How can we better prepare teachers to teach sustainability competencies? and 2) Which empirical studies are most informative for designing curricula to teach sustainability competencies?

In this text, we first describe a course for educators on integrating ESD in their lectures at a technical university. We used insights from this course to design the exploratory seminar for ESERA 2025. Then we describe the structure of the exploratory seminar, in which participants engaged in a grouped think-pair-share activity to collect ideas to answer the key questions. This was followed by short presentations from group representatives in a plenary discussion. Finally, we summarize the discussion to inform future curriculum development and research initiatives.

Keywords: Education for Sustainable Development; Competencies; Curriculum Development

Introduction: Education For Sustainable Development (ESD)

Sustainable development is such a central political goal that, in some countries, it is enshrined in the constitution (e.g., in Switzerland, Art. 2 & Art. 73; Bhutan, Art. 5; partially also in Ecuador, Art. 14). The way to achieve this goal can be informed by science. Scientifically based mitigation strategies involve a reduction of emissions at the individual and global levels (Wynes & Nicholas, 2017). In schools, however, such mitigation strategies are rarely discussed, or if so, they focus on private-sphere actions (Kranz et al., 2022). When economic alternatives such as degrowth are mentioned, this is done only sporadically or decontextualized (Díez-Gutiérrez et al., 2024). System-critical questions are rarely addressed, which led Huckle (2012) to conclude that "Mainstream ESD […] uncritically embraces economic growth, globalization and consumerism" (Huckle, 2012, p. 366).

On the other hand, ESD and sustainability competencies are increasingly included in curricula as educational goals. The goal is to prepare students for an unknown future. Many competence frameworks require students to obtain competencies in sustainable development. For example, in Switzerland, the framework curriculum for high schools, such as the Gymnasium, wants students to achieve a deepened social maturity. Such a deepened social maturity requires, among other things, networked, interdisciplinary thinking and education for sustainable development (Schweizerische Konferenz der Kantonalen Erziehungsdirektoren, 2023). As a result, there is a mismatch between current educational practices and the desired outcomes. This warrants research to identify the barriers to changing current practices and to develop effective curricula for ESD.

How should effective ESD curricula be implemented? Whereas it is desirable that ESD includes those strategies that are scientifically backed up to mitigate climate change, ESD must follow certain principles to be ethically valid. The Beutelsbacher Consensus (Wehling, 1977) prohibits instrumental education. It emphasizes that students should develop competencies to form independent opinions rather than being indoctrinated. For example, ESD must not educate pupils 'for' degrowth. On the other hand, the Beutelsbacher Consensus also mandates the inclusion of diverse viewpoints, including those unfamiliar to students, to promote reflective thinking and avoid indoctrination through omission. Paradoxically, this turns the current practices of rarely mentioning alternatives to the current system (see Díez-Gutiérrez et al., 2024) into a form of indoctrination.

The Role Of Science Education

Every subject in science education has inherent links to sustainability: From the chemical basis of the carbon cycle or processes of material corrosion, the physics of climate change, the geographical impact of human activities, the biological damage of biodiversity loss, to the mathematical modelling of exponential growth. These links provide a foundation for interdisciplinary discussion of mitigation strategies. However, this requires that teachers are prepared to link sustainability issues to their subject and to promote sustainability competencies.

To address this need, the following sections describe an exemplary course designed to support university faculty in integrating ESD into their curricula. This course served as the inspiration for our seminar, as the experiences and pedagogical gaps identified during its implementation directly inspired the research questions and organizational structure of the exploratory seminar held at ESERA 2025. Following the description of this course, the method section details the structure of the ESERA seminar itself. We then present the results derived from that seminar and conclude with a discussion and an outlook for future research.

An Example Course

We developed a course on ESD for university educators at a technical university. The course is divided into three parts: a digital self-study activity, an in-person workshop, and an implementation phase.

Self-Study Activity

In the self-study activity, educators complete a learning module on an online platform. The module starts with a quiz as a formative assessment that also activates prior knowledge about the topic and uses pretesting effects to convey information (Pan & Carpenter, 2023). Afterward, they work through videos and texts describing the climate crisis, the idea of sustainability, and how sustainability relates to ecology, society, and economy. Afterward, to support educators in drawing connections to their teaching, we present the Sustainable Development Goals (SDGs). Using the wedding-cake depiction (see Figure 1), we draw the connection between the three pillars of sustainability (ecology, society, and economy) and cluster the 17 SDGs. The SDGs help as a framework to conceptualize sustainability from different perspectives. All educators should then identify 1-3 SDGs that relate to their teaching. Finally, they also need to formulate a teaching goal.

In-Person Workshop

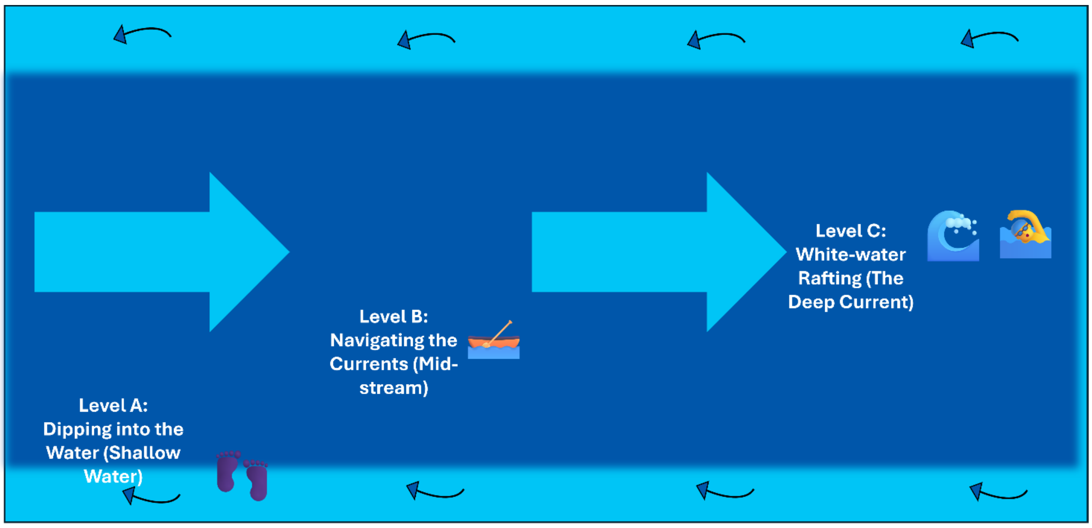
The in-person workshop starts with thought-provoking quotes about sustainability and an introduction of the participants. Then we discuss the result of the quiz, highlighting questions where participants had a lot of prior knowledge as a motivation, and those questions where participants answered mostly incorrectly. We also repeat core concepts around the problem, such as the 1.5-degree goal, the tipping points, and the relation of energy use, economic growth, and emissions.

Figure 1. Wedding cake depiction of the Sustainable Development Goals.

Credit: Azote for Stockholm Resilience Centre, Stockholm University CC BY-ND 3.0. Reproduced with permission.

To encourage educators to reflect on the extent to which they want to integrate sustainability in their teaching, we utilize the metaphor of fluid spaces, specifically as a river (adapted from Bellina et al., 2018). This metaphor categorizes ESD engagement into three levels, as illustrated in Figure 2. At Level A) on the riverside, they could dip their feet into the water to gain initial experience of teaching sustainability issues, e.g., by adding a few teaching or learning situations related to sustainability. At Level B) they start navigating the currents. Thus, they could create a stronger focus on sustainable development by having dedicated learning goals and cross-referencing between topics that relate to sustainability. At Level C) they engage in white-water rafting in the middle of the river. There, they completely adapt their teaching toward sustainability.

Figure 2. River metaphor of integrating ESD in one's teaching.



Every level comes with challenges: At Level A) we refer to a river-swimming experience from outdoor education (Thurn et al., 2025), where in shallow waters, there is a strong eddy flowing upwards. That is, in shallow waters one is literally swimming upstream. We use this analogy, to vividly explain what could happen when educators add a single activity on sustainability and disregard it in other contexts. Such small actions might evoke the image of greenwashing or lead to rebound effects, such as the perception that sustainability is already discussed once and does not need further attention. In the literature, this is discussed as single-action bias (Zhao & Luo, 2021). It is not wrong to start with baby-steps when changing one's lecture, but one needs to be aware of such countermovements. At Level B) teaching the complexity of the climate crisis and sustainability in relation to one's lecture topics might become overwhelming for teachers and students. It might also lead to strong reactions by students, who do not see a connection. At Level C) it will become clear that sustainable development comes with lots of ambiguity. It will also be relevant to discuss one's own personal behaviour with regard to sustainability here at the latest.

In the workshop, educators reflect on the different levels and decide at which level they want to implement sustainable development in their lecture. We assign them to groups that aim for the same level, as these groups face similar challenges. During a group activity in the form of a collegial coaching, educators present their lecture and explain which SDGs it covers and how the content relates to sustainability. They present their learning goal and how they will include it in their lecture. The other group members listen and ask themselves: Where do you see chances and risks in the plan? Then they exchange ideas before moving on to the next person presenting their lecture. In a consolidation phase with all participants, each group summarizes its discussion. We then discuss how to deal with frequently mentioned challenges such as emotions (solastalgia, Albrecht et al., 2007; climate change anxiety, Clayton, 2020), rebound effects (e.g., Colmenares et al., 2018), or the single action bias (e.g., Zhao & Luo, 2021).

Implementation And Reflection Phase

In the last phase of the course, educators work on their plan for how to include sustainability in their teaching. During the next weeks, they implement their plan. Afterward, they write a short reflection reporting what their learning goal was and how it went.

Experiences From The Course

A takeaway from the course was the effectiveness of think-pair-share activities (e.g., Kaddoura, 2013). Think-pair-share activities transcended simple classroom participation, often into a form of collegial coaching. By allowing educators to first reflect individually, we cognitively activated them. The share phase led to peer-to-peer support, discussing the complexities of teaching across disciplines.

The course also revealed two areas where even motivated educators lacked important concepts: Whereas most participants were familiar with the ecological footprint, there was a lack of awareness regarding the ecological handprint. The handprint focuses on positive actions that reduce the footprints of others and is a crucial motivator for ESD (Kühnen et al., 2019). Furthermore, there was a gap in understanding the tipping points. Participants often had not heard of this concept or viewed climate change as a linear progression.

The Exploratory Seminar At ESERA

Derived from the research desiderata described above, and the experiences we gained through giving a course on sustainability integration for educators, we aimed to work on the following questions in the exploratory seminar at ESERA 2025:

1) What barriers exist in implementing ESD curricula, and how can these be overcome?

2) How can we better prepare pre-service teachers to teach sustainability competencies?

3) Which empirical studies are most informative for designing curricula to teach sustainability competencies?

At the beginning of the seminar, we introduced these key questions and explained the structure of the seminar. In the setting of a grouped think-pair-share activity, attendees would share their views on these questions. To foster exchange and the documentation of the results, we asked that each group presents its results to the plenum at the end. Attendees could join one of the three groups to address one of the questions. As participants favored questions 2 and 3, we did not discuss the first question in the seminar. For the sake of completion, we thus cover this question in the discussion section, where we summarize key barriers identified by scientific studies.

In the groups, attendees followed a think-pair-share activity. In the first step, they had individual time to think about answers to the respective questions. Afterward, attendees paired with their group members to discuss how they might contribute to solving their group's question.

In the share phase, all groups came together to exchange their developed ideas and receive feedback from all other attendees. The aim was to arrive at specific ideas for promising next steps in this research area. These could include collaborative research projects, theoretical or empirical research papers, or the establishment of discussion groups to continue working on the ideas after the conference.

Results From The Exploratory Seminar

Here we present the aspects that participants discussed in the exploratory seminar at ESERA 2025 regarding the two questions.

How Can We Better Prepare Pre-Service Teachers To Teach Sustainability Competencies?

Participants emphasized that teachers require tools to facilitate difficult classroom discussions. These conversations often involve navigating high levels of tension. This requires teachers to be prepared to handle the intense emotions students bring to these topics. To address this, participants specifically recommended the Climate Emotion Wheel (Pihkala, 2022, 2024). This tool serves as a reflective framework, helping teachers anticipate and categorize the wide variety of emotional responses—ranging from anxiety to empowerment—that sustainability topics can trigger.

Participants also highlighted the importance of experiential learning. They advocated for place-based education that increases immersion and nature connectedness. Place-based education grounds lessons in local environments to make abstract concepts tangible (Smith, 2013). Outdoor, project-based education is suitable for place-based education (Thurn et al., 2025). Nature connectedness is the subjective connection to nature (Capaldi et al., 2014). It describes one's personal relationship with the natural world, and studies showed that it is a strong predictor for environmental action (Nisbet et al., 2009). Participants also named public speakers and non-profit associations that could serve as resources for teachers.

Finally, participants underscored the necessity of providing teachers with a comprehensive understanding of the sustainability competencies specific to their regions. This includes clarity on the frameworks that are used, the rationale behind why specific competencies were selected, the relevance of these competencies, and their integration into existing curricula. By analysing how different countries embed sustainability into their educational systems, teachers can establish a collective understanding of the topic. Participants termed this blend of subject expertise and teaching strategy as Pedagogical Content Knowledge (PCK) about sustainability.

Which Empirical Studies Are Most Informative For Designing Curricula To Teach Sustainability Competencies?

Participants emphasized the importance of defining sustainability competencies to ensure that they are practically applicable in educational settings. For example, useful frameworks exist, such as the Sustainable Development Goals (SDGs), the framework of Wiek (2011), or the European Green Competence Framework. However, in competence-based education, there is a challenge of teaching and assessing such competencies.

A central goal of competence-based education is the development of action-competence, which moves beyond passive knowledge toward the willingness and ability to take actions. To achieve this, a research desideratum exists regarding the professionalization of teachers. Educators require more sophisticated tools to navigate the complex landscape of emotions and norms that sustainability topics inevitably evoke. This includes developing specific strategies for dealing with controversy and facilitating meaningful climate action while maintaining pedagogical integrity. Whereas the participants did not name specific further tools for these dialogues, current research highlights approaches for dealing with emotions. For instance, Finnegan and d'Abreu (2024) argue for the integration of hope (see also Grund & Brock, 2019), while Ranney and Velautham (2021) point toward socio-emotional and social justice education as essential foundations for managing complex topics.

The participants also mentioned the necessity of more diverse and robust methodological approaches to better understand how these competencies are acquired. Participants suggested mixed methods designs and multi-lab studies to address the cultural diversity inherent in global environmental challenges. This could help identify universal versus context-specific educational strategies. It is equally vital that research investigates the progression of ESD across all age groups, which stretches from the early foundations in kindergarten all the way through to higher education.

A recurring challenge that participants named in relation to this is how to effectively connect the local with the global, a concept often referred to as the 'glocal' approach. The idea of glocal is that by rooting global sustainability issues in local contexts, educators can increase the personal relevance of the material for their students. Studies could examine how such approaches can incorporate intergenerational aspects, enabling students to see how their current local actions impact both their own future and the global community at large.

Discussion

What Barriers Exist In Implementing ESD Curricula, And How Can These Be Overcome?

As we did not cover this question in the exploratory seminar, we describe key findings from the literature here. Borg and colleagues (2012) list a lack of examples and a lack of expertise as frequent barriers. Pompeii and colleagues (2019) report a detailed list of teacher-identified barriers, with the most frequent being discipline restrictions and personal priorities. They also list student-identified barriers. Disciplinary silos and a lack of adequate professional training opportunities also appear in Parry & Metzger (2023). The barriers thus seem to revolve around a factor comprising lack of "know-how", including best-practice examples and trainings on the topic, and a factor related to the perceptions of one's discipline. Ways to overcome these barriers seem easier to implement for the first factor. More resources, such as professional training, lists of successful examples, or exchange with colleagues, could provide teachers with more ideas in implementing ESD curricula.

Conclusion

In this text we have discussed three key questions regarding the progress of ESD. For the question of existing barriers, the literature revealed that teachers lack the know-how and see discipline restrictions. In the exploratory seminar, participants' answers revealed that to prepare teachers better to teach sustainability competencies, we need to equip them with better Pedagogical Content Knowledge on ESD. This includes how to navigate emotions and norms. It also includes preparation to design experience-based instruction. For the question of informative empirical studies for the design of ESD curricula, participants' answers revealed that such studies should investigate effective strategies for dealing with controversy and emotions.

In conclusion, with a strong foundation in literature on ESD, we identified key areas to guide future research and curriculum design. Integrating these areas into teacher-education programs can enhance the preparation of teachers for building sustainability competence in their profession.

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‘How Sustainable Is ...?’ A Teaching Approach In The Field Of Education For Sustainable Development

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Science education can make an important contribution to supporting the 17 Sustainable Development Goals of the United Nations through Education for Sustainable Development (ESD). The paper describes the development of the teaching approach ‘sustain.able?!’ within the framework of design-based research. The approach implements ESD into science lessons by enabling students to systematically assess controversies (e.g. bio-based plastics, vegan diet) considering the three dimensions of sustainability environment, economy and society. At the core of the teaching approach are the so-called 'AssessmentBubbles'. These contain information on the respective controversy, which the students assess from different perspectives based on specific criteria. The assessments are then recorded and reflected on an AssessmentDisc by Banse & Marohn (2021, 2022). This paper outlines the development of the method AssessmentBubbles within the framework of two research cycles involving 46 teachers, 12 experts and 17 students. A trial using the example of vegan diet with 28 students (aged 14-15) shows that the AssessmentBubbles method enables students to assess information from multiple perspectives in terms of sustainability and that they evaluate the method positively.

Keywords: Sustainability, Education for Sustainable Development, design-based research

Introduction

We encounter sustainability in many areas of everyday life, from food shopping and clothing to mobility. Schools should therefore play a key role in showing students the many facets of sustainability, while also promoting their ability to make judgements and take action in this context. But how can learners assess the sustainability of controversies based on criteria?

One possible approach is offered by the teaching approach *nachhaltig.bewerten (assessing sustainability)* which enables students to assess the sustainability of controversies (e.g. *electromobility*) from multiple perspectives (Banse, 2025; Banse & Marohn 2021, 2022). Furthermore, it provides three *AssessmentLevels* (space, time and group) to guide the assessment process systematically. The *AssessmentDisc* enables a didactically reduced conclusion about the sustainability of the controversy.

Although the teaching approach has been successfully tested (Banse, 2025) there is still room for improvement, especially in terms of supporting the students during the assessment process. The teaching approach *sustain.able?!* presented below is a further development of the approach *nachhaltig.bewerten*, which aims to bridge existing research gaps.

Theoretical Background

Sustainability

The guiding principle for sustainable development, published in 1987 by the United Nations World Commission on Environment and Development, states that development is considered sustainable if it ‘meets the needs of the present without compromising the ability of future generations to meet their own needs’ (World Commission on Environment and Development, 1987, p. 16). The Agenda 2030 adopted by the United Nations contains 17 Sustainable Development Goals and expresses the multifaceted nature of sustainability. Thus, it points out that sustainable development cannot only focus on the environment (United Nations, 2015).

Instead, it raises the question of how development can be organized to be ecologically compatible, economically efficient, and socially fair, while enabling current and future generations to lead a good life (MSB NRW, 2019).

This understanding of sustainability with its dimensions of *environment*, *economy* and *society* form an important basis for the teaching approach.

Education For Sustainable Development

Global education systems are also important for the realization of sustainable development. The global UNESCO programme ‘Education for Sustainable Development, ESD 2030’ emphasises the importance of ESD for achieving the Sustainable Development Goals (Bundesministerium für Bildung und Forschung, n.d.). Education for Sustainable Development should empower children and young people to take responsibility for shaping their own future and that of their generation in line with the principles of sustainable development (UNESCO, 2020).

The school should provide students with the necessary subject-specific and interdisciplinary skills to help them judge and act on important future issues (MSB NRW, 2019). In Germany, ESD is regarded as an important part of school education and is anchored as a mandatory cross-cutting topic in all subjects (ibid.). The teaching approach integrates ESD into the students' learning process.

The Basis Of The Teaching Approach *sustain.able?!*

The teaching approach presented in this contribution is based on the approach of *nachhaltig.bewerten* by Banse & Marohn (2021, 2022), which will be outlined briefly below.

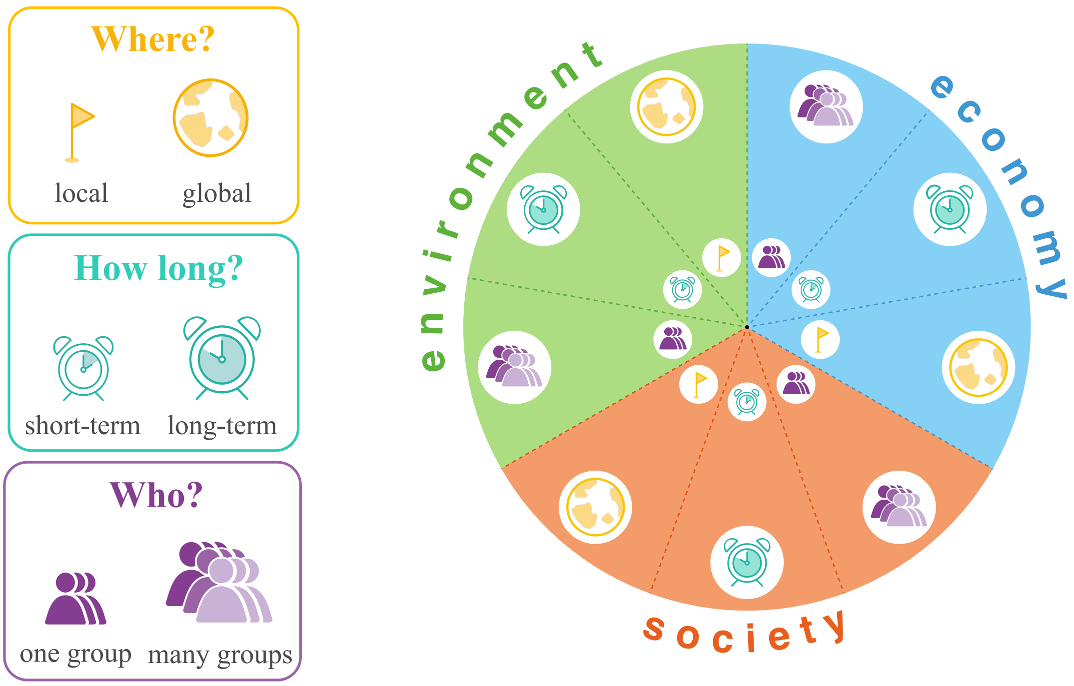
The teaching approach enables students to assess controversies in the context of sustainability based on criteria, taking into account the three dimensions of *environment*, *economy* and *society*.

The process of assessment involves the *AssessmentLevels* of space, time and group (Figure 1, left). When students ask whether a controversy such as the expansion of electromobility is beneficial or harmful to sustainability, they can consider it on these three levels of assessment. *Where* are the benefits or harms visible – only locally, e.g. in one city or globally, all over the world? *How long* do the benefits or harms last – are they only short-term, affecting those living today or long-term affecting future generations? *Who* benefits or suffers harm – just one group, such as farmers, or many groups? The teaching material on the controversy surrounding *electromobility* includes, for example, the information that electric cars emit less CO_2 than cars with combustion engines. This describes a *global*, *long-term* impact that affects *many groups*.

The methodological tool used to structure the assessment process is the *AssessmentDisc* (Figure 1, right), which combines the *AssessmentLevels* with the sustainability dimensions *environment*, *economy* and *society*. The *AssessmentDisc* thus visualizes that the questions about *where*, *how long*, and for *whom* a controversy has a beneficial or harmful effect can arise within all sustainability dimensions. When assessing information relating to a controversy, students can mark the corresponding symbols of the *AssessmentLevels*: green for a benefit and red for a harm.

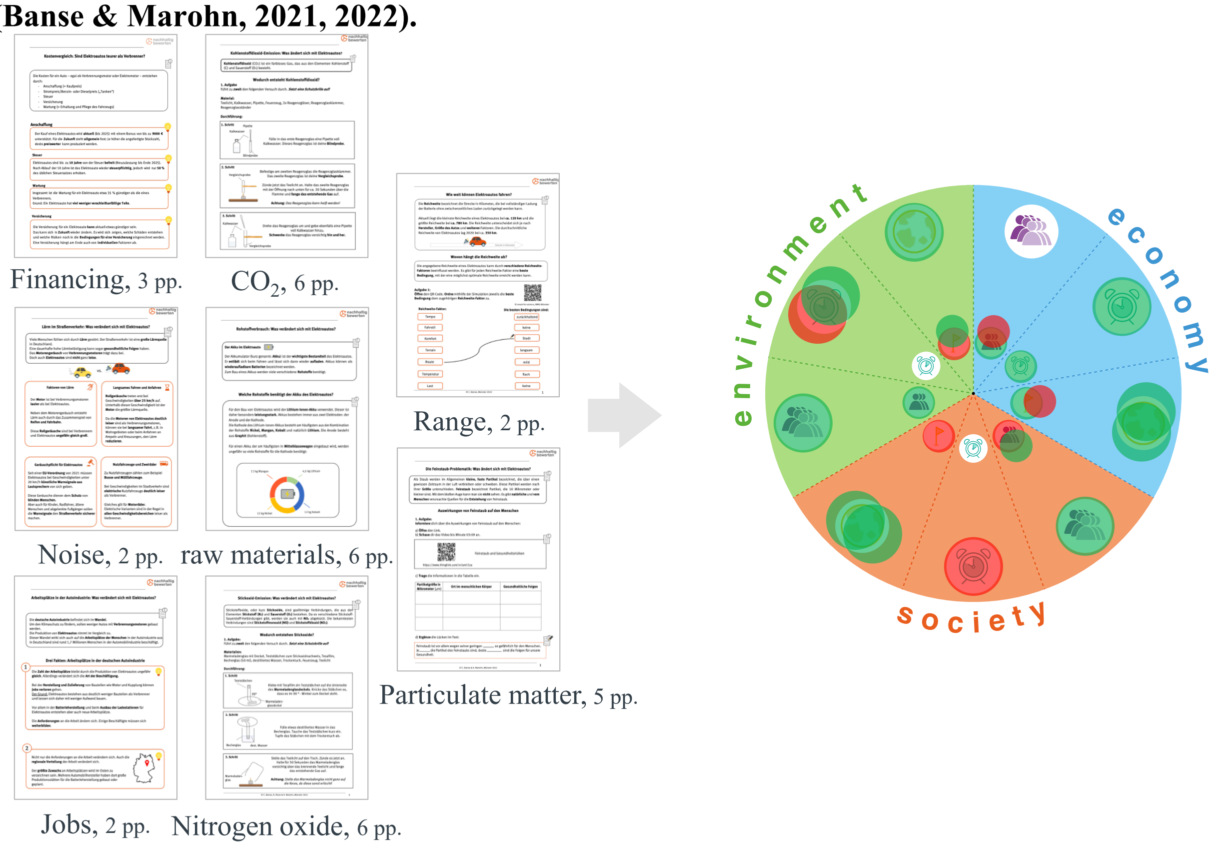
The example just mentioned regarding the reduction of CO_2 emissions describes a *benefit* provided by electric cars. Accordingly, the three *AssessmentLevels* affected – *global*, *long-term*, and *many groups* – are marked *green* on the *AssessmentDisc*. The green markings on the *AssessmentDisc* are in the area of the *environment*, as the information can be assigned to this sustainability dimension.

Figure 1. AssessmentLevels (left) and AssessmentDisc (right) (Banse & Marohn, 2021, 2022).



In order to assess the sustainability of a controversy (here: *electromobility*) the students first work out comprehensive information on various aspects of the controversy (e.g. CO_2 emissions, noise pollution or raw material extraction). To this end, they receive a total of 32 worksheets with tasks and factual information on eight aspects. In the next step, all this information is assessed and visualized using green and red markings on the *AssessmentDisc* (Figure 2).

Figure 2. Extensive information material, assessed and marked on the AssessmentDisc (Banse & Marohn, 2021, 2022).



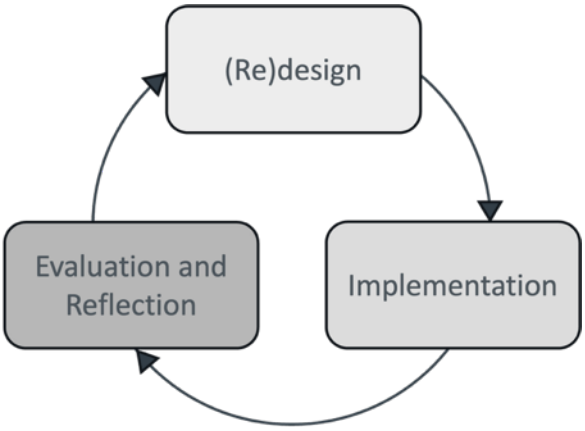
At the end, a conclusion can be drawn. The more green markings on the outer circle, the greater the controversy's impact on sustainability, because this means a *global*, *long-term* benefit for *many groups*.

Research Framework

Design-Based Research

The research uses the framework of design-based research (DBR) (Brown 1992; Collins, 1992) and follows the three phases of *Framing, Design Experiment* and *Re-Framing* (Gravemeijer & Cobb, 2006). In the *Design Experiment* phase there are iterative cycles (Figure 3) that include the development of a design (in this case: teaching approach *sustain.able?!*), its implementation and evaluation (Rohrbach-Lochner & Marohn, 2018). Each cycle is characterized by its own objectives and sub-research questions. The overarching goals of the DBR research process are to develop an innovative design for practical application (What works?) and to develop a theory about how the design works (How does it work?).

Figure 3. Iterative cycles in DBR (adapted from Rohrbach-Lochner & Marohn, 2018).



Research Gaps

A workshop with teachers ($N = 20$) showed that the teaching approach *nachhaltig.bewerten* still has some weaknesses (Banse, 2025). The majority of teachers criticized the high complexity and the large amount of information material that was provided to the students.

This resulted in students taking a long time to process the key points from the large amount of information material. Consequently, they only had little time left to assess the information. These areas for further research and additional ideas should be addressed in the approach *sustain.able?!*.

This paper focuses on just one of several research gaps and its solution.

Research Questions

Due to the research gaps described above, the presentation at ESERA focused on a stronger support for the assessment process. The following research questions were formulated:

RQ 1: How can the process of assessing information be made more structured and methodologically viable for students?

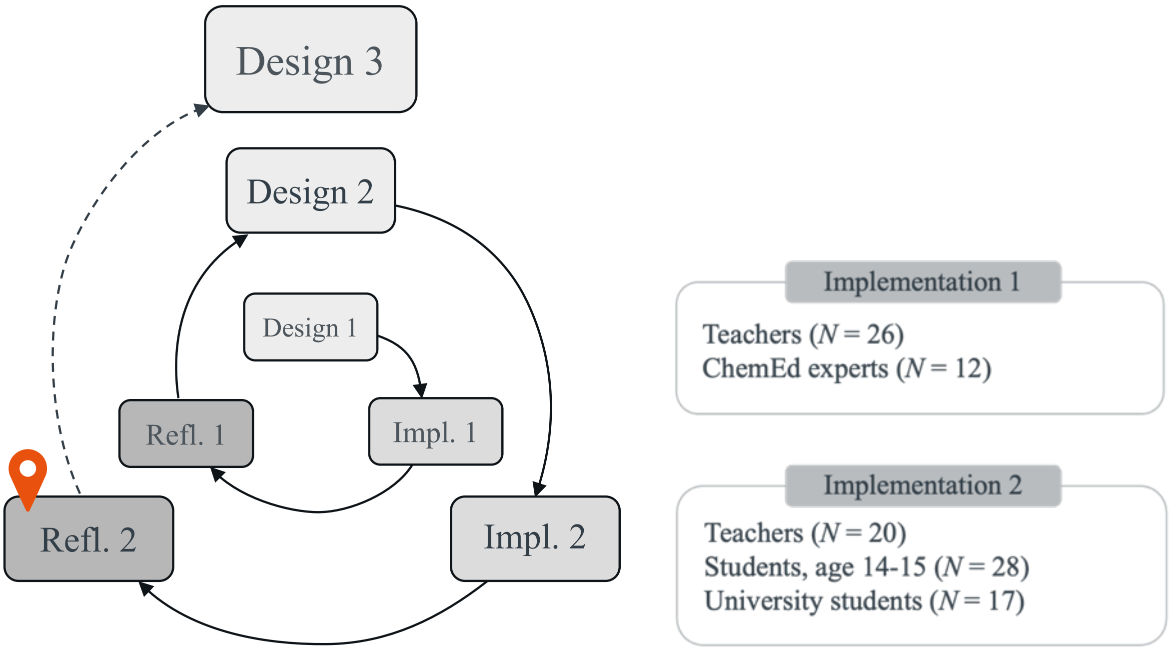
RQ 2: To what extent do students assess the information as intended?

RQ 3: How do students evaluate the new methodological tool of '*AssessmentBubbles*'?

Method

The design (here: teaching approach *sustain.able?!*) for stronger support of the assessment process was tested, analysed and optimized in several trial cycles with students aged 14-15 ($N = 28$), teachers ($N = 46$), university students ($N = 17$) and experts in chemistry education ($N = 12$) (Figure 4). Data was collected via questionnaires for all samples. During the testing with the students, pre-post-tests and audio and video recordings were also collected. This data was evaluated using qualitative content analysis (Kuckartz & Rädiker, 2024).

Figure 4. Iterative development of teaching materials within the sustain.able?! project.



Results

The Methodological Tool Of 'Assessmentbubbles' (RQ 1)

The *AssessmentBubbles* (Figure 5) were developed as direct outcomes of research question 1 to provide greater support for the assessment process for students. Compared to the previous approach, the assessment is supported by three measures:

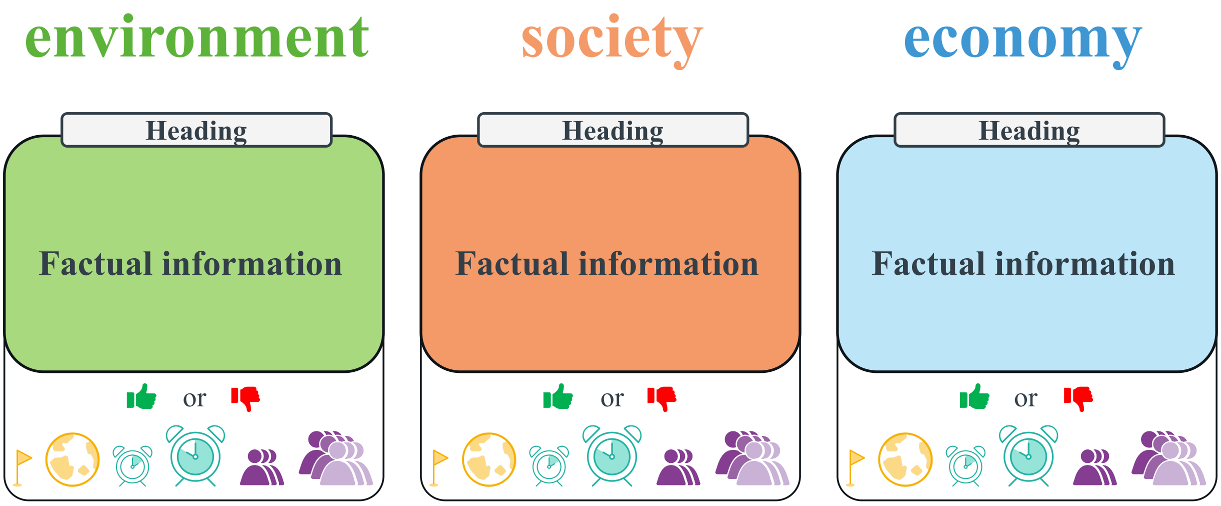
a) Students receive much more compressed factual information. They do not have to work through numerous worksheets to gather the information themselves.

b) The information is assessed directly in the immediate proximity of the information. In addition to scientifically based information, an *AssessmentBubble* also contains an assessment section. The assessment of the information takes place in two steps. First, students decide whether the information describes a benefit or harm and circle the corresponding symbol (green or red thumb). Afterwards, they assess the *AssessmentLevels*, considering the space (*local* or *global*), the timeframe (*short-term* or *long-term*) and affected groups (*one group* or *many groups*) for demonstrated benefits or harms. They mark the corresponding symbols of the *AssessmentLevels* from Banse & Marohn (2021, 2022).

c) The colour of the *AssessmentBubble* directly indicates the dimension to which the information refers*: environment* (green), *society* (orange) or *economy* (blue).

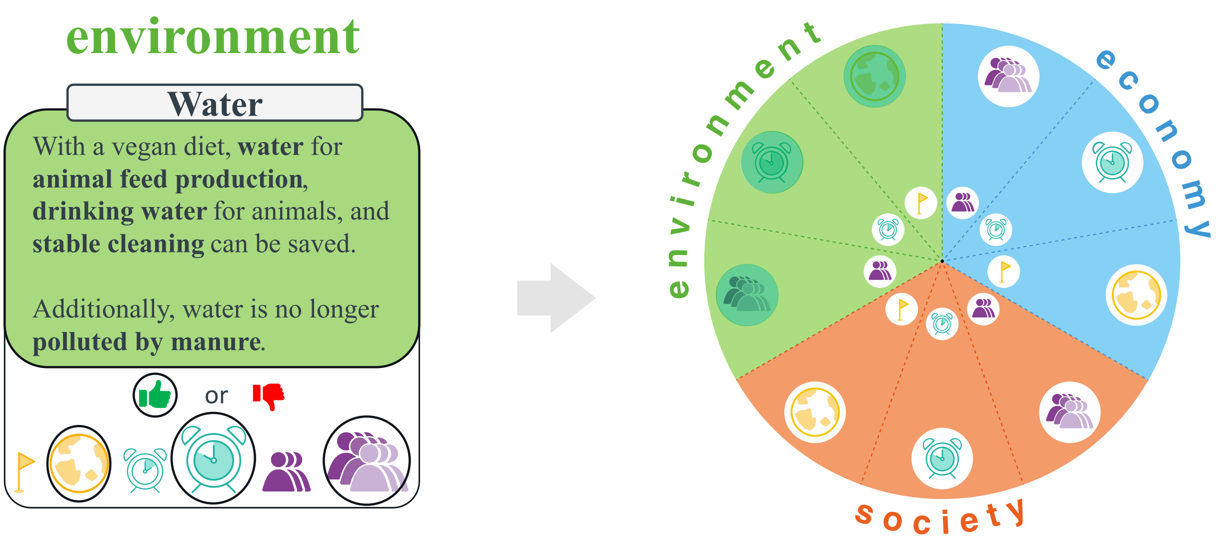
In the next step, the assessments from the bubbles are transferred to the *AssessmentDisc*. This can be illustrated with the example of *vegan diets,* where the sustainability of a plant-based diet is compared to one that includes animal products. This context was chosen because of its relevance to the students' lives, the breadth of available information and its alignment with the German biology curriculum.

Figure 5. AssessmentBubbles in the project sustain.able?!.



The 'water' aspect describes the lower water consumption and avoidance of water pollution caused by manure in the case of a *vegan diet*, representing a *global*, *long-term* benefit for *many groups*. Accordingly, the symbols are circled on the *AssessmentBubble* and transferred to the *AssessmentDisc* with green markings (benefit) within the *environment* dimension (Figure 6).

Figure 6. Transfer from the AssessmentBubble to the AssessmentDisc.

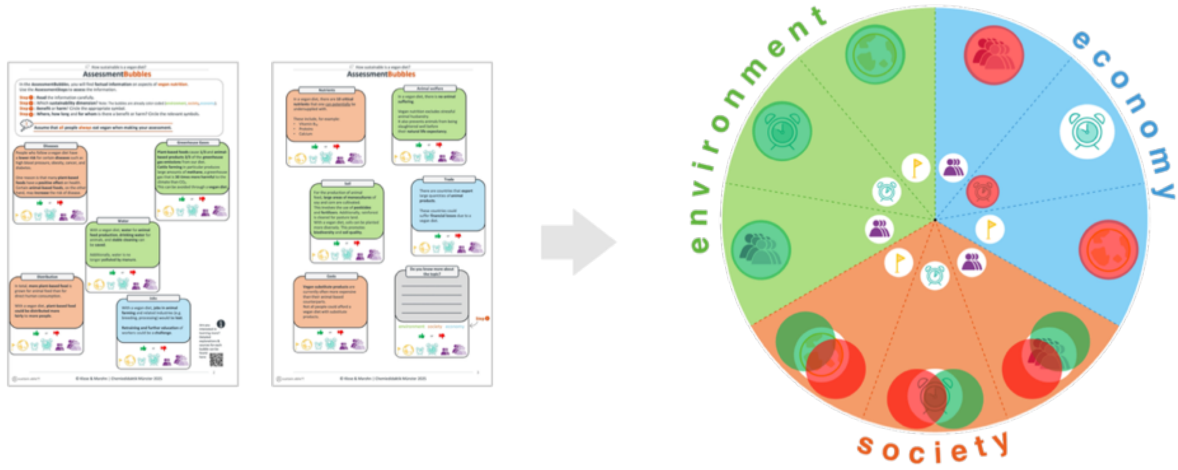


In a sustainability controversy students receive several *AssessmentBubbles* containing information from all three dimensions. The *AssessmentBubbles* are all included on only two worksheets (Figure 7). Once all *AssessmentBubbles* have been transferred to the *AssessmentDisc*, a differentiated picture of the sustainability of the controversy under consideration emerges (Figure 7).

Assessment Of The Information In The Assessmentbubbles (RQ 2)

To draw conclusions about the understanding of the new method *AssessmentBubbles*, the information in the bubbles assessed by the learners ($N = 28$) were analysed. Each student assessed 10 information (in 10 bubbles), so a total of 280 bubbles were evaluated.

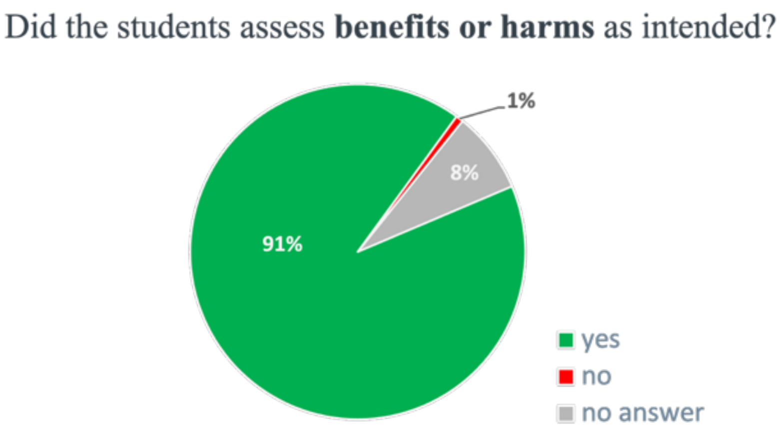
Figure 7. Example 'vegan diet', AssessmentBubbles and AssessmentDisc.



Benefits And Harms

Examining the results of the first step, in which students classified the information in the bubbles as a benefit or a harm, reveals a high accuracy: Over 90 % of the bubbles were classified correctly (Figure 8).

Figure 8. Assessment of benefits and harms by students.



AssessmentLevels

For each *AssessmentBubble* the three *AssessmentLevels* (*Where? How long? Who?*) are considered in addition to the benefits and harms. Therefore, an analysis was conducted to determine how many of the intended levels were assessed per bubble – one, two, or all three. In more than 80 % of the bubbles at least 2 out of 3 *AssessmentLevels* were correctly assessed (Figure 9).

Feedback On The Tool 'Assessmentbubbles' (RQ 3)

After the trial the students provided feedback on the method *AssessmentBubbles* via a five-point Likert scale questionnaire containing the following items, translated from German:

1 It was easy for me to assess whether the information described a *benefit* or a *harm.*

2 It was easy for me to assess *where*, for *how long*, and for *whom* the benefit or harm is shown.

3 It was easy for me to transfer from the Bubbles onto the *AssessmentDisc*.

4 The *AssessmentBubbles* gave me a good overview of the topic of *vegan die*t.

The results show predominantly positive feedback (Figure 10).

Figure 9. Assessment of AssessmentLevels by students.

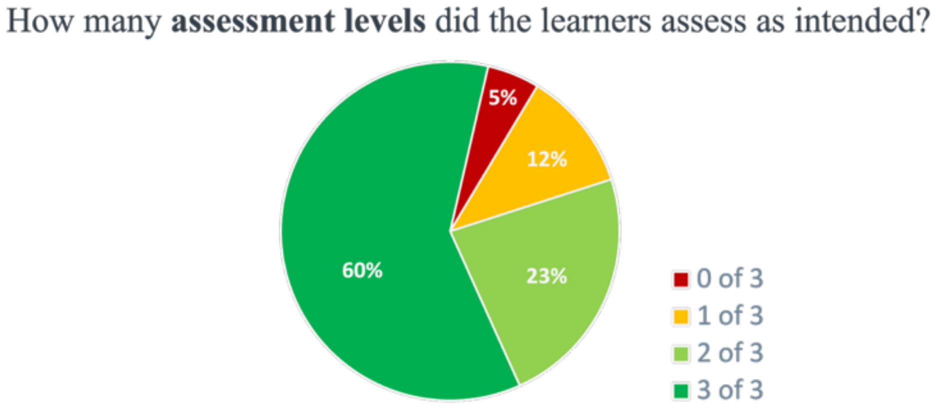
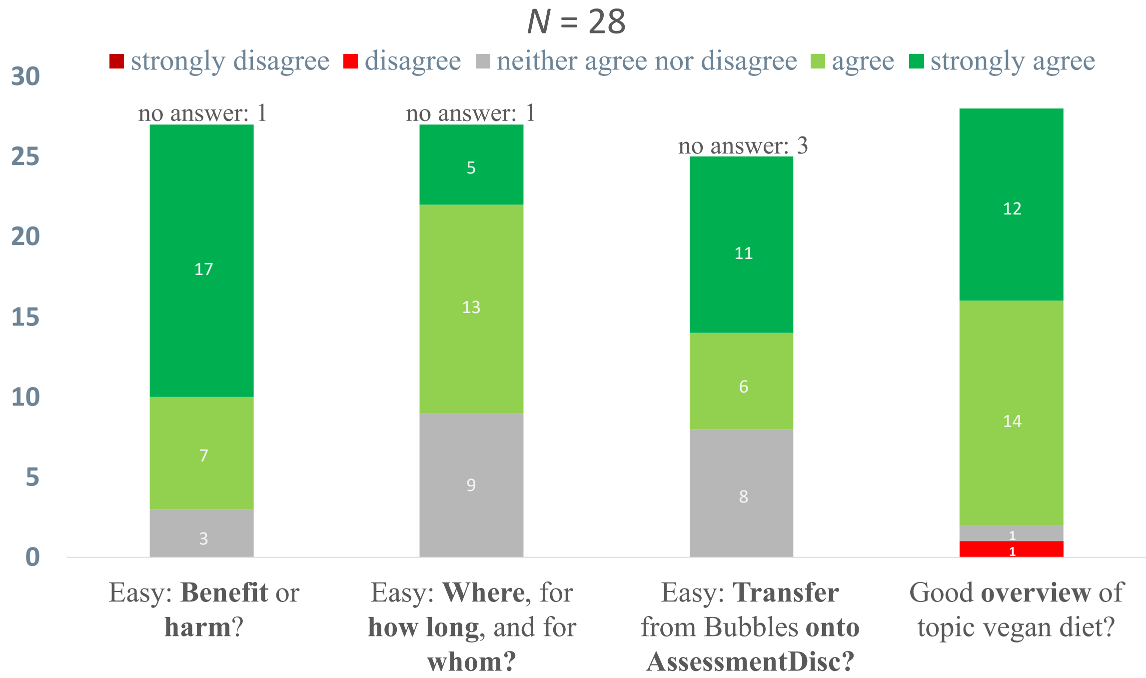


Figure 10. Assessment of AssessmentLevels by students.



The evaluations of the initial results indicate that *AssessmentBubbles* can support the assessment process for learners.

Summary And Outlook

The *sustain.able?!* teaching approach as a further development of the *nachhaltig.bewerten* approach aims to enable learners to assess the sustainability of a controversy in a criteria-based manner considering the three dimensions of *environment*, *economy* and *society*. Both approaches leverage *AssessmentLevels* (space, time, group) and the *AssessmentDisc* to guide this process.

The new methodological tool *AssessmentBubbles* in the teaching approach *sustain.able?!* has succeeded in simplifying and supporting the process of assessing information through a) compressed information, b) the immediate proximity of information and assessment and c) the color-coding of information according to sustainability dimensions.

Initial trials with students aged 14-15 demonstrate that the *AssessmentBubbles* effectively support learners in assessing sustainability controversies.

Expanding the approach to other scientific topics, increasing support for implementation in the classroom (e.g., developing a free app), and encouraging deeper reflection among students on sustainable decisions will be the next steps in this research project.

Furthermore, in line with the iterative process in DBR, Design 3 (Figure 4) is developed following an in-depth analysis of the data from the trial with the students. These revised teaching materials will then be tested with a larger sample of students.

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How To Teach In Times Of Biodiversity Loss: Pedagogical Approaches To Transform Our Relationship With Nature

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Biodiversity loss, exacerbated by climate change, represents a critical challenge that demands an integrated educational response. This article presents a narrative review exploring pedagogical approaches aimed at improving students' attitudes towards biodiversity and fostering pro-environmental behaviours. Recent literature identifies four main educational challenges: promoting positive attitudes towards biodiversity, increasing environmental literacy, fostering environmental efficacy, and reducing maladaptation due to climate anxiety. In response, three key pedagogical approaches are proposed: place-based education (PBL), Field Environmental Philosophy (FILAC), and the development of personalized ecologies. These strategies, including field trips, nature journaling, and the creation of gardens and green spaces, are highlighted for their ability to connect students with nature while fostering socioemotional and critical thinking skills. However, their implementation faces barriers such as limited time, resources, and adequate teacher training. It is concluded that integrating these approaches into school curricula can help build a citizenship committed to sustainability and environmental regeneration, especially if supported by teacher professional development programs that enhance their application across diverse educational contexts.

Keywords: Environmental education, biodiversity loss, place-based pedagogy

Introduction

Human-driven alterations to ecosystems are producing profound and cascading effects that compromise their functioning, stability, and resilience. Processes such as forest fragmentation, agricultural intensification, and the widespread use of pesticides disrupt species richness, trophic networks, nutrient cycling, pollination, and pest regulation, generating long-term consequences for ecosystem integrity (Haddad et al., 2015; Sánchez-Bayo & Wyckhuys, 2019; Dirzo et al., 2014). These pressures are expected to intensify under climate change, which further alters population dynamics, ecological interactions, habitat connectivity, and ecosystem resilience (IPBES, 2019).

Despite the magnitude of biodiversity loss, its consequences are often difficult to perceive and evaluate. Individuals, including scientists, tend to assess environmental change relative to the conditions they first experienced, a cognitive bias known as the shifting baseline syndrome, whereby progressively degraded states become normalised across generations (Soga & Gaston, 2018). This phenomenon is closely linked to the extinction of experience, referring to the gradual decline in meaningful human–nature interactions, which in turn shapes environmental attitudes and behaviours (Gaston & Soga, 2020; Colléony et al., 2020).

Understanding how people relate emotionally and cognitively to the natural world is therefore central to biodiversity conservation. Concepts such as biophilia—the affective affinity toward other living beings—and biophobia—negative emotions and attitudes toward nature—capture the emotional dimensions of human–nature relationships, both of which are strongly shaped by cultural, social, and educational contexts (Woods & Knuth, 2023; Albuquerque & Silva, 2024; Soga & Evans, 2024). While biophilic relationships are associated with greater willingness to engage in conservation actions, biophobic responses can reduce support for biodiversity protection and even promote species persecution (Soga et al., 2023). Consequently, fostering positive, experience-based relationships with nature through education has been identified as a key strategy for counteracting biophobia and promoting conservation-oriented behaviours (Deutsch et al., 2021; Zsido et al., 2022).

However, strengthening connections with nature is not without tension. Greater environmental awareness and emotional identification with nature have also been linked to increased psychological distress, as individuals perceive climate change and biodiversity loss as threats to their own well-being and future (Curll et al., 2022; Wullenkord et al., 2024). These responses have been conceptualised as climate anxiety and eco-anxiety, which, while not pathological in themselves, may exacerbate mental health challenges and lead to maladaptive coping strategies if left unaddressed (Crandon et al., 2024). Educational approaches that seek to promote environmental engagement must therefore balance ecological awareness with emotional support and resilience.

In response to the intertwined ecological and emotional dimensions of the biodiversity crisis, educational systems are increasingly called upon to move beyond purely cognitive or technocratic models. This shift involves reimagining education as a space for cultivating ecological justice, relational understandings of humans as ecological beings, and forms of coexistence with the more-than-human world (Common Worlds Research Collective, 2020). Yet, implementing such transformations presents significant challenges for teachers, who must navigate not only curricular demands but also their own emotional responses—and those of their students—to the climate and biodiversity crises (Suarez et al., 2024). Within this context, science education emerges as a critical arena for integrating ecological knowledge, emotional engagement, and ethical responsibility in ways that support both biodiversity conservation and human well-being.

Aims Of Study

The study aims to:

1. Synthesize evidence on the formation of environmental attitudes and behaviours.
2. Synthesize the evidence on pedagogical approaches that promote positive relationships with biodiversity.
3. Propose evidence-based guidelines for designing impactful science education practices.

Methods

A literature review was conducted using Scopus, focusing on:

- Biodiversity, well-being, and human development.
- Educational strategies addressing biodiversity loss and emotional well-being.
- The intersection of environmental education and socio-emotional development.

Inclusion criteria emphasized recent (post-2014) empirical and theoretical studies relevant to primary and secondary education. Exclusions included higher education contexts, non-educational interventions, and studies addressing aspects of the climate crisis such as greenhouse gas emissions, pollution, or carbon footprints, without directly considering biodiversity. Emerging themes guided additional searches to refine the conceptual and practical recommendations.

The complete list of search terms included combinations such as:

- Biodiversity AND Wellbeing
- Environmental literacy
- Environmental literacy AND Teachers

- Climate change AND Education
- Wellbeing AND Environmental education
- Environmental education AND Chile
- Biophilia AND Education
- Biophobia AND Education

The findings of the review were synthesized and organized in alignment with the study aims. First, evidence was examined to identify key processes involved in the formation of environmental attitudes and behaviours. Second, the literature was analysed to characterize pedagogical approaches and educational strategies that promote positive relationships with biodiversity. Finally, insights from both strands of evidence were integrated to inform the development of evidence-based guidelines for the design of impactful science education practices that intentionally address both cognitive and affective dimensions of human–biodiversity relationships.

Results

The results are organized into four sections that collectively address the three aims of the study. The first two sections synthesize evidence on the formation of environmental attitudes and behaviours, responding to the first aim. Specifically, the section on *Relationships with Nature* examines theoretical and empirical contributions that explain how affective, experiential, and cognitive dimensions—such as personalised ecologies, biophilia, and species knowledge—shape human–biodiversity relationships. The section on *Climate anxiety and eco-anxiety* complements this perspective by focusing on emerging emotional responses to environmental degradation, highlighting how these emotions can both motivate and constrain pro-environmental action depending on factors such as environmental efficacy and emotional competencies.

The third section addresses the second aim by reviewing educational strategies that intentionally foster positive relationships with biodiversity in school contexts through locally grounded, experiential, and affectively rich approaches. Finally, the fourth section responds to the third aim by synthesizing evidence from the previous sections to identify key educational challenges and propose evidence-based guidelines for designing science education practices that intentionally integrate attitudinal, emotional, and action-oriented dimensions of environmental learning.

Relationships With Nature

Personalised ecologies have emerged as a useful framework for examining how individuals relate to nature through direct, sensory interactions with other species and their ecosystems (Gaston et al., 2018). These ecologies are shaped by the dynamic interplay of external and internal factors, including opportunities to engage with nature, individual capacities to participate meaningfully in such interactions, and the motivations guiding behaviour toward natural environments (Gaston, 2024). Evidence suggests that rich and diverse personalised ecologies are associated with more positive attitudes toward biodiversity and a greater willingness to engage in conservation actions, whereas impoverished or predominantly negative experiences with nature are linked to increased biophobia (Gaston et al., 2023).

This perspective aligns with broader research on the development of human–nature relationships, which highlights the importance of formative experiences during childhood. In particular, exposure to influential social models and engagement in meaningful nature-based activities, such as observing natural processes or cultivating plants, have been identified as strong predictors of higher levels of nature connectedness in adulthood (Gong & Li, 2024). Furthermore, perceived knowledge of local species has been shown to reduce emotions associated with biophobia, including fear, disgust, and misperceptions of danger (Soga et al., 2020). In educational contexts, strategies aimed at enriching personalised ecologies, such as fostering species identification skills, providing regular opportunities for interaction with natural elements, and facilitating contact with experts in natural history and conservation, may therefore play a key role in promoting biophilia, ecological literacy, and pro-environmental behaviours.

Climate Anxiety And Eco-Anxiety

Growing evidence indicates that younger people, particularly those belonging to Generation Z, experience climate and eco-anxiety with greater intensity and emotional awareness in response to the global climate crisis (Tsevreni et al., 2023; Wullenkord et al., 2024). These heightened emotional responses are not uniformly maladaptive; when accompanied by a strong sense of environmental efficacy—the belief that individual and collective actions can meaningfully contribute to climate mitigation—climate anxiety has been shown to motivate pro-environmental behaviours (Becht et al., 2024). However, research also suggests that differences in emotional education shape how individuals cope with these emotions, with gendered patterns emerging in which men tend to report fewer emotional resources for managing climate-related anxiety (Wullenkord et al., 2024). Taken together, these findings underscore the importance of educational approaches that integrate emotional competencies to reduce distress while supporting constructive engagement with environmental challenges.

Educational Strategies

Place-based education (PBE) has emerged as a pedagogical approach aimed at addressing environmental challenges by situating learning within local communities and their socio-environmental issues, thereby integrating formal education, environmental stewardship, and community development (Smith, 2017). Drawing on multiple educational traditions, PBE employs strategies such as project-based learning, field trips, scientific camps, and nature journaling to connect disciplinary knowledge with students' lived environments (Bollich, 2023; Yemini, Engel, & Ben Simon, 2023). Empirical evidence suggests that this approach enhances learning outcomes, particularly when students perceive opportunities to make decisions about their learning processes and recognize that their work contributes meaningfully to environmental protection or restoration. Nevertheless, its implementation is often constrained by limited instructional time, insufficient funding, and gaps in teacher preparation (Hamilton & Marckini-Polk, 2023).

Complementary to this approach, playscapes—designed environments that recreate local natural landscapes under controlled conditions—seek to promote exploration, sensory engagement, and diverse forms of play (Carr & Luken, 2014). The variation in topography and the availability of both natural and artificial movable elements support predominantly exploratory and physical play, while also enabling social interaction and self-care activities (Loebach & Cox, 2022). Research indicates that learning and play within playscapes foster intrinsically motivated forms of inquiry, encourage environmentally responsible behaviours, and stimulate creativity and goal flexibility, all of which contribute to a stronger emotional bond with the environment by promoting feelings of safety and agency (Wight et al., 2016; Yuan et al., 2024).

In the Chilean context, related initiatives provide further evidence of the educational potential of locally grounded, nature-based approaches. The implementation of Life Labs—student-managed school gardens integrating emotional skills, empathy, and critical thinking—has been associated with increased pro-environmental behaviours, the development of dispositions such as open-mindedness, self-confidence, and truth-seeking, and a reduction in disruptive behaviours, particularly among younger students (Ampuero et al., 2015). Similarly, Field Environmental Philosophy (FILAC) combines ecological and philosophical knowledge to design ethically and ecologically oriented educational experiences, including contemplative practices, drawing as a tool for observation and interpretation, sensory exploration, creative engagement with local species, and the development of school-based scientific projects linked to fieldwork (Rozzi, 2018; Lewis et al., 2018; Rendoll-Cárcamo et al., 2020).

Educational Guidelines To Promote Positive Attitudes And Relationships Toward Biodiversity

Based on the reviewed literature on the formation of attitudes and relationships with nature, as well as the challenges that biodiversity loss poses for society in general and the educational system in particular, the reviewed literature indicates that education faces the following challenges:

1. Enriching personalized ecologies by fostering biophilia and mitigating biophobia, understanding them as positive and negative emotions and attitudes toward biodiversity and living beings, respectively.
2. Increasing environmental literacy and, therefore, individuals' capacity to recognize both the different components of biodiversity and the potential threats it faces.
3. Promoting environmental efficacy, that is, the belief that individual and collective actions have a significant impact on mitigating climate change.
4. Reducing the likelihood of maladaptation due to climate anxiety and eco-anxiety through emotional management skills.

Based on the reviewed evidence, we propose that education aimed at promoting positive attitudes and relationships toward biodiversity should follow three guidelines to guide educational practices:

1. Create opportunities for meaningful interaction with nature, both inside and outside the classroom.
2. Promote positive impacts on the immediate local environment through projects that connect students with their context.
3. Develop emotional and critical thinking skills that enable students to face environmental and emotional challenges.

Discussion

Accelerated biodiversity loss, intensified by climate change, poses complex challenges that require educational responses aimed at fostering environmentally respectful societies. Within this context, incorporating the concept of personalised ecologies into education involves recognising that individuals' interactions with the natural environment vary across social groups and life experiences, and that these interactions are fundamental for building meaningful relationships with nature. Enriching students' personalised ecologies aligns with the objectives of Natural Sciences education, which seeks not only to develop scientific knowledge about biodiversity but also to cultivate curiosity, wonder, and engagement with the natural world (MINEDUC, 2024).

The literature indicates that rich and diverse personalised ecologies are associated with higher levels of environmental literacy, stronger pro-environmental behaviours, and a reduced susceptibility to shifting baseline syndrome, which limits individuals' capacity to perceive environmental degradation over time (Gaston et al., 2023). This evidence supports the integration of approaches such as place-based education (PBE) and Field Environmental Philosophy

(FILAC), both of which promote sustained, direct engagement with local environments and thus contribute to the development of enriched personalised ecologies. In Chile, environmental education teachers have emphasised the need to incorporate outdoor learning spaces and practical, collaborative approaches that actively involve local communities, reinforcing the relevance of these pedagogical frameworks (Prosser-Bravo et al., 2022).

Flexible strategies such as field trips and nature journaling further support these aims, as they can be adapted to diverse curricular contexts, contents, and time constraints. Nature journals, in particular, may function either as components of inquiry-based projects or as pedagogical activities in their own right, fostering students' connections with their environment, their peers, and themselves (Bollich, 2023; Lewis et al., 2018; Tsevreni, 2021). Through these practices, opportunities emerge not only to enrich personalised ecologies but also to strengthen positive emotions toward nature and develop socio-emotional competencies.

Despite their potential, the implementation of these approaches in the Chilean educational system faces persistent challenges, including limited time for planning and execution, restricted access to resources, uneven levels of institutional support, and variations in teachers' prior experience with environmental education (Prosser-Bravo et al., 2020). While PBE and FILAC can be integrated into the regular curriculum—particularly within subjects designed to apply scientific knowledge to interdisciplinary and socially relevant contexts—their effectiveness ultimately depends on sustained commitment from the broader school community.

Community engagement is also central to initiatives aimed at promoting biophilia through the creation of educational green spaces, such as gardens, orchards, playscapes, green roofs, and living walls. These environments have been shown to support the development of pro-environmental attitudes and socio-emotional skills; however, both the underlying biological processes and the associated attitudinal and emotional changes require time to emerge. Importantly, the skills and dispositions fostered in these settings align with Chile's Cross-cutting Learning Objectives and, in the current curricular framework, are increasingly integrated into subject-specific learning goals (MINEDUC, 2016, 2018, 2024). This alignment highlights the broader educational value of such practices, particularly in relation to emotional regulation and resilience, which are critical for mitigating the negative effects of climate and eco-anxiety.

Finally, teacher education and professional development represent key leverage points for the effective integration of these approaches. Research in Chile has documented that environmental education is frequently delivered by teachers without specialised scientific training, limiting the integration of cognitive, procedural, and affective dimensions of environmental learning (Torres-Rivera et al., 2017; Karelovic-Vargas & Kong, 2022). Moreover, these challenges extend beyond non-specialist teachers, as even educators with scientific backgrounds report insufficient preparation to address sustainability in educational contexts (Quiroz-Martínez, 2024). Consequently, embedding these pedagogical frameworks within both initial teacher education and ongoing professional development is essential. As prior studies suggest, successful environmental education requires not only exposure to natural settings but also pedagogical practices that intentionally foster affectivity, empathy, play, and interaction with both the environment and others (Bertling, 2019; Gong & Li, 2024).

Conclusion

Education is at a crucial moment to address environmental challenges, such as biodiversity loss and its effects on human well-being. This work identifies four key challenges: fostering positive relationships and emotions toward biodiversity, increasing environmental literacy, promoting environmental efficacy, and reducing eco-anxiety. Three guidelines are proposed to address these challenges: creating meaningful interactions with nature, generating positive impacts on the environment, and developing emotional and critical thinking skills. Place-based education and Field Environmental Philosophy approaches, along with strategies such as field trips, nature journaling, and the creation of green spaces, are presented as effective tools. However, it is crucial to overcome obstacles such as lack of time, resources, and community support, as well as to have trained teachers, to achieve an education that shapes citizens committed to the conservation and regeneration of the environment.

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Cross-Cultural Analysis Of Stem Human Resources Community Influences On Gender: Focus On Higher Education Students In Japan, America, And Malawi

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In countries such as Japan, which strongly promotes science, technology, engineering, and math (STEM), human resource policies have increased. In education, the importance of a competency model is widespread; however, because many aspects of competency are influenced by the cultural background of individuals, certain considerations must be made for international comparisons. This study examines the culture of STEM and proposes a competency model for STEM human resources in a global context, particularly focusing on gender. For this, a 21-question survey was conducted among culturally diverse Higher education students (Japan, America and Malawi); 252 males and 157 females. There were significant differences between male and female students in the target country for 10 of the 21 ability elements. Significant gender differences were observed in STEM human resource consciousness and recognition, such as "collaboration," "ability to apply rules and regulations," and "ethics."

Keywords: Gender in STEM, Higher Education, STEM education

Introduction

In Japan, fostering science and technology-related human resources and innovation has become increasingly important in recent years. This is evident in the establishment of a Minister's Meeting task force at the Ministry of Education, Culture, Sports, Science and Technology (MEXT, 2018) based on the concept of "Society 5.0" (Cabinet Office, 2016). In this context, three abilities have been proposed: (1) ability to accurately interpret and respond to writing and information; (2) ability to engage in and apply scientific thinking and inquiry; and (3) sensitivity and ability to discover and create value, as well as curiosity and inquisitiveness, within a human resource profile.

However, because many aspects of competency are influenced by individuals' cultural backgrounds, certain considerations must be made when making international comparisons. This study focuses on the culture of science, technology, engineering, and math (STEM) and proposes a competency model for STEM human resources in a global context, particularly focusing on gender.

While previous studies, such as those by Kuroda (2021) and Kuroda (2022), have used Japan and Africa (Malawi) as case studies, Kuroda (2024) examined Japan and the America. This study focuses on gender and considers Japan, Malawi, and the America as case studies. America is an advanced country that has been actively promoting STEM education. In 2010 and 2012, the President's Council of Advisors on Science and Technology published reports to increase the number of people working in STEM fields (President's Council of Advisors on Science and Technology, 2010 / 2012). These policies have been in effect for over a decade. Malawi is one of the poorest countries worldwide, with a gross national income per capita of 600 US dollars (World Bank, 2023). For many years, the Japanese government has provided educational support for science and mathematics in Malawi as part of its official development assistance. Consequently, Malawi shares some characteristics of science and mathematics education with Japan, making it a suitable candidate for comparative analysis.

Therefore, the following research questions (RQs) were established to examine competencies common to the global STEM workforce:

RQ1: What are the characteristics of the STEM human resources community among students in the target country, and do these perceptions differ by gender?

RQ2: How can RQ1 be clarified by examining common consciousness and recognition among students in the target country?

Methods

In this study, a survey was conducted among culturally diverse Japanese, American, and Malawian students. The Japanese students were first- year students in the Faculty of Science at a local national university. The survey was conducted at the end of Quarter 2, as the university operates based on a quarter system). In this faculty, students can major in mathematics, physics, chemistry, biology, and geography, with approximately 36% advancing to graduate schools. The American students were recruited from freshman biology classes at a large midwestern university, while the Malawian students were first- and second-year students at an ICT vocational school, and a survey was conducted at the end of the year.

A total of 228 Japanese (male: 172, female: 56), 116 Americans (male: 44, female: 72), and 82 Malawian (male: 36, female: 29, not answered: 17) students participated in the study. Overall, the number of males and females was 252 and 157, respectively. This study extends previous research by Kuroda (2021, 2022, 2024), and other studies, utilizing the ability elements in the survey. The questionnaire consisted of 21 items based on the Fundamental Competencies for Working Persons, published by various Japanese government departments (1; Expertise (general), 2; Leadership, 3; Management, 4; Information, Media, and Technology Literacy, 5; Initiative, 6; Ability to Influence Others, 7; Executing Plans, 8; Ability to Detect Issues, 9; Creativity, 10; Critical Thinking, 11; Collaboration, 12; Communication, 13; Innovation, 14; Ability to Deliver Messages, 15; Ability to Listen Closely and Carefully, 16; Flexibility, 17; Ability to Grasp Situations, 18; Ability to Apply Rules and Regulations, 19; Ability to Control Stress, 20; Ethics, 21; Career Development and Planning).

The questions included: “How important are these skills and abilities for people with STEM careers?” Responses were recorded on a 5-point Likert scale, where 5 indicated “very important,” 4 “important,” 3 “somewhat important,” 2 “not very important,” and 1 “not at all important.” Average values were calculated based on the responses.

Results And Discussion

The survey results are summarized in Figure1 and Figure2. The options with more than 80% positive responses (responses to Options 4 and 5) were 13 for males (1, 2, 4, 5, 6, 7, 8, 9, 10, 12, 15, 16, and 17) and 19 for females (excluding 3 and 19). This indicates that the women exhibited a particularly strong awareness of the importance of the abilities assessed in the survey.

To confirm the difference in awareness more strongly, a *t*-test was conducted, revealing a significant difference in 10 items (Table 1). By contrast, Kuroda (2021), who focused on students in Japan and Malawi, found five items with significant differences. Thus, by expanding the target country, there is a possibility of a greater gender difference. In particular, the items “collaboration,” “ability to apply rules and regulations,” and “ethics” exhibited differences of more than 0.3 points in the responses, indicating a possibility of a greater gender-based influence.

Additionally, 11 items showed significant differences, and these items could be considered common factors for STEM human resources who can actively contribute to the STEM human resources community. However, the degree of positive response for “Management” and “Ability to Control Stress” was only approximately 70%. Therefore, the degree of positive response should also be considered an element that must be examined.

Figure 1. Results of importance perceptions (Male)

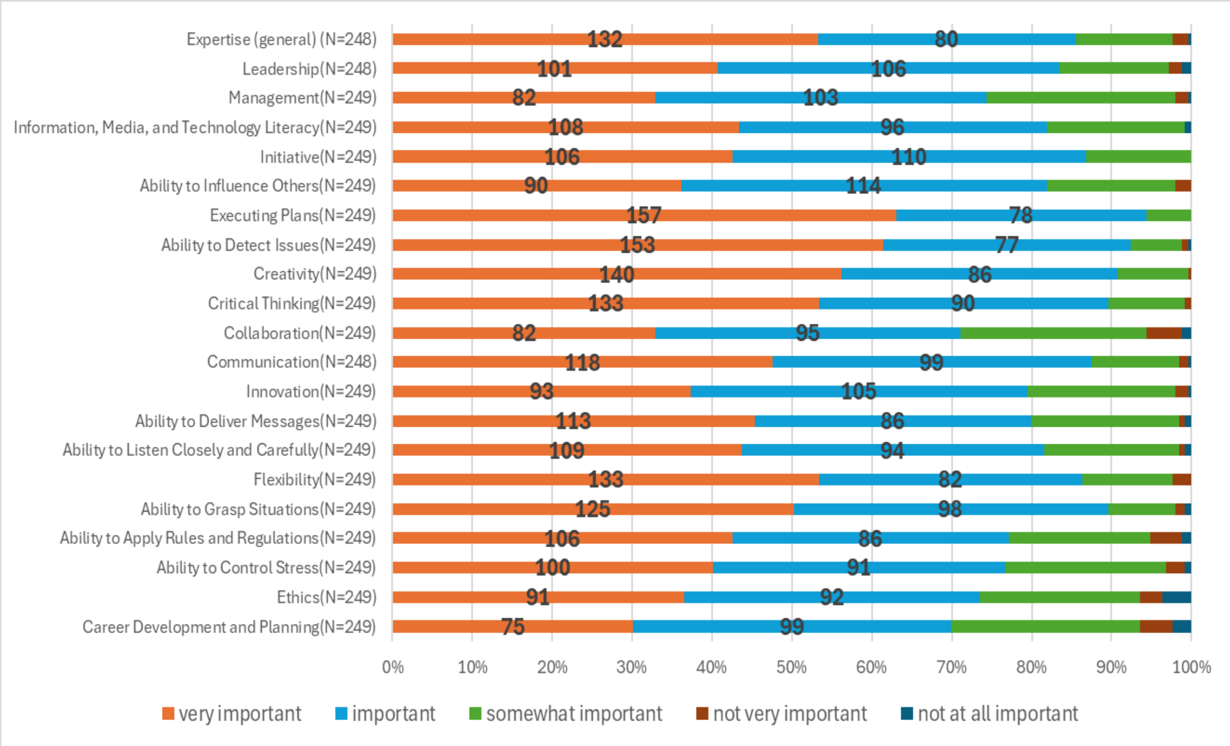
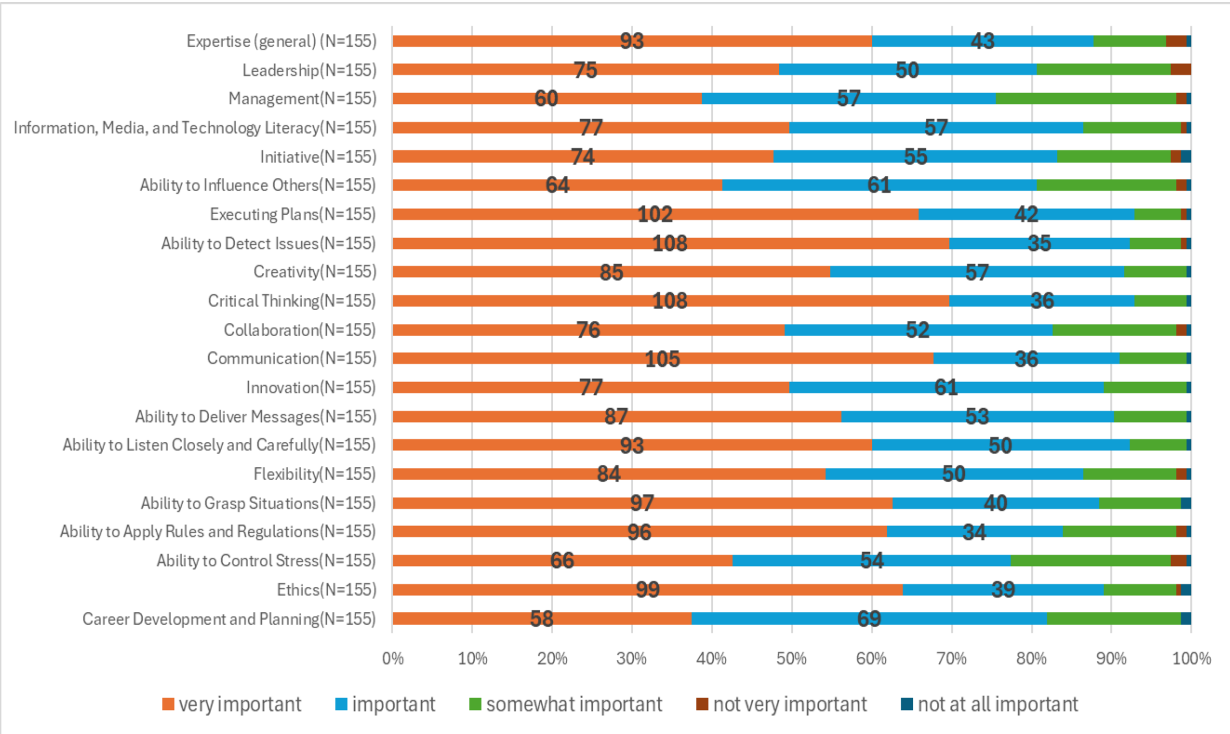


Figure 2. Results of importance perceptions (Female)



Conclusion

This study focuses on abilities within the STEM human resource community. Significant differences were found between male and female students in the target country for 10 of the 21 ability elements. Significant gender differences were observed in STEM human resource consciousness and recognition factors such as "collaboration," "ability to apply rules and regulations," and "ethics."

Table 1. STEM human resources community ability *t*-test

	Male Mean(SD)		Female Mean(SD)	*t*	df
Expertise (general)	4.36(0.802)		4.44(0.815)	-0.963	323.3
Leadership	4.20(0.825)		4.26(0.830)	-0.742	325.3
Management	4.05(0.817)		4.12(0.845)	-0.796	318.4
Information, Media, and Technology Literacy	4.24(0.791)		4.34(0.768)	-1.32	333.9
Initiative	4.29(0.689)		4.27(0.848)	0.288	402.0
Ability to Influence Others	4.16(0.761)		4.19(0.815)	-0.405	309.9
Executing Plans	4.57(0.599)		4.57(0.693)	0.0973	291.1
Ability to Detect Issues	4.52(0.690)		4.60(0.699)	-1.09	323.7
Creativity	4.47(0.672)		4.45(0.695)	0.203	318.4
Critical Thinking **	4.42(0.698)	<	4.61(0.668)	-2.72	402.0
Collaboration **	3.97(0.922)	<	4.29(0.822)	-3.61	354.7
Communication **	4.33(0.750)	<	4.57(0.702)	-3.30	343.1
Innovation **	4.14(0.800)	<	4.37(0.722)	-2.98	351.8
Ability to Deliver Messages **	4.23(0.833)	<	4.45(0.713)	-2.76	402.0
Ability to Listen Closely and Carefully **	4.23(0.813)	<	4.51(0.687)	-3.58	402.0
Flexibility	4.37(0.778)		4.38(0.792)	-0.0889	322.6
Ability to Grasp Situations *	4.37(0.757)	<	4.48(0.784)	-1.44	317.9
Ability to Apply Rules and Regulations **	4.13(0.926)	<	4.43(0.830)	-3.38	353.4
Ability to Control Stress	4.13(0.870)		4.17(0.859)	-0.444	330.0
Ethics **	4.00(1.00)	<	4.50(0.793)	-5.52	379.9
Career Development and Planning **	3.92(0.955)	<	4.17(0.796)	-2.79	402.0

※ * : $p < .05$ ** : $p < .001$

However, this study has certain limitations. First, it considers data from only three countries, and second, it only considers freshman-level students. Therefore, it is necessary to collect data from different countries and grade levels. Future studies should gather information from other countries and conduct further interviews with survey respondents.

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In Science We Trust? Examining Institutional Trust, Information Sources, and Climate Literacy Among Future Teachers

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Climate literacy is vital for future educators, the key facilitators of public understanding of climate change. This study examines how climate literacy, knowledge sources, and trust in scientific institutions interact to influence pre-service teachers' climate understanding. A survey of Greek University students assessed their climate knowledge, sources of information, environmental education, and trust in scientific institutions. Results indicate that formal education enhances reliance on structured sources, while digital platforms increase misinformation risks. A Climate Literacy Index (CLI) was developed, revealing that trust in scientific institutions strongly predicts climate literacy, while social media use correlates with climate misconceptions.

Keywords: climate literacy, teacher education, information sources

Introduction

Climate literacy is widely recognized as essential for informed decision-making and pro-environmental behaviour. For educators, and pre-service teachers in particular, climate literacy is of added importance, since they are actors of shaping public understanding of climate change. The challenge is that climate literacy extends beyond factual climate knowledge; it involves understanding climate systems, human–environment interactions, and the capacity to make evidence-based decisions (McCright et al., 2013). Accordingly, contemporary frameworks conceptualize climate literacy as a multidimensional construct that combines core climate science knowledge of the climate system, its causes, impacts, and response options (Leve et al., 2023; Aeschbach et al., 2025) with information skills related to accessing, evaluating, and communicating scientifically credible climate information (Shwom et al., 2017; Lubej et al., 2025). It further incorporates values, attitudes, and agency, including concern, responsibility, and willingness to engage in mitigation, adaptation, and public-sphere action (Choi et al., 2021; Kranz et al., 2022; Kolenatý et al., 2022), alongside a systems-oriented social-science perspective that accounts for human behaviour, social drivers, justice, and political dimensions shaping climate action (Shwom et al., 2017; Beach, 2023; Kranz et al., 2022).

Climate Literacy Components

Prior research indicates that information sources of high quality and credibility are essential to the "understanding" element of climate literacy (Dong et al., 2018). Traditional sources such as formal schooling, books, and government services have been associated with higher climate literacy scores (Höttecke & Allchin, 2020). Conversely, reliance on digital platforms, particularly social media, has been linked to greater exposure to misinformation and misconceptions about climate science (Lewandowsky et al., 2017). Therefore, integration of environmental education in academic curricula can reinforce the "decision-making" element of climate literacy as well, by enhancing learners' ability to critically evaluate information and by increasing reliance on structured sources over unverified online content (Clayton et al., 2015).

Table 1. Key components of climate literacy for educators

Component	Examples for (pre-service) teachers
Content knowledge	Greenhouse effect, drivers, impacts, solutions (Leve et al., 2023; Aeschbach et al., 2025)
Critical evaluation	Judging source credibility, evidence, statistics (Shwom et al., 2017; Ranney & Clark, 2016)
Communication	Explaining mechanisms, discussing tradeoffs (Shwom et al., 2017)
Normative/political literacy	Policy tools, justice, public vs private action (Kranz et al., 2022; Pan et al., 2023; Lestari et al., 2024)

However, climate literacy is not shaped only within academic settings. Outside formal education, individuals with greater trust in scientists, meteorological agencies, and environmental organizations demonstrate higher levels of climate literacy (van der Linden et al., 2017) and are less susceptible to climate-related misinformation (Feldman et al., 2011). Large international surveys show that scientific literacy and trust in science jointly predict climate change understanding and threat perception, with trust partially mediating the effect of literacy on understanding (Van Vleet & Fuller, 2024; Larrain et al., 2024; Pan et al., 2023).

In this study we examine how climate literacy, knowledge sources, and trust in scientific institutions interact to shape pre-service teachers' understanding of climate change.

Methodology

The study focuses on the following research questions:

RQ1: What are the primary sources of climate change knowledge for pre-service teachers, and how does having formal environmental education influence their reliance on these sources?

RQ2: How do different sources of climate information, formal education experiences, and demographic factors correlate with climate literacy (knowledge and behaviour), as measured by an integrated Climate Literacy Index?

RQ3: To what extent does trust in scientific institutions influence climate literacy among pre-service teachers, as measured by an integrated Climate Literacy Index?

Participants & Demographics

The sample consisted of 307 pre-service teachers enrolled in the 5th semester Geography course at a Greek University. Participants were 72% female, 27% male, and 1% identifying as non-binary or other. Their age ranged from 18 to 30 years old, with the majority (65%) falling within the 18-24 age range. Most participants were in their third year of study, and a small subset reported having prior degrees or higher education beyond the current program (this was captured as "higher education level" in our analysis). Participants' political orientation was assessed on a scale (ranging from more conservative to more liberal), given the potential influence of ideology on climate perceptions. Socioeconomic background information such as approximate household income and parental education was also collected for context. Participation in the study was voluntary and anonymous.

Data Collection

Data was collected through an online questionnaire administered during a scheduled laboratory session of the teacher education course. Participants received a survey link and completed the questionnaire on their personal devices under the supervision of the researchers. The survey took approximately 20 minutes to complete. To encourage honest responses, participants were assured that their individual answers would remain confidential and would not affect their course standing. The questionnaire comprised several sections measuring climate literacy and its potential determinants, as described below.

Climate Literacy Measures

Climate literacy was assessed using a combination of knowledge-based items and behaviour/self-efficacy measures, reflecting its widely recognized multidimensional character encompassing knowledge, attitudes, and behaviours. Rather than adopting an existing single instrument, we developed a **Climate Literacy Index (CLI)** specifically for this study. This decision was informed by evidence that many available climate literacy measures are either predominantly knowledge-focused or designed for specific age groups, countries, or educational contexts, which limits their transferability to pre-service teacher populations (Leve et al., 2023; Lubej et al., 2025; Sato & Park, 2024). In addition, existing tools often insufficiently capture behavioural intentions, self-efficacy, and action readiness, dimensions increasingly considered central to climate literacy in education research (Kolenatý et al., 2022; Aeschbach et al., 2025). Developing a context-specific composite index therefore allowed us to integrate climate science understanding with behavioural and self-efficacy components relevant to the professional role and common misconceptions of future teachers, in line with contemporary calls for multidimensional and population-sensitive climate literacy assessments (Matlack et al., 2023; Nayan et al., 2020).

The knowledge component of the CLI comprised 15 multiple-choice and true/false items assessing core climate change concepts, including causes, evidence, impacts, and scientific consensus. Several items targeted well-documented misconceptions, such as confusing ozone depletion with climate change or perceiving impacts as exclusively future-oriented. Item development was informed by climate literacy frameworks and prior research on public misconceptions, and content validity was ensured through expert review by two climate science educators. Correct responses were summed to yield an individual knowledge score (range 0–15).

The behavioural component included 16 Likert-type items measuring self-reported climate-relevant behaviours and intentions related to mitigation and adaptation, such as energy conservation, sustainable transport, waste reduction, civic engagement, and climate-related discussions. Behaviours were included to capture the action-oriented dimension of climate literacy, particularly relevant for pre-service teachers as future role models. Items were adapted from established environmental behaviour instruments and contextualized for climate change.

To construct the composite Climate Literacy Index (CLI), knowledge and behaviour scores were normalized to a common 0–1 scale and then averaged, giving equal weight to both components. The resulting CLI ranged from 0 to 1, with higher values indicating greater overall climate literacy. The CLI was used as the primary outcome variable, representing the joint presence of climate understanding and climate-responsible action.

Results

RQ1: Information Sources Used And Influence Of Environmental Education

Pre-service teachers reported relying on a combination of digital, institutional, and traditional media sources for climate change information, with clear differences in frequency of use. Digital platforms dominated: the internet was the most frequently used source ($M = 3.17$ on a 1–4 scale, approaching “often”), followed by social networks ($M = 2.76$). Formal education also remained influential, with school-based sources reported at relatively high levels ($M = 2.84$). Books constituted another important channel (M = 2.65), while family and friends played a more moderate role (M = 2.59), suggesting some informal discussion but not a primary reliance.

Institutional and legacy media were used less frequently. Government services (M = 2.27) and magazines/newspapers (M = 2.24) fell between "rarely" and "sometimes." Television occupied a similar mid-range position (M = 2.41), whereas museums and zoos were less commonly cited (M = 2.14). Cinema and radio were the least utilized sources, with mean values of 2.03 and 1.91 respectively, indicating that audiovisual and broadcast media play a comparatively minor role in shaping climate information practices among pre-service teachers.

Figure 11. Frequencies of climate information sources.

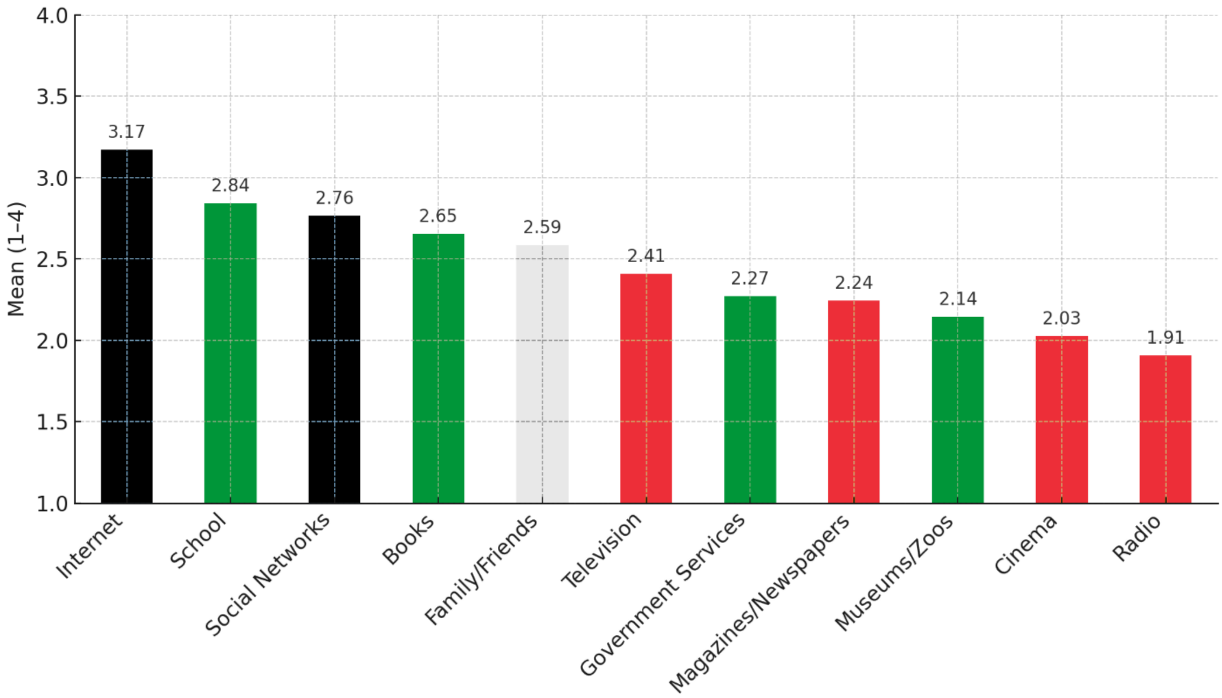


Table 2. Mean frequency of use of climate information sources with and without formal environmental education. (Scale: 1 = Never, 4 = Often).

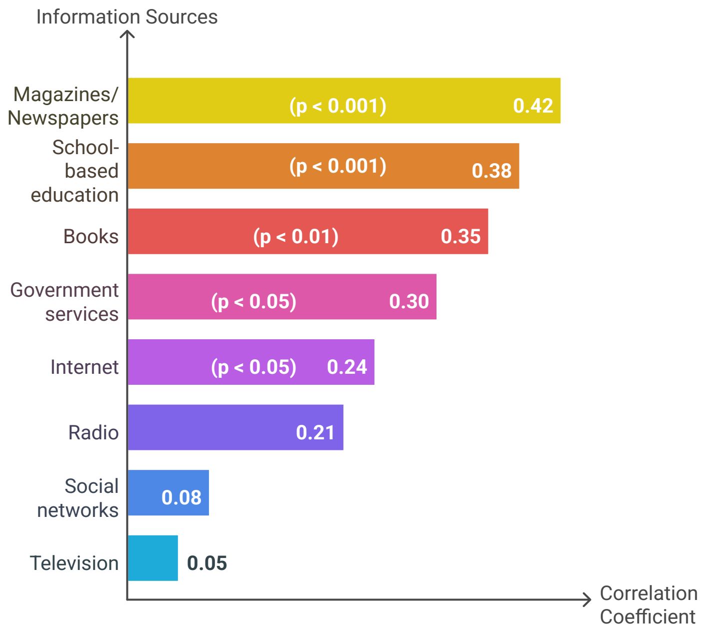
Climate Information Source	Mean (With EnvEdu)	Mean (Without EnvEdu)	p-value
Internet	3.25	3.10	0.048
Social Networks	2.85	2.69	0.045
Books	2.73	2.59	0.038
Government Services	2.42	2.14	0.007
Magazines/Newspapers	2.65	2.54	0.062
Family/Friends	2.50	2.48	0.081

Table 2 summarizes the comparison of source usage means between those who have had formal environmental education (EnvEdu group) and those who have not. Several significant differences emerged. Pre-service teachers with an environmental education background reported greater use of authoritative sources such as books and government services, compared to those without such background. For instance, the EnvEdu group had a higher mean frequency for using books as a climate information source (Mean = 2.73) than the No EnvEdu group (Mean = 2.59), a difference that was statistically significant ($p = .038$). Similarly, use of government or scientific agency sources was higher among those with environmental education (Mean = 2.42 vs. 2.14, $p = .007$). Interestingly, those with environmental education also showed slightly higher usage of online sources: they reported using the internet (general web resources) more often on average (3.25 vs. 3.10, p = .048) and similarly for social media (2.85 vs. 2.69, p = .045) compared to the group without environmental education. This suggests that students who had prior environmental lessons might be more engaged overall in seeking out climate information from a variety of sources (possibly due to greater interest or awareness of climate issues). In contrast, for sources like magazines/newspapers and family/friends, the differences between groups were small and not statistically significant (e.g., 2.65 vs. 2.54 for magazines, p = .062; 2.50 vs. 2.48 for family/friends, p = .081, both n.s.). Traditional media (TV, radio, films) had generally low usage in both groups, with no notable differences.

RQ2: Predictors Of Climate Literacy (CLI) – Information Sources, Education, And Demographics

To assess climate literacy beyond knowledge scores, we constructed a Climate Literacy Index (CLI) that integrates both climate knowledge (the respondents' score on climate-related questions) and pro-environmental behaviours, as described above.

Figure 12. Correlation of CLI with climate info sources.

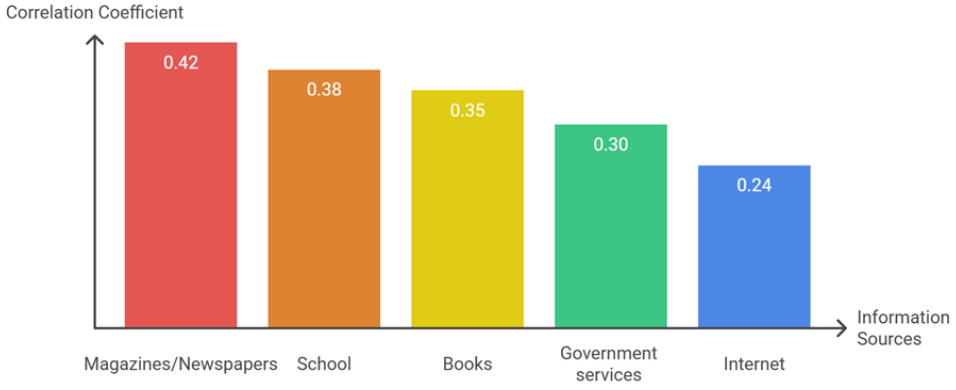


Examining the relationship between information sources and CLI, we found that magazines/newspapers ($r = 0.42$, $p < 0.001$) were the strongest positive predictors of CLI, followed by school-based education ($r = 0.38$, $p < 0.001$). In contrast, television ($r = 0.05$, $p = 0.48$) and social networks ($r = 0.08$, $p = 0.35$) showed weak or negligible effects (Figure 2).

Formal nvironmental education had a significant but complex impact. Individuals with environmental education scored higher on CLI ($p = 0.0255$, t-test). However, multiple regression analysis showed that when examining information sources, formal education alone was not an independent predictor of CLI.

Demographic variables also influenced CLI, with higher education levels ($r = 0.41$, $p < 0.001$) and political orientation ($r = 0.33$, $p < 0.01$) being the strongest predictors. In contrast, income ($r = 0.18$, $p = 0.08$) and gender ($r = 0.09$, $p = 0.31$) showed weaker and non-significant effects.

Figure 13. Correlation between Information Sources and Climate Literacy (CLI).



RQ3: Trust In Scientific Institutions And Climate Literacy

When comparing individuals who rely on scientific institutions (universities, government research bodies, and meteorological services) vs. social media users showed significant differences in climate literacy scores. CLI scores for scientific institution users were 18% higher than for social media users. A t-test comparing CLI scores between these groups found $t = 5.37$, $p < 0.001$. Regression analysis further confirmed that reliance on scientific sources significantly predicts CLI ($\beta = 0.41$, $p < 0.001$), while social media reliance has a negative association with CLI ($\beta = -0.27$, $p = 0.002$).

A correlation analysis between social media reliance and common climate misconceptions found that social media users were more likely to believe false climate claims:

"Snowfall disproves global warming" (r = 0.38, p < 0.01)

"Climate models are unreliable" (r = 0.34, p < 0.01)

"Climate change is natural and not caused by human activity" (r = 0.29, p = 0.02)

Trust in scientific institutions is strongly associated with higher climate literacy levels. The highest correlations with the Climate Literacy Index (CLI) were found for Trust in Scientists ($r = 0.47$, $p < 0.001$), Trust in Meteorological Services ($r = 0.42$, $p < 0.001$), and Trust in Scientific TV Programs ($r = 0.39$, $p < 0.01$). Individuals with higher trust in scientific institutions had significantly higher CLI scores than those with low trust. A t-test comparing high vs. low trust groups revealed a significant difference ($t = 4.21$, $p < 0.001$), with high-trust individuals scoring, on average 14% higher on CLI score.

Discussion

Information Sources And Climate Literacy

Consistent with prior research, reliance on structured and credible information sources was found to be associated with higher climate literacy, as education and media coverage from reliable institutions significantly enhance climate understanding and policy support (Pan et al., 2023). Participants engaging with formal education, reputable news media, and written science-oriented sources demonstrate stronger climate knowledge, reinforcing the importance of science education and media literacy in fostering acceptance of climate science (Pan et al., 2023; Loy et al., 2020). Reading climate-related articles in newspapers or magazines emerges as a strong predictor of climate literacy, suggesting that self-directed engagement with quality science journalism improves both accuracy and depth of understanding (Loy et al., 2020). In contrast, social media use shows no positive association with climate literacy, supporting concerns that digital platforms often amplify misinformation and reinforce confirmation biases (Cheng & González-Ramírez, 2020; Cosby et al., 2025). This aligns with research documenting how online environments contribute to spreading organized climate skepticism and undermining scientific understanding (Cheng & González-Ramírez, 2020). Television also shows limited contribution to climate literacy, consistent with findings that generalized or politicized broadcast coverage rarely deepens climate knowledge unless explicitly science-focused (Cosby et al., 2025; Almansa-Martínez et al., 2024).

Trust In Science As A Key Predictor

Trust in scientific institutions is one of the most robust predictors of climate literacy, with global evidence showing that trust in scientists strongly correlates with better climate knowledge and resistance to misinformation (Van Vleet & Fuller, 2024; Cologna & Siegrist, 2020; Cologna et al., 2024). In some studies, trust in science has been found to outweigh formal environmental education as a predictor of climate literacy, highlighting trust as a foundational mechanism for internalizing scientific information (Larrain et al., 2024; Osborne & Allchin, 2024). Research also emphasizes that building trust is critical for effective science communication and education, suggesting that fostering trust may be as important as delivering content in teacher education (Cooper, 2011; Lacey et al., 2017). Meta-analyses confirm that trust in scientists and scientific institutions strongly correlates with climate-friendly attitudes and behaviours, reinforcing the central role of trust in shaping climate literacy (Cologna & Siegrist, 2020). Overall, these findings underscore the importance of cultivating informed epistemic trust to enhance public understanding and engagement with climate science (Osborne & Allchin, 2024; Cologna et al., 2024).

Ideology And Demographic Patterns

Political orientation consistently predicts climate literacy, with more conservative individuals scoring lower on climate literacy indices, reflecting ideological influences on how scientific information is processed even within relatively homogeneous university cohorts (Arroyo-Barrigüete et al., 2023; Hamilton, 2011; Fischer et al., 2022). While outright climate denial is uncommon, ideological differences often appear in the depth of knowledge and perceived urgency of climate change, suggesting cultural cognition shapes interpretation rather than outright rejection of science (Arroyo-Barrigüete et al., 2023; Trémolière & Djeriouat, 2021).

No significant gender differences in climate literacy were observed, indicating a narrowing gender gap among younger populations (Kranz et al., 2022; Zummo et al., 2020). Similarly, income effects were absent in student samples (Kranz et al., 2022).

These findings highlight the importance of addressing political and cultural factors alongside education to improve climate literacy effectively.

Formal Environmental Education: Limits And Implications

Although participants with prior environmental education tended to display higher climate literacy, its effect was not independent in regression models and appeared mediated by information engagement. This suggests that the presence of environmental education alone is insufficient; its impact depends on quality, recency, and integration with active engagement. This finding aligns with research emphasizing that exposure without sustained engagement has limited long-term effects (Trott, 2020; Trott & Weinberg, 2020). For teacher education programs, this underscores the need for integrated, longitudinal approaches rather than isolated coursework.

Implications, Limitations and Future Directions

These findings suggest that formal education alone is insufficient and must be supplemented with structured, credible knowledge sources. The negative association between social media reliance and CLI highlights the risk of misinformation, emphasizing the need for media literacy in climate education. For pre-service teachers, climate literacy is particularly crucial, as they serve as knowledge transmitters in society. The incorporation of structured, evidence-based climate education in teacher training programs can enhance their ability to evaluate sources critically and disseminate accurate climate information (Stevenson et al., 2013). Finally, the more trust fostered in scientific institutions, the better the negative influence of misinformation can be counteracted, ensuring that pre-service teachers are well-equipped to guide students toward climate-responsible behaviours.

First, the sample was drawn from a single university and largely from one teacher education program within a specific national context, limiting generalizability. Climate literacy, trust, and information practices may differ across countries, institutions, and teaching specializations. Future research should include more diverse samples and comparative designs to examine how disciplinary background, national curricula, and sociopolitical context shape pre-service teachers' climate literacy.

Second, the study relied on self-reported measures for behaviours, information sources, and political orientation, which may be subject to social desirability and reporting biases. Although anonymity was ensured, participants may have over-reported socially valued behaviours or reputable sources. More fine-grained measures of ideology and complementary behavioural or observational data could strengthen future analyses.

Finally, while the Climate Literacy Index (CLI) integrates knowledge and behaviour, it does not capture all dimensions of climate literacy. It does not directly assess higher-order skills such as critical evaluation of information, misinformation detection, emotional engagement, or communication competence. Moreover, validation of the CLI was limited to content review and internal consistency.

Future studies should extend validation using external criteria and consider expanding the index to include skills that are especially relevant to teachers' professional practice.

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Potentials And Challenges Of Serious Games In Environmental And Sustainability Education

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Sustainability challenges are increasingly recognized as "wicked problems" that require complex, non-linear responses and systemic reasoning. Despite this, traditional education often emphasizes linear thinking, leaving a gap in students' ability to engage with the interconnections of social, ecological, and economic systems. This paper investigates the efficacy of Game-Based Learning (GBL) as a method to bridge this gap in higher education. Specifically, the study examines the FRACTALgame, a cooperative strategic board game designed to enhance awareness of Green Infrastructures (GI) and Ecosystem Services (ES) within Alpine ecosystems. Developed through an interdisciplinary process combining the Educational Game Design Model and the Three-Layered Thinking Model, the game targets three domains: ecological knowledge, EU-GreenComp competencies (such as systems thinking), and soft skills. A mixed-methods playtest involving university students revealed significant gains in conceptual clarity. Participants transitioned from vague, aesthetic definitions of GI to functional, systemic understandings. While the cooperative mechanics fostered engagement and mirrored real-world environmental collaboration, the study identified challenges, including cognitive overload from complex manuals and the "nebulous" nature of Ecosystem Services. Results suggest that while serious games are potent tools for cultivating green competencies, they require a structured GBL framework—including educator facilitation and debriefing—to prevent student paralysis when facing systemic complexity.

Keywords: Sustainability education, game-based learning,

Introduction

Sustainability is widely recognised as a *wicked problem*, defined as a complex and multi-faceted challenge that resists linear solutions and requires adaptive and evolving responses (Lönngren & Van Poeck, 2020). Sustainable land management represents a clear example of such complexity. Balancing land and resource preservation with the fulfilment of human needs remains one of the central challenges of contemporary societies (Verburg et al., 2022). Ongoing population growth and consumption patterns continue to intensify pressure on land systems, making sustainable land management essential for maintaining ecological integrity, promoting social justice and wellbeing, and supporting long-term economic development. As articulated in the UN 2030 Agenda, sustainability challenges are characterised by uncertainty, value conflicts, and strong interdependence across social, ecological, economic, and political domains. Addressing these challenges requires not only disciplinary scientific knowledge—such as ecology, biology, chemistry, and physics—but also transversal competences including systems thinking, futures literacy, negotiation, and collaborative problem-solving. These competences are explicitly articulated in the European Sustainability Competence Framework (GreenComp), which aims to equip learners with the knowledge, skills, and attitudes needed to act as agents of change while recognising human embeddedness within natural systems (Bianchi et al., 2022). Systems thinking is identified as a core competence for sustainability, defined as the ability to consider time, space, and context in order to understand interactions within and between systems. Similarly, the PISA 2025 science framework introduces the concept of *Agency in the Anthropocene*, emphasising learners' capacity to understand human–Earth system interactions, evaluate evidence-based solutions, and navigate uncertainty and limits. However, in traditional educational settings, students are often trained to approach problems through linear reasoning and the isolation of variables. Sustainability challenges, by contrast, are inherently systemic, operating through feedback loops, non-linear dynamics, and delayed effects (Souliotis & Voulvoulis, 2025). When sustainability concepts are addressed in abstract or fragmented ways, learners may develop awareness without acquiring the analytical tools necessary for systemic reasoning and futures-oriented decision-making (Castaño et al., 2025; Weber et al., 2021). This gap highlights the need for educational approaches capable of fostering systems thinking and equipping students to engage meaningfully with the complexity of sustainability issues.

Game-Based Education For Environmental And Sustainability Education

In response, learner-centred and experiential approaches aligned with Environmental and Sustainability Education (ESE) have gained increasing attention. Among these, game-based education (GBE) offers promising opportunities to engage learners in exploring complexity, negotiating trade-offs, and experimenting with decision-making in collaborative settings (Plass et al., 2015). GBE has proven effective in sustainability education by providing immersive and interactive experiences in which learners can apply theoretical concepts in realistic contexts (Bergen & Fromberg, 2009). Environmental serious games integrate game mechanics and narrative structures to foster both scientific and humanistic competences (Fernández-Galeote & Hamari, 2021; Janakiraman et al., 2018). Grounded in an embodied–enactive cognition model, these approaches connect physical and cognitive engagement through game dynamics, supporting transformative learning experiences that translate abstract knowledge into more concrete understandings of environmental systems and behaviours (Plass et al., 2015). Game-Based Learning (GBL), as a pedagogical approach rooted in GBE, refers to the use of games—played and/or designed—as part of instructional activities, with learning as the primary intended outcome (Plass et al., 2015). Educational games, whether digital or analogue, are thus used to convey disciplinary content while simultaneously fostering transversal skills. Serious games, as a subset of educational games, are developed with explicit learning objectives and require an interdisciplinary design process that integrates pedagogy, scientific knowledge, and game design principles (Plass et al., 2015). Empirical studies indicate that well-designed serious games can increase awareness of environmental and social issues, support understanding of ecosystem complexity and decision-making processes, and enhance motivation, engagement, and information retention. By embedding learners in scenarios where decisions have tangible consequences, serious games support the development of key twenty-first-century skills essential for addressing sustainability challenges (Fernández-Galeote & Hamari, 2021). In this paper, we aim to contribute to the discussion on how game-based learning can support sustainability education goals.

Research Objective

This research is driven by the urgent need to bridge the gap in higher education curricula, where, despite growing efforts, many students still lack adequate exposure to sustainability education. Consequently, the research investigates the feasibility of GBL as a method to effectively equip learners with the necessary knowledge and attitudes to address complex sustainability challenges. More specifically we present and discuss potentials and weaknesses of the FRACTALgame, developed as part of an EU-funded project to increase the awareness of young people on Green Infrastructures and their role in supporting ecosystem services and ecosystem conservation in the Alps.

This study investigates the efficacy of serious games in sustainability education by addressing three specific research questions; i) is FRACTALgame effective in teaching specific ecological contents, such as Green Infrastructures and ecosystem services, ii) which green, social, or emotional skills are most commonly activated from the students' perspective and iii) which skills students utilized with confidence and which were the most difficult to apply during the cooperative experience.

Methods And Materials

For the game-design process, we combined some technical and theoretical principles from the Educational Game Design Model (Ibrahim & Jaafar, 2009) and the Three-Layered Thinking Model (TLTM) (Fong-Ling, & Sheng-Chin, 2008). The EGDM and the TLM have been adopted to design the scientific contents and educational output and how to fit them with mechanics, dynamics, and aesthetics.

Game Characteristics

Table 1. List of the expected educational outcomes and game elements and rules.

Research Domain	**Game Rules & Structure**	**Specific Mechanic / Tool**
1. Ecology Knowledge	Rebuild ecosystems and restore their functions. Setup: Players must identify and manage five distinct Alpine ecosystems: mountains, forests, rivers/lakes, agroecosystems, and urban areas.	GI & ES Cards: Using Green Infrastructure (GI) and Ecosystem Services (ES) cards to counter specific threats. Point Cards: Visualizing the loss of "Supporting," "Regulating," "Provisioning," and "Well-being" services through marker placement.
2. EU-GreenComp	Anticipate and mitigate the effects of overexploitation and climate change in the year 2050. Systems Thinking: Navigating interconnections where a loss in biodiversity or soil (Supporting) leads to crises in human health (Well-being).	Threat Deck: Drawing "Extreme Weather Event" and "Overexploitation" cards that intensify systemic collapse. Resiliency Sets: Building a 5-card set (1 GI + 4 ES categories) to achieve long-term ecosystem protection.
3. Soft Skills	Goal: Cooperative gameplay where players "Team up to save Alpine ecosystems". Rules: Players are encouraged to keep hands open so everyone can see the cards in play to facilitate group discussion.	Cooperative Actions: Using moves to trade cards with other players on the same ecosystem to complete necessary sets. Characters Powers: Utilizing four distinct characters (e.g., Expert, Activist) with special powers that must be coordinated to win.

The FRACTALgame is a cooperative and strategic board game. The primary scope of the game is to bridge the gap between theoretical ecology and practical sustainability competencies. The overall scope of the game is to foster collaboration among players to mitigate the negative impacts of overusing natural resources, rebuild ecosystems to restore their functions, and ultimately save local communities. The gameplay involves players in saving five specific at-risk ecosystems: mountains, forests, rivers and lakes, agroecosystems, and urban areas. To achieve this, players must strategically utilize Green Infrastructure (GI) and Ecosystem Services (ES) cards to address environmental challenges. Its pedagogical structure is divided into three core domains to achieve specific educational outcomes (Table 1).

In terms of ecological knowledge, the game aims to teach players what ES and GI are and how they function, alongside the ecological principles necessary for sustainable land management. Regarding skills and competencies, the game explicitly targets the development of systems thinking, helping learners identify system elements, interconnections, delays, and feedback loops. Furthermore, the cooperative mechanics require players to engage in future scenario building, problem-solving, and critical thinking. Ultimately, the game fosters social competencies by requiring negotiation to design common scenarios and cooperation to face complex future challenges.

Implementation Phase And Data Collection

Starting from the expected educational outcomes we designed two game-test rounds. The playtest of FRACTALgame took place as part of the SO|STA - Lo Spazio dello Stare project, an initiative aiming to enhance the use of green spaces of Matera University campus, involving six university students with different ages (20-20 years old) and backgrounds (Architecture, Urban Planning and science education).

The test sessions took three days (11-13 September 2024) and a total of 6 hours (2 hours for day) were used for the test session. The research employed a mixed-method approach to evaluate the game's effectiveness, utilizing four distinct tools. To measure gains in ecology knowledge, ex-ante and ex-post surveys were administered, grounded in national educational outcomes for secondary schools and civic education guidelines. To examine the stimulation of specific skills, the study used open-ended questionnaires (also pre- and post-game) based on a revised MEEGA+ model, which was aligned with both the EU Green Skills framework and the PISA 2025 Environmental Science Competences. These quantitative measures were complemented by qualitative tools, including a game-logbook for student self-reflection and a focus group session to gather deeper insights.

Results

The preliminary findings from the initial playtest of the FRACTALgame indicate a good level of student engagement and a strong alignment with sustainability education objectives. Quantitatively, the experience was positively received: five out of six participants reported enjoying the game, and four out of six expressed a willingness to play it again. A primary driver of this success was the cooperative dynamic, which players identified as an added value that effectively mirrored the collective efforts required for real-world environmental action. As one participant observed, the "*ability to save an ecosystem collectively represents one of the most educational aspects of the game*".

Conceptual Learning And Aesthetic Utility

The integration of aesthetic design with pedagogical goals proved to be a significant asset. The graphical elements served as more than mere decoration; they functioned as a powerful medium for communicating complex ecological concepts. Results suggest that the game is a potent tool for introducing nuanced topics like GI. Participants demonstrated a marked shift from vague conceptualizations toward concrete, post-game definitions as demonstrate some of the examples reported in Table 2.

Table 2. Evolution of student conceptualization of Green Infrastructures (GI) comparing pre-game (vague/aesthetic) and post-game (functional/systemic) definitions.

Phase	**Student Conceptualizations of Green Infrastructures (GI)**
Pre-Game (BEFORE)	*"Green areas."*
Question: *Please define what a Green Infrastructure is.*	*"Infrastructures that follow low environmental impact guidelines."*
	"Infrastructures aimed at environmental protection, such as creating green spaces in urban areas."
	"Semi-anthropized spaces designed to enhance and develop ecosystem services for both humans and nature."
Post-Game (AFTER)	*"Human designed structures mimicking nature and enabling ecosystem services across different ecosystems."*
Question: *After playing the FRACTALgame, please define what a Green Infrastructure is.*	*"Natural structures designed by humans with the scope of preserving ecosystems from being altered by human activity."*
	"Structures that contribute to the proper functioning of an ecosystem (green for land/reforestation, blue for marine ecosystems)."

The transition shown **in Table 2 confirms** that the **FRACTALgame** functions as an effective vehicle for translating abstract theory into concrete understanding. This evolution is supported by the game's structural design, which explicitly targets three distinct research domains:

- **Ecology Knowledge:** *P*articipants moved from general "low environmental impact" statements to identifying specific roles in "*preserving ecosystems from being altered by human activity*". Additionally, where initial definitions were focused on "*green areas*," in the post-game responses students recognise GI as "*human designed structures... enabling ecosystem services*". Additionally,
- **EU-GreenComp:** Post-game definitions reflect an understanding of "proper functioning of an ecosystem," aligning with the EU-GreenComp goal of fostering systems thinking.

Skill Activation And Strategic Complexity

Regarding the development of competencies, the study observed a dominance of cognitive and social skills, though these were not immediate. Students noted that moving from linear to systemic reasoning required an iterative process: "*At the beginning... we didn't plan strategically. thinking strategically, understanding how the system works required time*".

The complexity of the mechanics, specifically the Threat Cards, forced students to move beyond static planning. One participant highlighted how these mechanics simulated real-world pressures: "*The cards representing the overexploitation of resources and... extreme weather events pushed to our limits... they required to change strategy, seeing different possible scenarios. Stimulating but challenging even though they were also realistic*".

Similarly, while collaboration was a key strength, it was described as a skill that had to be learned through gameplay:

Gradual Mastery: "Collaboration was the key to win... but it required some turns before we found a good way to strategically collaborate in building our deck".

Iterative Adjustment: "The collaboration wasn't immediate and required some effort, a lot of adjustments and time".

Despite these positive outcomes, the research highlighted significant barriers to autonomous learning. The concept of Ecosystem Services (ES) remains inherently "nebulous" for many students; game mechanics alone were insufficient to fully clarify the link between ES and sustainability. Furthermore, the instructional design presented a hurdle. Participants reported an "*excess of information*" in the manual, which led to cognitive overload

Conclusions

In conclusion, the findings substantiate the potential of serious games as effective instruments for advancing environmental and sustainability education, particularly in cultivating EU green competencies such as cooperative future scenario building. However, the study also revealed significant pedagogical challenges; difficulties in navigating game mechanics and conceptualizing abstract topics like Ecosystem Services indicate that the game cannot function in isolation. Instead, these findings highlight the necessity of a structured Game-Based Learning (GBL) framework where the educator's facilitation and post-game debriefing are critical to scaffolding the learning experience. Implementation in higher education remains complex, necessitating substantial educator expertise and a shift in institutional mindsets. Furthermore, students may find the demand for soft skills, such as negotiation and cooperation— overwhelming, particularly in the absence of extrinsic grade-based rewards. The results suggest that university students outside of specialized programs exhibit a marked deficit in sustainability skills. Consequently, they experience a form of paralysis, where the complexity of systemic interactions hinders their agency despite a willingness to engage. Therefore, it is imperative to advance a systemic ESE that empowers students to construct a new paradigm of sustainability, one that intrinsically links planetary well-being with peace, human rights, and cultural enrichment.

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Designing Future Cities: Using Futures Literacy To Promote Youth Agency

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Cities are at the forefront of the climate crisis, consuming 75% of global resources and driving urgent sustainability challenges. Concurrently, the erosion of democratic norms has created a pressing need to empower young people with skills to envision and shape sustainable futures. This paper explores the potential of futures literacy in informal science education using the 'Design Your Future City' programme as a case study.

'Design Your Future City' is a week-long informal learning initiative for 15-17 year olds, combining workshops and technology demonstrations to address urban sustainability challenges. Students collaborate with experts and local stakeholders to develop and present creative solutions, fostering systems thinking, creativity and agency. Rooted in Design Thinking, the programme aims to enhance futures literacy and emphasise the ethical, social and environmental dimensions of local sustainability challenges alongside scientific and technological solutions.

This mixed-methods study examines four iterations involving 80 students, educators, and civil society partners. Preliminary findings demonstrate the transformative impact of futures literacy pedagogies on students' ability to address sustainability challenges, with student projects showcasing innovative, actionable solutions. Reflective feedback highlights increased critical awareness, creativity, and aspirations for civic engagement.

The study underscores the importance of embedding futures literacy in education to cultivate youth agency and democratise urban planning. This research contributes a scalable model for integrating futures literacy into informal science education to shape sustainable, inclusive urban futures.

Keywords: Agency, Futures-Oriented Science Education, Out-of-School learning

Introduction

Cities are central contributors to the climate crisis, responsible for 75% of global resource consumption, and this figure is projected to rise from 40 billion in 2010 to 90 billion tons in 2050 (Bibri & Krogstie, 2017). Simultaneously, the erosion of democratic norms has contributed to a growing climate of uncertainty about society's capacity to envision and achieve equitable, resilient futures (Howell, et al., 2021). These issues highlight the need to empower citizens, especially young people, with the skills to envision and shape sustainable futures. This has prompted responses from academics, cultural institutions, civic organizations, and community groups to envision alternative futures. This paper explores the role of futures literacy in informal science education programmes.

Using the 'Design Your Future City' education programme as a case study, this paper will explore how futures literacy can empower young people to address sustainability challenges. 'Design Your Future City' is a free week-long programme of workshops and technology demonstrations for 15-17 year old students exploring urban challenges and climate change. The education programme is a partnership between academia and the Dublin City local authority. Students work with city officials and domain experts in mobility, environment and sustainability, participate in hands-on creative workshops to explore city challenges, and develop creative solutions to a sustainability challenge of importance to them. Throughout the programme, technology demonstrations are integrated to help students analyse the challenges they face and how others have addressed them. This informs the speculative design process and the envisioning of future solutions. The programme takes place in an informal learning setting outside of school time, that students apply to and attend independently. At the end of the week student present their solutions to key stakeholders including leadership in the city council, industry and academia.

The case studies discussed in this paper were developed in collaboration with the EU-funded Critical ChangeLab project. One of the project's key objectives is to strengthen critical democratic education among young people through participatory action research (PAR) and creative methods inspired by the Change Laboratory approach (Engeström, 2015) and critical pedagogies (Freire, 2017). In the examples featured in this paper, the Critical ChangeLab model has been integrated into the 'Design Your Future City'' programme to foster futures literacy and democratic engagement (Council of Europe, 2016)

Research Question And Aims

This paper will address the following research question: What is the potential of futures literacy in informal science education programmes?

To explore this question, the study focuses on three key aims:

- Identifying the barriers and enablers in promoting futures literacy among young people, particularly those from underrepresented groups.
- Examining the impact of futures literacy in informal science education on sustainability education.
- Investigating how futures literacy fosters youth agency in shaping sustainable futures.

Theoretical Frameworks

Futures literacy is increasingly recognised as an essential skill for young people. Häggström & Catarina (2021) argue that in order for young people to develop agency and voice in addressing global crises, they must acquire futures literacy—the ability to imagine and shape the future. UNESCO (2023) similarly emphasises that "being futures-literate empowers the imagination. It enhances our ability to prepare, recover and invent in the face of change" (P.1). Futures literacy is particularly important in the context of sustainability education and working with youth, as Stuart Candy (2020)) noted "our collective future as a species depends on using our capacity to imagine worlds together".

Central to fostering futures literacy is the concept of agency, as it empowers individuals and communities to take informed, purposeful action toward shaping the future. Social Cognitive Theory (Bandura, 2002) provides an initial framework for understanding agency in social contexts. Bandura identifies three forms of agency: personal agency (individual action), proxy agency (influencing others to act), and collective agency (group efforts to shape a shared future). In this project, these frameworks are integrated into the programme design by supporting young people to imagine sustainable futures, and collaborate in acting towards them.

This understanding of agency is developed through Stetsenko's Transformative Activist Stance (TAS) (Stetsenko, 2014). Rather than viewing the world as a fixed context to which individuals adapt, TAS positions the world as "in the making," realised through goal oriented action. From this perspective, agency is not only the capacity to act within existing structures but to transform them in pursuit of socially and ethically desirable futures. Accordingly in this project, the programme design moves beyond individual foresight skill-building, toward collective, participatory activities in which young people identify issues they care about, articulate preferred futures, and collectively design actions oriented toward social and environmental transformation.

The United Nations' Sustainable Development Goals (SDGs), comprising 17 interconnected goals, aim to address global challenges related to the environment, economy, and society. These goals guide global efforts to achieve sustainability, with SDG 4 focusing on ensuring inclusive and equitable quality education (United Nations, 2015). UNESCO's Education for Sustainable Development (ESD) agenda plays a pivotal role in advancing these goals by fostering critical thinking, global citizenship, and the skills needed to address interconnected sustainability challenges. UNESCO advocates for integrating sustainability into education systems globally, empowering learners to become active agents in shaping sustainable futures (UNESCO, 2020)

Research Method And Design

This research was undertaken through four iterative cycles of the 'Design Your Future City' programme from the 2024-2025 academic year, involving 80 students, 3 researchers, 21 educators, and 2 civil society organisations. Within the programme, youth participate in workshops that draw from methodologies such as design futuring (Howell, et al., 2021), speculative design (Dunne & Raby, 2013), and speculative fiction (Haraway, 2016) as well as workshops that introduce them to scientific, ethical, social and environmental dimensions of local urban planning and sustainability challenges. They subsequently participate in a design sprint to develop and present creative solutions to these challenges, consulting with scientific experts and local stakeholders. Design Thinking—a human-centred problem-solving approach—guides students through five iterative stages: Empathy, Define, Ideate, Prototype, and Test (Razzouk & Shute, 2012).

A mixed-methods research approach was utilised to assess how the programme supported futures literacy development. Data was generated through a set of instruments, including pre- and post-programme surveys of participating students to measure attitudinal and cognitive shifts; facilitated focus groups conducted at the end of each programme iteration to capture participant experiences and perspectives; analysis of learning artifacts to assess conceptual engagement; and structured workshop observations conducted by a research observer to document pedagogical processes and interactions. These instruments were used in combination to examine participants engagement with futures literacy practices, expressions of agency and approaches to sustainability challenges across programme iterations.

Findings

Findings indicate that futures literacy exercises increased young people's confidence in articulating their vision of sustainable urban planning. Artefact analysis showed students actively designed future-oriented solutions to sustainability challenges, highlighting youth perspectives on issues such as public green space accessibility and air pollution caused by car dependency. For example, one student project, 'Traffic Jam,' proposed an interactive light installation to create safer movement through urban space, reflecting a desire to travel independently that was articulated by participants in workshop discussions. This student project illustrates how futures literacy—i.e. using a desired sustainable future to innovate in the present—cultivates systems thinking and creative problem-solving, both important sustainability competences (Bianchi et al., 2022). In the above example, the concept generated was taken up for further exploration by a local authority, with a student engaging through a short work placement. This offers an initial indication of how futures literacy practices may open pathways for youth participation in institutional sustainability contexts.

Across participant reflections and post-programme surveys, recurring themes included increased critical awareness, creative confidence, and attention to systems-level aspects of urban challenges. A participant reflected:

> "The week really opened my eyes to the amount of things that need to be considered when trying to solve a problem. You have to think about people it will affect, the environment, different ethical issues, but I found that I really enjoyed thinking about all these things. It is something that I would like to do in the future. Before this I thought of urban planning as more just deciding where to put houses and buildings, now see how much technology is involved in it."

This reflection aligns with the aim of fostering futures literacy by cultivating systems thinking, creativity, and critical problem-solving skills.

Evaluations of the case studies indicate that futures literacy methodologies support critical reflection on eco-social challenges (Maxwell et al., 2019) foster inclusive values (Millsap-Spears, 2018) and encourage imaginative problem-solving (Hardy, 2019).

Discussion

The 'Design Your Future City' programme, uniquely utilising design thinking, and the Critical Change Lab method provides valuable practice implications by offering a scalable model for promoting futures literacy into science education. Grounding sustainability education in place based, future-focused scenarios, promotes a deeper understanding of how individual actions can shape local environments. By encouraging students to envision the future of their area and take action based on that vision, the programme supported young people's sense of agency by helping them see themselves as having the ability to shape a sustainable futures in their area.

Practical insights from implementing the programmes with different cohorts across different learning environments have informed our understanding of the barriers and enablers to imagining alternative futures and fostering futures literacy in informal science education programmes. The impact of the learning space, the methods used, and the facilitation styles can be observed in the futures imagined and solutions presented as part of the programme. These insights, alongside evaluation using a mixed-methods approach (Rincón & Díaz-Domínguez, 2022) provide the basis of our argument that futures literacy is a crucial skill to cultivate in youth.

Future iterations of the programme aim to amplify student impact beyond the programme week by developing their ideas further into pilot projects within the city. This would promote youth agency and create tangible connection between futures literacy and civic action. However, practical limitations exist when transitioning from speculative ideas into feasible solutions, particularly in the risk-averse environment of local authorities.

Conclusion

This case study of the 'Design Your Future City' programme explores how futures literacy might serve as a tool in science education by encouraging young people to envision and create sustainable futures for the areas they live in. At the time of presentation, four iterations of the programme provided a comparative empirical base for examining futures literacy in informal science education. The early findings indicate that futures-oriented, participatory approaches can create conditions in which young people articulate preferred futures, engage with complex socio-technical issues, and experiment with forms of collective action.

Building on these insights, future research will focus on examining how expanded learning environments, such as sustained mentoring, partnerships with civic and community actors, and opportunities for continued engagement beyond the programme week, influence the development of youth agency and futures-oriented thinking. This research will explore how such conditions mediate the translation of speculative ideas into forms of civic action within the constraints of real-world contexts. This focus will contribute to a more precise understanding of how futures literacy is enacted in informal science education, and how it can support young people to see themselves having a role in shaping sustainable futures for their local area.

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Implementation Process And Outcomes Of School Climate Assemblies: Exploring The Views And Perceptions Of Secondary School Students

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Student participation and decision-making are essential to address various complex global challenges such as the climate crisis, biodiversity loss and social inequalities. This study presents the applied research project EDU4CLIM, which aims to involve young people in sustainability issues through the implementation of Climate Assemblies as an innovative and collaborative educational strategy. The main objectives of this research are: 1) to analyse secondary school students' perceptions of the strengths and areas for improvement of the school climate assemblies organised, 2) to explore the changes in their daily actions as a result of their participation and the sustainability competences they feel they have developed. For this purpose, an ad hoc questionnaire was designed and administered to 206 students in 7 secondary schools in the province of Tarragona (Spain) in the school year 2023-24. A descriptive and qualitative content analysis was carried out. The findings show that the assemblies promoted sustainability competences such as collective action and future thinking according to students' perceptions. Teamwork and learning new knowledge were seen as strengths, and aspects to be improved included making the assemblies more dynamic and devoting more sessions to them. Students comment that their participation in the school climate assemblies has contributed to changes in their everyday environmental behaviour. In particular, students highlight improving waste management through recycling. This study shows that assemblies can be an effective pedagogical strategy to promote sustainability competences.

Keywords: climate assemblies, secondary education, sustainability competencies

Context And Relevance To Science Education

Today's societies are characterised by their complexity and globalisation, as they face various global challenges, such as the climate crisis, and economic and social inequalities. To deal with these challenges, individuals and societies must learn how to adapt and take action. Target 4.7 of SDG 4 - Quality Education of the United Nations 2030 Agenda specifically addresses Education for Sustainable Development (ESD) and the importance of schooling and developing sustainability competencies (UNESCO, 2017). Science education for sustainability promotes natural transformation, emancipation and continuous human progress that contributes to positive change towards sustainability (Sterling, 2017).

Conceptual Rationale

EDS is focused on key learning processes such as collaboration and dialogue, systems thinking, continuous innovation of the educational curriculum and active and participatory learning, as well as learning related to asking critical questions, questioning one's values, envisioning future scenarios, responding in an informed manner and exploring the dialectic between tradition and innovation (UNESCO, 2017).

In the school context, sustainability involves reorienting the content, competencies, expected outcomes, and objectives of education (Sterling et al., 2017). To foster these curricular improvements, it is essential to define the sustainability competencies that will enable students to critically reflect on their own actions. According to Mulà et al. (2022), sustainability competences are the combination of knowledge, skills, attitudes, and ethical values needed to effectively address sustainability challenges.

In this context, one of the increasingly popular deliberative democratic processes related to climate change are citizen climate assemblies. In recent years, school and youth climate assemblies have emerged internationally to give young people a voice and empower them on climate action (Cebrián et al., 2025; Wilson et al., 2024). These processes seek to ensure children's and youngsters' participation and environmental rights are realised, as most policy decision-making processes exclude the participation of the youngest members of society (Reid, 2023).

Research Aims

This research aims to analyse the implementation of school climate assemblies as an innovative method for learning, deliberating, and addressing climate change. The research was conducted in the EDU4CLIM project, a R&D&I project funded by the Spanish Ministry of Science, Innovation, and Universities, and the EU-Next Generation.

The specific objectives of this study are to:

1. Analyse secondary school students' views and perceptions of the strengths and areas for improvement of school climate assemblies.
2. Explore the sustainability competencies that the students have developed due to their participation in school climate assemblies.

Research Method And Design

An ex post facto study was conducted using the interpretive paradigm to analyse secondary students' perceptions of school climate assemblies (Bisquerra, 2019). The research involved 7 schools in Vendrell and Valls (Tarragona, Spain) during the 2023-24 school year, with the intervention occurring from January to May 2024. School climate assemblies were implemented, supported and guided by facilitators and experts, members of the project's research team (Cebrián et al., 2025). The assemblies are structured in three phases:

1) **Learning phase**: includes materials, preparatory activities and the participation of climate change and sustainability experts.
2) **Deliberation phase:** consists of facilitating dialogue and debate among participants on the environmental issues addressed in the assemblies, through collaborative activities.
3) **Decision-making phase:** focuses on facilitating the development of joint and consensual conclusions based on the reflections and discussions of the participants through voting.

Each assembly consisted of four sessions, organised per class group in each participating secondary school.

- **First session:** In each class, four groups focus on different climate change topics (water, energy, biodiversity, tourism and mobility), discussing both positive and negative aspects. They create a conceptual map and develop a decalogue with 10 action proposals for their community. Finally, each student votes on the top 3 priority actions.
- **Second session:** the group class reflects on the most voted actions, then holds a group vote to select the most relevant action for the community. Afterwards, students work in groups to develop and present the chosen action at the Sustainability fair (third session).

- **Third session:** meeting with the political leaders and municipal technicians of the territory to discuss and share the actions proposed and delve into it to then share and disseminate it in a Sustainability Fair.
- **Fourth session:** a Sustainability Fair is organised where all the class groups from the participating schools present their proposed actions, exchanging perspectives and receiving feedback from the political and social actors of the territory on the actions proposed by the students.

In order to determine the perception of secondary school students in relation to the climate assemblies, an ad hoc questionnaire was designed and administered to 206 students after the Sustainability Fair, at the end of educational intervention. The designed questionnaire consists of two parts; the first consists of ten items related to ten competences of the GreenComp framework (Bianchi et al., 2022), with a Likert scale 1→4, namely: Disagree (1), Neither agree nor disagree (2), Agree (3) and Strongly Agree (4). The items of this first part of the questionnaire and their link to the sustainability competences of the GreenComp framework are presented, indicating the competence and its descriptor (table 1).

Table 1. Questionnaire items, sustainability competence and descriptor from the European GreenComp framework.

The school climate assemblies have helped me to be able to...		**Sustainability competence (acronym) and descriptor**
1	Reflect on my actions and, at the same time, detect whether they are environmentally friendly.	**Valuing Sustainability (VS):** reflect on personal values and assess them in a coherent way
2	Thinking, deciding and proposing ideas that will benefit present generations, like yours, and future generations.	**Supporting fairness (SF):** support equity and justice for present and future generations.
3	Imagine the future that is most favourable to the well-being of the planet.	**Future literacy (FL):** Projecting alternative sustainable futures.
4	Understand an environmental problem from different interconnected perspectives (personal, environmental, cultural and social).	**Systems thinking (ST)**: Address sustainability issues from all points of view.
5	Make decisions in a critical way without falling into false information.	**Critical thinking (CT):** Evaluate arguments and reflect on how they influence thinking.
6	Identify real situations that occur in my village, neighbourhood or town.	**Problem framing (PF):** Formulating current challenges to identify approaches to anticipate problems

7	Change actions in my daily life for the wellbeing of the planet.	**Adaptability (A):** Making decisions about the future in the face of uncertainty and risk.
8	To find out about activities that are organised in my village, neighbourhood or town to improve the environmental situation.	**Political agency (PA):** Navigating the political system and identifying political accountability
9	Recognise the importance of working collectively in groups to solve problems.	**Collective action (CA):** Acting for change in partnership with other actors.
10	Gain initiative and take individual action to solve a climate change problem.	**Individual initiative (II):** identify one's own potential for sustainability and actively contribute to improving the prospects of the community.

The second part includes four open-ended questions related to strengths and areas for improvement of climate assemblies.

The analysis process consisted of creating a frequency table to calculate the percentage of the different levels of agreement or disagreement in relation to the sustainability competences acquired. To analyse the responses to the open-ended questions, a qualitative content analysis was carried out, in which the responses were coded, and the codes were inductively grouped into categories to identify the main strengths and areas for improvement as perceived by students.

Findings And Coherence Of Argument

In relation to strengths, three main categories emerged: 1) new knowledge about climate change and the well-being of the planet, 2) Sustainability Fair and 3) methodology and dynamics. As students emphasised:

> [S74]: That we have proposed things to improve the situation of the planet. (category: New knowledge about climate change
>
> [P120]: A lot of people participated, and it was very cool. (category: Sustainability Fair)

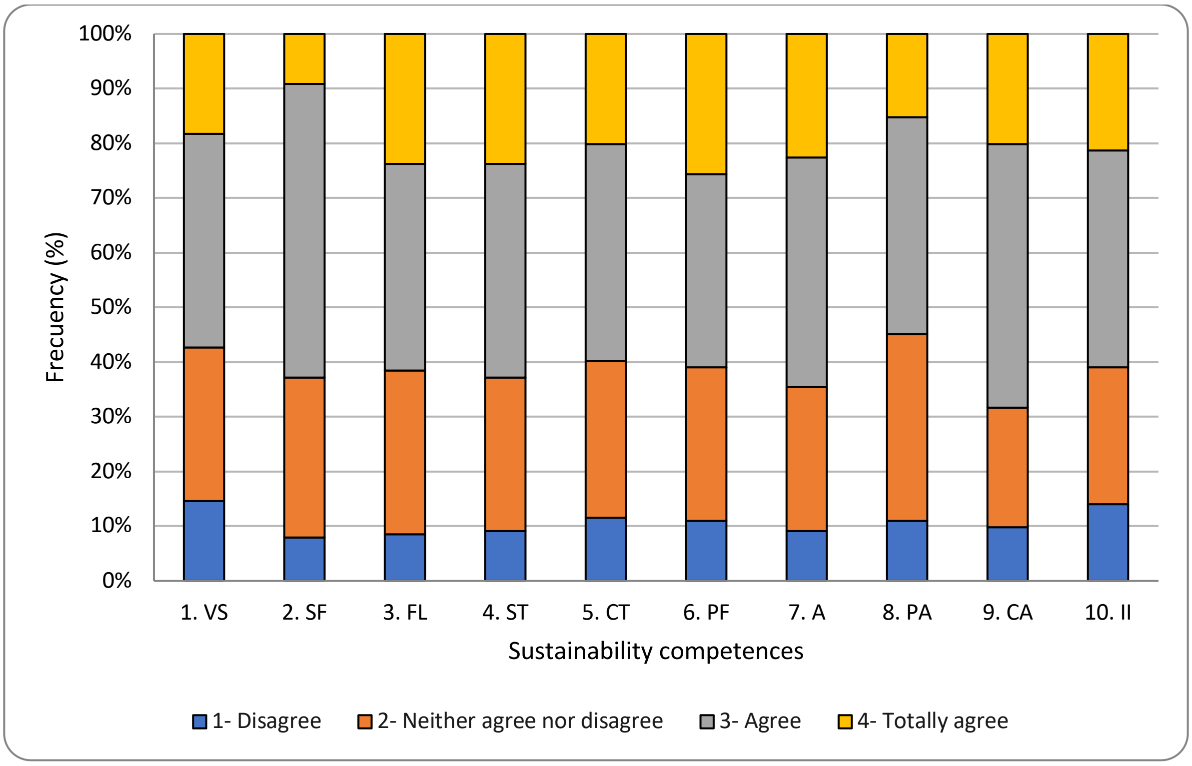
In terms of areas for improvement, two categories emerged, relating to 1) Phases of the assemblies and 2) promoting awareness. As some students commented:

> [S122]: We need to do better at not polluting so much (category: promoting awareness)
>
> [S129]: The topics could be improved, not given so broad a scope. (category: Phases of assemblies)

In line with the acquisition of sustainability competencies, the findings show that the school climate assemblies promoted competences such as collective action (CA), by recognising the importance of working together to find solutions after participating in the assemblies; systems thinking (ST), understood as the ability to analyse environmental problems through multiple interconnected perspectives (personal, environmental, cultural and social) and to recognise the relationships and interdependencies among them; supporting fairness (SF), reflected in thinking, decision-making and the proposal of ideas oriented towards social and intergenerational justice, aiming to benefit both present generations, such as students themselves, and future generations;

and future literacy (FL), related to imagining the most favourable future for the well-being of the planet (Figure 1).

Figure 1. Students' assessment of sustainability competencies acquired in school climate assemblies.



Discussion Of Findings And Implications

According to the first objective focus on analysing secondary school students' views and perceptions of the strengths and areas for improvement of school climate assemblies, the findings of this research show that secondary school students consider the collective action and cooperation promoted by school climate assemblies to be a strength. In terms of areas for improvement, the students consider the dynamism and timing of the assemblies, and the need to extend the sessions and make the topics covered more specific. This is consistent with the findings of previous studies of climate assemblies, which highlight the need to allow sufficient time for deliberation and decision-making (Reid, 2023; Wilson et al., 2024).

In relation to the second research objective, which sought to the explore the sustainability competencies that the students have developed due to their participation in the assemblies, the findings of this study show that students consider that they have acquired various sustainability competences such as collective action and future thinking, which are in line with previous studies. In turn, assemblies promote critical thinking among students, which can help them become aware of climate change and strengthen their engagement and well-being (Trott et al., 2022).

In particular, this research offers contributions for interested academics, teachers and educators, such as a detailed description of the methodological phases used in the assemblies, evidence of the impact of the assemblies on the learning of secondary school students, an ad-hoc questionnaire designed to collect data on the learning achieved in the assemblies from the students' perspective, and documentation of the students' acquisition of sustainability competences following their participation in the climate assemblies from their own perspective.

In response to one of the fundamental questions raised by the ESERA Congress, which is related to living in a globalised society undergoing constant environmental change, there is an urgent need to rethink the role of education in promoting change towards a more conscious society committed to sustainability. In this sense, the implementation of the school climate assemblies presented here could be a very appropriate strategy to support this process, adaptable to different contexts and educational levels.

Acknowledgement

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Placemaking Reimagined: Examining The Role Of Imagination In Critical Place-Based Learning

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Youth are seldom presented with meaningful opportunities to design their own futures through civic engagement and design, despite their potential as imaginative placemakers. Drawing from critical place-based scholarship, this study aims to reconceptualize placemaking as entwined processes of decolonization, reinhabitation, and imagination. Our work delves into how a critical place-based curriculum empowered youth in imagining and re-envisioning the future of Creekside Plaza, a local plaza-mall under redevelopment. The curriculum supported students' imaginative placemaking through maps, plans, community engagement, and 3D design tools. Although some of the curriculum's activities simultaneously augmented and curtailed youths' creative expression, we argue for the necessary inclusion of youth and their imagination in placemaking roles to design hopeful, vibrant futures.

Keywords: Placemaking, Critical Place-Based Education, Imagination

Introduction

Harvey (2015) speaks to people's collective rights to cities and our rights to (re)make them, where all humans should necessarily share the responsibility for shaping the future of the places we inhabit (Gruenewald, 2003a). Unfortunately, young citizens continue to be excluded from placemaking processes despite instances of youths' authentic contributions to designing for environmental change (Malone, 2013). In this study, we explore placemaking as an integral approach that enables youth to become designers of their own (hopeful) futures as rightful placemakers. We draw from Gruenewald's understanding of placemaking as "the process of shaping what our places will become" (2003a, p. 627). We argue that dwelling in imaginative, "what if" spaces is particularly critical in placemaking, which is an imaginative process in and of itself (Judson, 2019). Furthermore, this conceptualization of placemaking enables children to engage with the sense of possibility for thriving places. Hence, this qualitative study centers the following inquiry: How did youths' imaginative engagement support and constrain their placemaking practices in a local civic design project?

Conceptual Framework: Placemaking As Decolonization, Reinhabitation, And Imagination

Placemaking As Decolonization

Geographical spaces have been exploited as tools of power, domination, and control (Lefebvre, 1997). To restore democratic rights to cities, individuals must first recognize how places represent various histories of struggle and resistance (Cresswell, 2014). Mehrez (1991) writes about decolonization as contesting and liberation from dominant forms of language and ideologies or undoing the hegemonic forces of Western knowledge systems (Shaw et al., 2006). Thus, decolonization requires youth to also critically reflect on their own positions in their local communities to recognize the social and ecological harm imposed on places across temporal scales (Gruenewald, 2003b).

Placemaking As Reinhabitation

Once youth have identified the ways in which their environments have been disrupted through social hegemony, they must learn how to thrive in previously-damaged spaces amongst their human and more-than-human cohabitants in the present day (Gruenewald, 2003b). Thus, we conceptualize reinhabitation as largely relational work that urges people to practice socioecological care despite powered nature-culture relations that might constrain youths' consideration of more-than-human perspectives. Therefore, we design ways for youth to assume shared collective responsibility towards "intergenerationally connected and morally responsible" multispecies communities (Bowers, 2001, p. 20; Kerkham & Comber, 2013).

Placemaking As Imagination

What distinguishes placemaking as a unique and invaluable practice that instills agency and critical hope in youth is the richness of possibility. However, contemporary schools have become places that suppress young people's imaginative minds rather than nurture them (Benjamin, 2024). Additionally, the romantic nature of imagination often presents questions regarding the legitimacy of imagination as a valid epistemic resource, but Egan (1977) noted that this romantic understanding of imagination is what helps youth make sense of the world in rational ways.

Methods

Study Design

Our team designed a two-week curriculum around critical place-based education and digital storytelling around Willow Creek, a local waterway that flows through a large part of the diverse neighbourhoods of Newtown. We worked with diverse middle school youth (n = 23) from two schools closely located near upstream Willow Creek. Some of the camp activities included: embodied creek play, local map studies on environmental justice, interviews of invited guests and local residents, and the creation of podcasts, zines (short for magazines), and AR (augmented reality) stories about Willow Creek.

We designed this curriculum based on the Connect–Investigate–Interrogate–Imagine–Act (CI^3A) pedagogical framework (Figure 1) developed by Carlone et al. (2024) for critical place-based education. Based on the CI^3A framework, we created opportunities for youth to connect with place through embodied and affective experiences in the field (e.g., care, wonder, joy, and stillness) (Stapleton & Lynch, 2021). We conceptualized investigation as transdisciplinary epistemic practices drawing from science, history, art, and technology. By analysing maps that illustrated relationships between environmental health and social justice, the curriculum also offered opportunities for youth to interrogate the social and environmental inequities that represent distributional injustice (Campbell et al., 2022). To design for imaginative spaces, we supported students' speculative storytelling, futuring, and placemaking practices as youth took on the role as civic designers advocating for just and sustainable futures of Willow Creek. Lastly, we provided space for youth to share their placemaking stories and act as advocates for the Willow Creek community.

Given our research question regarding the role of youths' imaginative work towards placemaking, this paper focuses on the last three days of the larger summer curriculum based on Creekside Plaza, a local area currently undergoing redevelopment located near Willow Creek and students' schools. Students engaged in a series of civic design activities using government-led development plans, local maps, community interviews, and technical tools (e.g., AR). Table 1 further outlines the central activities that took place during the AR civic design unit.

Figure 1. Connect–Investigate–Interrogate–Imagine–Act (CI^{3}A) Framework.

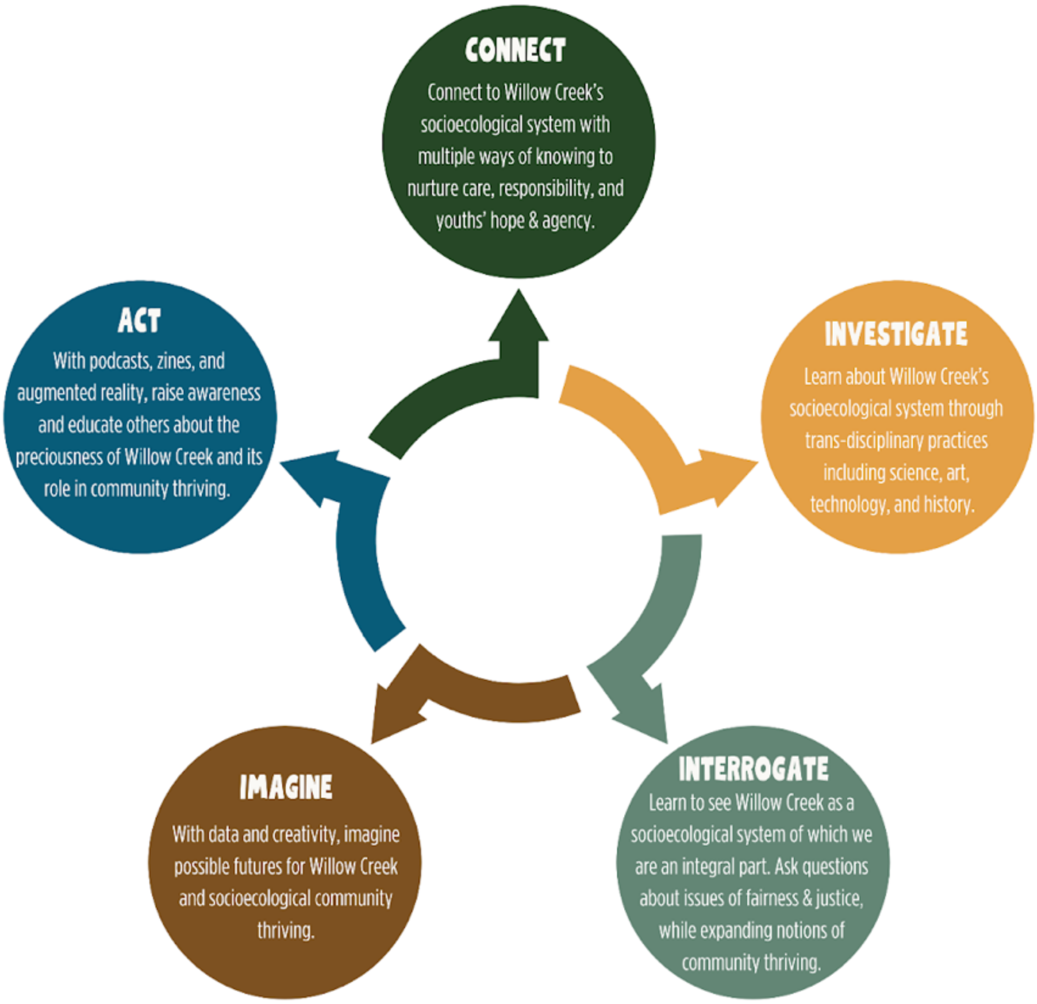

Table 1. Curricular Activities during Civic Design Project with Creekside Plaza.

Creekside Plaza Map Study	Community Eco-Survey	Collaborative Redesign	3D Design with AR
Evaluate government's master plan of Creekside Plaza in small groups	Interview local development professionals and visitors at Creekside Plaza	Generate collaborative proposals to redesign Creekside Plaza	Create individual AR projects that visualize a select portion of group's proposal

Data Collection & Analysis

Our data corpus consisted of video, student artifacts, and end-of-unit interview transcripts. Artifacts included student-created maps, plans, and AR projects that visualized youths' imagined versions of Creekside Plaza. During our first phase of analysis, we examined the videos to identify key moments in the data that informed our understanding of youths' imaginative engagement in the context of placemaking. As a result, we largely focused our analysis around the Creekside Plaza Map Study and Collaborative Redesign activities, creating content logs (Miles et al., 2013) based on those 10 hours of video data as our first "pass" of processing data. We triangulated multiple sources of data to confirm our emerging assertions about the data. Our team drafted analytic memos related to the purposes, moments, forms, affordances, and limitations of imaginative engagement, and debriefed our analytic decisions with other researchers.

Findings

Playful (But Purposeful) Futuring

About a fourth of our students overtly presented child-like, fantastical assets in their final AR projects. In Nathan's case, his portrayal of a talking racoon named Jim as an environmental advocate illustrates an ontological shift through anthropomorphizing a racoon. He illustrates a vulnerable animal as one with agency, who is eager to educate others about her environment and is passionate about protecting their home. In essence, Nathan is layering his own advocate agenda onto this racoon. Admittedly, selecting a raccoon specifically was a rather fortunate "accident." Although Nathan's selection of a specific species was rather spontaneous, his intent to centre more-than-human advocates was part of his purposeful design: "I kind of just was thinking of someone else besides a human to use, so I just thought of a raccoon. I was just looking through everything, and I just saw a raccoon, and I was going like, "I'm going to use this, and name him Jim" (Nathan). He went ahead and named the racoon and leveraged his imagination to tell Jim's story about "how deforestation is ruining his life almost, and how his home has just been taken away, and it allows him to not be safe."

Figure 2. Nathan's AR Project.

Relational Care: Imagining *For* And *With* Others

Our design of the AR unit challenged youth to centre relationality and care for others. The intergenerational conversations in which adult facilitators modelled relational care and perspective-taking drove students to design for others. For instance, Ms. Castillo advocated for a "young people hangout spot," such as a bowling alley. Brett pushes back, stating that not all plazas and malls have bowling alleys. Ms. Castillo models perspective-taking: "I know, but if [Creekside Plaza] doesn't have what the community needs, the only place to go is in [central] Newtown. So [as a] college student, if I don't have a car, I don't have anything to do on a Friday night." Realizing that the nearest bowling alley from Creekside Plaza's college campus is 4.5 miles away, Brett soon made space for a bowling alley in their group's proposed design. Throughout the unit, Brett had already emphasized the need to design spaces "for everybody;" yet Brett's engagement with international imagination with adults had augmented Brett's pre-existing values of collective care in their designs of Creekside Plaza.

Material Engagement In Physical And Digital Spaces

Our curriculum designed multiple opportunities for youth to interact with physical (e.g., paper maps) and digital materials (e.g., 3D assets). Youths' interactions with diverse materials allowed to expand imaginative engagement beyond cognitive and ideological spaces, towards material ones. Specifically, our use of AR and virtual visualizations of youths' futured Creekside Plaza offered opportunities for youth to be positioned as co-imaginaries. Ms. Yana noted the affordance of scanning QR codes to students' AR projects: [the audience is] gonna be able to see this world that we're creating," where she positions AR as the object that allows them to become co-visionaries of their imagined worlds. Having physical and digital artifacts when interacting with adults enabled youth to enact their voices and be positioned as advocates within their communities. When interviewing local visitors at Creekside Plaza, Addison's group requested to use their maps during their interactions, which made her "happy because then people would listen to me and stuff." Similarly, Nathan noted the important role of having a technology-enabled design that captures his imaginative work because AR "allows you to go inside of it, and get more detail of stuff" compared to "just words." As such, both physical and digital materials instilled a sense of ownership and confidence in youth as civic designers who were eager to inform adults about their imagined futures.

Conclusions

Our findings inform us about youths' imaginative placemaking during the civic design unit in three notable ways. First, youths' imagination was recognized as a legitimate epistemic resource for placemaking. Second, youth engaged in placemaking through intergenerational care, albeit reproducing anthropocentric values. Lastly, their engagement with and production of materials (e.g., maps, AR) coupled with their imagination further enabled their authority as imaginative placemakers. Though young citizens have been excluded from placemaking processes despite directives towards creating better cities for children (Freeman & Tanter, 2011), we hope this empirical example contributes to the field's understanding of youths' imagination in placemaking towards increased opportunities for youth to act as agentic placemakers in the world.

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A Regression Analysis Of Environmental Attitudes And Interest In Environmental Topics

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The 21st century has been fruitful in contributions and initiatives for the conservation and sustainability of the environment. Environmental concern is visible in public spaces and media, and environmental education has become a cross-cutting aim of science education and general education. However, the relationship between the environmental attitudes and the environmental knowledge is relatively unknown, especially for young people, because this group rarely takes part in sociological environmental surveys, which are usually focused on adults. This study addresses the empirical exploration of this relationship for a large sample of 15-year-old Spanish students who participated in an international project where they answered an environmental attitude scale and rated their interest in some environmental topics. The results show overall positive attitudes and moderate interest in environmental topics, as well as pinpoint the specific best (people should care more about the environment) and worst (science and technology can solve all environmental problems) environmental attitudes and the most (protection of endangered species) and least (improve the harvest) interesting environmental topics. In addition, the regression analysis finds the environmental topics that are the best predictors of the environmental attitudes, which share over 27% of common variance. These results are discussed in light of other studies, and some recommendations are proposed so that science education can effectively contribute to improving the environmental attitudes and the interest in environmental topics, putting especial care into teaching about the worst attitudes, the less interesting topics, and the topics that are negative predictors of attitudes.

Keywords: Attitudes towards the environment, environmental topics, prediction of attitudes, education for sustainability

Introduction

Environmental awareness, concern, or attitudes are central concepts in environmental psychology research that the emergence of climate change has turned into socially relevant and educationally unavoidable issues to promote students' pro-environmental behaviours. According to social psychology, attitudes guide behaviour in general (Eagly & Chaiken, 1993), and environmental attitudes guide sustainable actions, pro-environment behaviours, media consumption, etc. (Liu et al., 2020). Further, environmental attitudes and environmental topics are intersectional and relevant to science education (Braun & Dierkes, 2019).

According to Eagly and Chaiken (1993), attitudes are psychological tendencies that express the evaluation of an entity with a certain degree of approval or disapproval. Obviously, the knowledge of the entity that assesses the attitude must be a key factor of the attitudinal acceptance or rejection degree so that both elements are related. In this case, environmental attitudes are related to people's interest in knowing environmental topics. The evaluative summary of the entity (approval/disapproval; agreement/disagreement; interest/disinterest) is the consequence of the dynamic interaction of the three basic elements of attitudes (cognitive, affective, and behavioural).

As a consequence, environmental attitudes are today a popular topic in media and in sociological surveys (CIS, 2020; European Union, 2014). Further, education for sustainability (ESD) and sustainable development goals (SDG) permeate all the educational levels and subjects of general education and science education in particular (UNESCO, 2006; UN, 2015). Thus, the investigation of environmental attitudes constitutes today a wide field of research and education.

Most of the research literature admits that environmental knowledge contributes to developing sustainable behaviours and attitudes, but that knowledge by itself does not produce these developments, so research is needed to determine the contexts and influences of knowledge on environmental attitudes and behaviours (Braun & Dierkes, 2019). Further, although a direct correlation between environmental knowledge and environmental attitudes is generally admitted, consensus on the best measurements of environmental knowledge is scarce, and no model is considered proven (Makki et al., 2003; Liu et al., 2020).

Interest in topics is key to attaining some knowledge and the Krapp and Prenzel's (2011) concept of interest as a particular case of the conceptualization of attitudes is adopted in this study, which addresses the diagnosis of environmental attitudes and analyses its relationship with the interest in environmental knowledge topics within the framework of science education.

The conceptualization of the environmental attitudes construct assumes the original psychological sources and is operationalized here through a specific and simple measurement tool, which is based both on its relevance for science education and on its systematic approach to the multidimensional and hierarchical nature of environmental attitudes, as suggested by psychological literature (Cruz & Manata, 2020; Milfont & Duckitt, 2010).

Data on environmental attitudes and interest in environmental topics are taken from the database of the international comparative study The Relevance of Science Education Secondary (ROSES-2022). ROSES explores 15-year-old students' science attitudes and their relevance for science education around the world (Jidesjö et al., 2020).

The research questions of this study are twofold:

What are young students' environmental attitudes and interests in environmental topics today?

Which environmental topics are the best predictors of environmental attitudes?

Methodology

Materials

This study draws its data from the questionnaire applied worldwide as the tool of the international project The Relevance of Science Education Second, which explores several categories of students' experiences that may be relevant to science education. An international group of experts developed the research survey for the ROSES-2022 project (ROSES-Q). This study elaborates on data from two categories of this survey to answer the research questions (Jidesjö et al., 2020).

The environmental attitudes are operationalized from the category of ROSES-Q "Me and the environment,", which contains 13 different attitudinal statements about the environment (Figure 1). For each statement, students are asked to answer the following question: To what extent do you agree with the following statements? The students tick their answers on a 4-point Likert scale, whose points are coded as follows: 1-disagree, 2, 3, 4-agree. The confirmatory factor analysis of this category (CFI = .964; TLI = .941; RMSEA = 0.068), within the framework of relevance for science education of the ROSES project, confirms a latent structure of a single factor formed by 6 items (D2, D4, D5, D6, D9, and D13) with statistically significant loadings and good internal consistency (ordinal Omega=.769).

Likewise, data from the interest in 14 environmental knowledge topics, which are taken from the category of ROSES-Q labelled "Things I would like to know more about." All items display environmental content (i.e., "E11. How to protect endangered species"), and the participants are asked to answer the following question about the topics: How interested are you in learning more about this topic? The students tick their answers on a 4-point Likert scale, whose points are coded as follows: 1-not interested, 2, 3, 4-very interested). The environmental knowledge is elaborated in this study as the students' interest along those 14 items (Figure 2).

The ROSES-Q items are enacted as direct, clear, simple, and short sentences (averaging eight words), mostly written in an affirmative and positive style, although some are written in a negative way to compensate for response bias.

Participants

A valid sample of 1912 Spanish students was surveyed through the ROSES-Q following the protocols of the ROSES project, whose target population is 15-year-old students (grades 9 and 10). They identified themselves as girls (49.4%), boys (46.9%), or did not indicate their sex (3.7%), and attended 23 schools (14 public and 9 private) throughout a Spanish region. Almost all (97.2%) were aged between 14 and 16 years old (mean age 15.1 years), and no one received incentives for participating.

The approval of the ROSES project by the Spanish State Research Agency implied the commitment to comply with the ethical principles and the relevant national, European, and international legislation on human rights. Students were informed that answering meant consent to participate, that they could leave items unanswered, and that the survey was anonymous.

Procedures

The students answered the ROSES-Q online as a class assignment directed by their teachers within their class group and applying the same protocol. The researchers did not have any personal contact with the participants, and the teachers did not have access to the database, warranting total anonymity.

The data gathering took place between late 2020 and 2024, and some data cleansing procedures were developed to improve the quality and validity of data through controlling and deleting invalid answers (homogeneous, highly incomplete, joking, random responses, etc.).

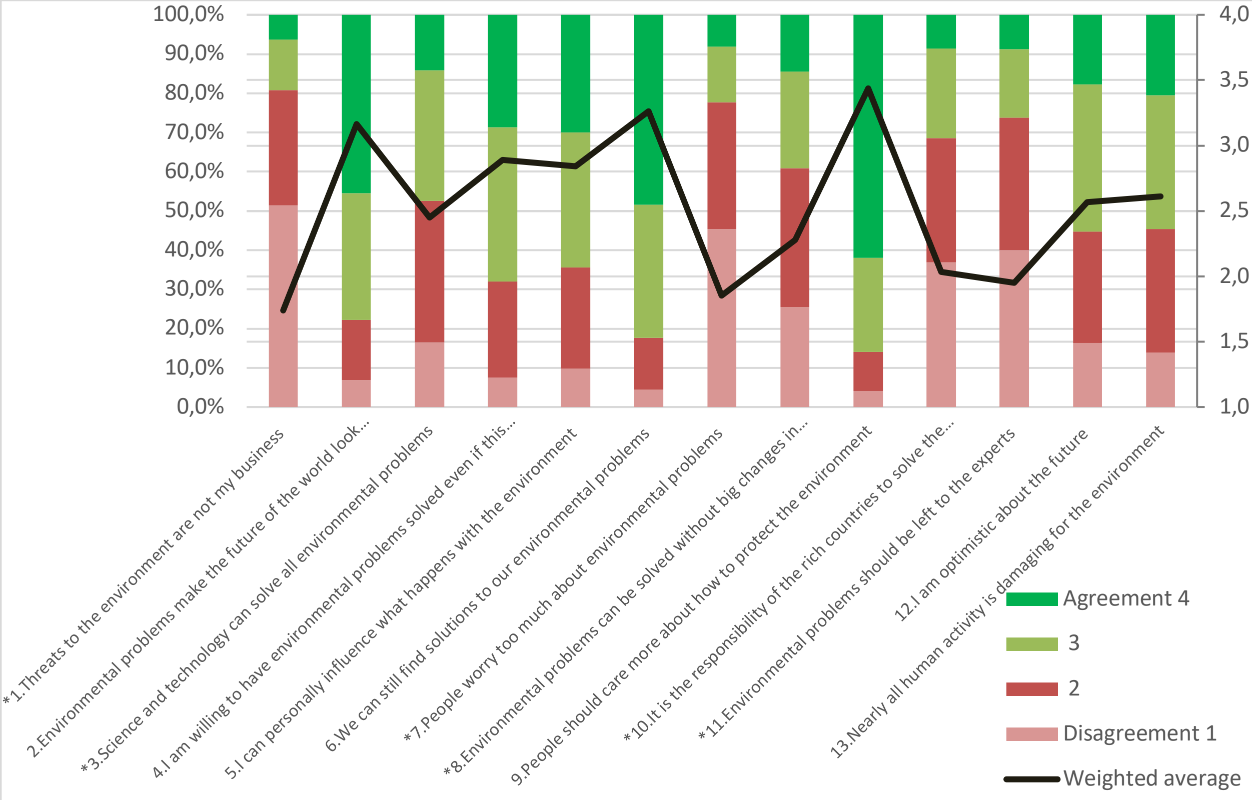
The mixed method, quantitative and qualitative, applies to students' responses. The percent and the weighted average of the Likert scale points quantify the valid responses. The latter is a fertile parameter for simply representing items and visualizing comparisons.

Six items from the category "Me and the environment," marked with asterisks in the figures (i.e., environmental threats are not my business), present content that is contrary (negative/anti-environment) to the direction of the remaining items (consciousness/pro-environment). The scores of these dysfunctional items must be interpreted in a complementary or reversed way to the functional/positive pro-environmental items so that the interpretation of all item scores has the same homogenous pro-environmental meaning throughout the scale.

Results

The first comprehensive finding of this study is the identification of globally positive environmental attitudes, since the responses to the functional statements of the category "Me and the environment" are above 50% global agreement (weighted averages greater than 2.50), and the dysfunctional phrases are below 50% global agreement (weighted average less than 2.50) (Figure 1).

Figure 1. Percentages of responses on each of the four points of the Likert scale (left vertical axis) and weighted averages (right vertical axis) of the 13 items of the category "Me and the environment" and the three complementary phrases.



* Items expressing anti-environmental content.

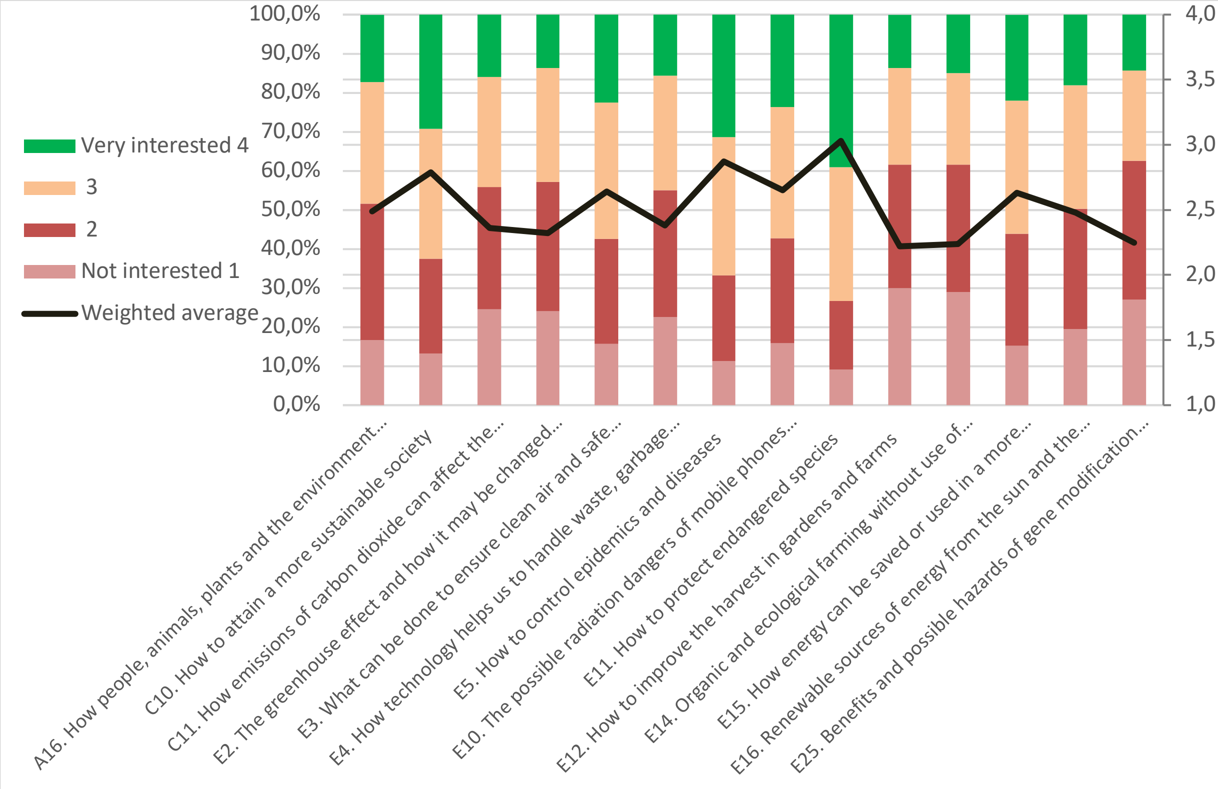
Another finding is the identification of the specific aspects that arouse the most and least favorable environmental attitudes, that is, the main strengths (agreement greater than 80%) and the weaknesses (lowest agreement) of the environmental attitudes. Three items reach the most favorable environmental attitudes scores, largely agreeing that people should feel more concerned about protecting the environment (D9, D7 reversed) and the ability to still find solutions to environmental problems (D6, D4) and largely disagreeing that environmental threats are not my concern (D1, D10, D11 reversed).

The item "D3. Science and technology can solve all environmental problems" reaches the lowest agreement rate though it is intermediate (48%; average 2.45). The remaining items display agreement scores in-between those already mentioned (note that the reversed interpretation of disagreement also applies to D8).

In regard to the students' interest in the 14 environmental topics surveyed, it could be described as moderately positive, since most of the issues reach interest percentages above 50% and weighted averages higher than the midpoint (2.5) of the Likert scale (Figure 2).

It is worth highlighting the large interest in the items about the protection of endangered species, the control of epidemics and diseases, and the path towards a more sustainable society. On the other hand, the lowest interest refers to the topics related to agricultural issues (improving crops, genetically modified organisms, and organic and ecological agriculture). The remaining eight environmental topics display intermediate interest scores that are placed between those rates achieved in the previous extreme issues.

Figure 2. Percentages of responses on each of the four points of the Likert scale (left vertical axis) and weighted averages (right vertical axis) of the 14 environmental topics.



Correlational Analysis

Most of the Pearson correlation indices between the scores of the environmental attitudes items and the items of the environmental topics reach statistical significance (Table 1).

The inspection of the correlation indices (Table 1) allows us to appreciate some general features regarding the relationships between the environmental topics and environmental attitudes.

First, the environmental attitude items displaying the highest correlation indices with the environmental topics are those items that were mentioned in the structure of the environmental attitudinal category as the most significant attitudinal in relation to the relevance of science education (D2, D6, D9, D5, D4, and D13 items).

Second, the group of attitudinal items with negative formulations clearly exhibits the lowest correlations (close to zero or negative) with topics. Item D1 (Threats to the environment are not my business), of this group, displays the lowest correlation of all.

For their part, the environmental topic items generally present a pattern of correlations quite similar among them, except for item A16 (How persons, animals, plants, and the environment depend on each other), which stands out for having significantly lower correlations compared to the others.

All in all, according to the former Pearson correlation analysis between environmental attitudes and topics, the environmental attitudes display highly different Pearson indices among them, whilst the differences of the environmental topic correlations seems much more homogeneous among them.

Linear Regression

Some linear regression analyses were performed. The total environmental attitude score obtained by adding some environmental attitude items (after reversing the scores of the dysfunctional items) is the dependent variable, and the environmental topics are the independent variables (predictors).

Table 1. Pearson correlation indices between the scores of the environmental attitude items and the environmental topic items.

Attitudes	Environmental issues													
	A16	A10	A11	C2	C3	C4	C5	C10	C11	C12	C14	C15	C16	C25
1	-.055*	-.125**	-.112**	-.078**	-.079**	-0.042	-.104**	-.072**	-.134**	0.018	-0.012	-.093**	-.051*	-0.032
2	.145**	.219**	.149**	.206**	.228**	.118**	.242**	.187**	.271**	.102**	.114**	.197**	.136**	.091**
3	.073**	.114**	.158**	.142**	.117**	.216**	.104**	.053*	.052*	.090**	.085**	.119**	.157**	.130**
4	.223**	.349**	.291**	.324**	.345**	.230**	.278**	.304**	.360**	.230**	.256**	.303**	.276**	.211**
5	.190**	.290**	.255**	.262**	.265**	.222**	.257**	.250**	.289**	.159**	.207**	.275**	.245**	.179**
6	.154**	.215**	.183**	.160**	.213**	.147**	.305**	.165**	.243**	.093**	.128**	.202**	.172**	.128**
7	-0.029	-0.032	-0.003	0.014	-0.030	.062*	0.000	-0.022	-.106**	.100**	.062*	0.016	.076**	.066*
8	.061*	0.050	.084**	.074**	.106**	.155**	.106**	.084**	.056*	.114**	.115**	.086**	.097**	.110**
9	.179**	.290**	.213**	.230**	.279**	.172**	.308**	.236**	.363**	.118**	.135**	.252**	.170**	.106**
10	0.035	.061*	.097**	.140**	.112**	.147**	0.037	0.021	0.002	.122**	.124**	.109**	.136**	.140**
11	-0.007	-0.010	0.040	.069**	0.048	.105**	-0.014	-0.014	-.071**	.118**	.081**	.061*	.100**	.107**
12	.103**	.096**	.137**	.087**	.147**	.150**	.113**	.088**	0.042	.138**	.137**	.111**	.148**	.128**
13	.116**	.159**	.135**	.209**	.160**	.149**	.135**	.150**	.182**	.152**	.167**	.181**	.144**	.129**

** $p < .01$. * $p < .05$.

The first linear regression analysis computed the total environmental attitudes score as the sum of all 13 items of the environmental attitudes scale (after reversing the dysfunctional items). The predictors (14 environmental topic scores) explained 22% of the environmental attitude variance (R^2), yet many predictors did not attain statistical significance. After eliminating the non-significant predictors, some different regression analyses were tried, but their estimators did not improve at all.

The second linear regression analysis computes the total environmental attitude score (dependent variable) by summing just the items (2, 4, 5, 6, 9, and 13), those obtained by confirmatory factor analysis. The linear regression analysis with all 14 environmental topics as predictors yields a model with 27.6% shared variance and four non-significant predictors. After removing the four non-significant predictors, the model (nine predictors) is more parsimonious and increases the shared variance to 28.8% (corrected R^2 = 28.4%). Seven predictors display positive standardized regression coefficients, where the highest regression coefficients correspond to the three most interesting issues, and two negative predictors correspond to two of the three least interesting issues (Table 2).

The strongest predictor of environmental attitudes is the item E11 (How to protect endangered species), which also has the highest interest rate. The weakest predictor of environmental attitudes (absolute score of its estimator) is the item E10 (The possible radiation dangers of mobile phones and computers). It is also worth highlighting the two negative predictors (E4. How technology helps us to handle waste, garbage, and sewage; E12. How to improve the harvest in gardens and farms).

Table 2. Linear regression model of the environmental attitudes (6-item empirical factor as dependent variable) with respect to environmental topics (significant predictors p < .05).

Predictors (environmental topics)	Estimator	p	Standard Estimator
Constant	11.317	< .001	
E11. How to protect endangered species	0.873	< .001	0.2353
C10. How to attain a more sustainable society	0.534	< .001	0.1510
E5. How to control epidemics and diseases	0.483	< .001	0.1329
E2. The greenhouse effect and how it may be changed by humans	0.451	< .001	0.1250
E3. What can be done to ensure clean air and safe drinking water	0.257	0.035	0.0722
E15. How energy can be saved or used in a more effective way	0.260	0.021	0.0717
E10. The possible radiation dangers of mobile phones and computers	0.218	0.028	0.0614
E4. How technology helps us to handle waste, garbage, and sewage	-0.303	0.007	-0.0843
E12. How to improve the harvest in gardens and farms	-0.340	< .001	-0.0958

All in all, the main finding of these analyses is the evidence of the overall significant and mainly positive empirical relationship between environmental attitude items (reversing the scores of negative items) and environmental topic items. Then, the regression model for the 6-item environmental attitudes (dependent variable) shows nine significant predictors, where strongest predictors are just the four most interesting environmental topics.

Discussion and conclusions

The discussion focuses first on evaluating the contribution of the results to answering the research questions. The surveyed students displayed globally positive environmental attitudes because they highly agree with the functional statements and disagree with the dysfunctional statements.

Further, the students' interests in environmental topics are also positive, but the interest-weighted mean scores are a bit lower than the environmental attitudes' agreement scores. The largest interest is displayed by the items about the protection of endangered species, the control of epidemics and diseases, and the path towards a more sustainable society. The lowest interest is displayed the topics related to agriculture (improving crops, genetically modified organisms, and organic and ecological agriculture).

In summary, the answer to the first research question is that young students hold clearly proactive environmental attitudes, while interest in environmental topics is positive, yet a bit lower and much dependent on the specific topic being considered. These overall findings on environmental attitudes confirm the results reported by Sa-ngiemjit et al. (2022) employing a sample from the same Spanish region and same age.

In the long run this study poses a fundamental question of social psychology (Eagly & Chaiken, 1993), namely, the degree that the knowledge of the attitude entity (in this case, the environment, represented by 14 environmental topics) influences the related attitudes (in this case, environmental attitudes). This question has been explored here through some correlational analyses that contribute to empirically confirming the relationship as well as to highlighting some weaknesses that provide implications for improving the educational practices on education for sustainability and sustainable development goals (UN, 2015).

The overall correlations between environmental attitudes and interest in environmental topics are significant and positive (after reversing scores of the dysfunctional attitudinal items), which gives support to the overall positive relationship between environmental attitudes and interest in environmental topics.

The linear regression analysis that takes the 6-item reduced empirical factor of environmental attitudes as the dependent variable demonstrates the significant empirical relationship between environmental attitudes and interest in environmental topics. A parsimonious prediction model consisting of nine significant environmental topics as predictors was found, where environmental attitudes and environmental topics share a significant proportion of common variance (28.8%). These results reinforce similar findings reported by Makki et al. (2003) and Liu et al. (2020) and allow drawing some educational consequences.

The implications of these results for the educational practice on sustainable development quality emphasize, as compensatory education, the careful educational planning of the less appreciated aspects of environmental attitudes and environmental topics (improving crops, genetically modified organisms, and organic and ecological agriculture) as well as of the topics identified as negative predictors of environmental attitudes (UN, 2015). The two predictor topics that display negative yet the lowest regression coefficients (garden and farm harvesting and waste management) suggest that this negative relationship may be a consequence of the invisibility of food and waste production in the current urban societies, in spite of being central elements for the sustainability of the planet. Further, in spite of the fact that mean environmental attitudes are overall positive, a minority group of students, ranging from 20% to 40% depending on the environmental attitudes item (Figure 1), hold negative environmental attitudes, so that this group should also be the preferential focus of a quality compensatory environmental education.

The main limitations of this study stand on the fact that its design is based on ROSES-Q, which provided the items on environmental attitudes and environmental topics, and these items were not specifically designed for the research questions posed in this study. For instance, the approach to environmental knowledge (as interest in environmental topics) is a bit different from the usual one, which often focuses on quantitative curricular knowledge rather than qualitative interest in knowledge (Braun & Dierkes, 2019). However, the findings are functional, since the regression confirms the empirical contribution of interest in environmental topics to predict the environmental attitudes, through the shared variance is moderate.

Finally, this study contributes a brief and reliable environmental measurement scale with universal meaning to environmental attitudes research. Further, the study opens a new approach to environmental topics through interest rather than traditional content knowledge scores.

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Exploring Competences Of In-Service Teachers In Implementing Education For Sustainable Development

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The 2030 Agenda for Sustainable Development underscores the importance of education in achieving its goals, with Education for Sustainable Development (ESD) pivotal in fostering sustainability competences. This study investigates in-service teachers' self-efficacy, perceived pedagogical content knowledge (PCK), and willingness to implement ESD using the Professional Action Competence in ESD (PACesd) framework. A quantitative survey design was employed with 475 in-service teachers from primary, middle, and high schools. Descriptive and inferential statistics were conducted, including MANOVA, to examine differences across professional areas and education levels where in-service teachers work (primary, middle and high school). Results showed no significant differences in PACesd dimensions among professional areas. However, among education levels, primary school teachers consistently demonstrated higher self-efficacy, PCK, and willingness compared to their middle and high school counterparts, with high school teachers scoring the lowest. Statistically significant differences in self-efficacy and willingness were observed among education levels. Post hoc analysis revealed primary school teachers scored significantly higher in these dimensions compared to high school teachers. These findings underscore the challenges faced by secondary education teachers, attributed to rigid, subject-specific curricula that hinder interdisciplinary and holistic ESD approaches. The study calls for targeted professional development, curricular reforms, and strategies to boost teachers' willingness to implement ESD, as it emerged as the lowest-scoring dimension. Future research should explore strategies for integrating interdisciplinary approaches and overcoming barriers to ESD adoption across educational levels.

Keywords: sustainability, teacher education, secondary education

Introduction

The 2030 Agenda for Sustainable Development (SD), adopted by the UN in 2015, outlines 17 Sustainable Development Goals (SDGs) and 169 targets for achieving sustainability by 2030 (UN, 2015). Reaching these goals requires individuals with the knowledge, skills, and values to become sustainability change-makers. Education for Sustainable Development (ESD), emphasized in SDG Target 4.7, is key to equipping learners with the tools to promote SD, including sustainable lifestyles, human rights, gender equality, peace, cultural diversity, and global citizenship (Rieckmann, 2017; UN, 2015). ESD fosters competences for critical reflection on actions, promoting sustainable behaviours and active socio-political engagement (Rieckmann, 2017). Its goal is to develop knowledgeable, active citizens committed to sustainability (Biasutti et al., 2016; Carbach & Fischer, 2017). Teachers, essential to ESD implementation, must have the competences to develop action-competent learners (Isac et al., 2022).

Existing studies largely emphasize teachers' knowledge and self-efficacy regarding their competences in implementing ESD or environmental education (e.g., Gardner, 2009; Moseley et al., 2010), while willingness, a crucial competence component (Sass et al., 2022; Vukelić, 2022), is often overlooked. This study adopts the Professional Action Competence in ESD (PACesd) framework by Sass et al. (2022) which integrates self-efficacy, perceived pedagogical content knowledge (PCK), and willingness to implement ESD among primary and secondary in-service teachers. The framework's holistic approach that incorporates holism, pluralism, and action-orientedness makes it particularly relevant for exploring ESD competences in depth.

The literature shows fewer studies on in-service teachers' competences in ESD or environmental education compared to pre-service teachers (e.g., Effeney & Davis, 2013; Gardner, 2009; Saribas et al., 2014). Moreover, existing research predominantly involves primary school teachers (e.g., Effeney & Davis, 2013; Gardner, 2009). While primary school teachers often find it easier to integrate ESD into their teaching practices due to the flexibility of their curricula (Taylor et al., 2019), teachers at higher education levels frequently encounter challenges arising from subject-specific curricula that limit interdisciplinary approaches (Borg et al., 2012). This highlights the importance of including teachers from higher education levels in studies on ESD competences. Investigating how teachers at these levels are challenged in implementing ESD, particularly within the constraints of their subject areas, is crucial (Isac et al., 2022). Accordingly, this study aimed to explore potential differences in ESD competences among primary (1st to 4th grade), middle (5th to 8th grade) and high school (9th to 12th grade) in-service teachers, as well as differences based on the disciplinary areas in which they teach. The research questions are as follows:

- What are the levels of self-efficacy, perceived PCK, and willingness to implement ESD among in-service teachers?
- Are there statistically significant differences in teachers' professional action competence in ESD among in-service teachers from different disciplines?
- Are there statistically significant differences in teachers' professional action competence in ESD among in-service teachers teaching at different levels of education (i.e., primary, middle, and high school)?

Method

Research Design

This study employed a cross-sectional survey research design to explore differences in self-efficacy, perceived PCK, and willingness to implement ESD among primary, middle, and high school in-service teachers.

Participants

A total of 475 in-service teachers participated, with 64.4% female and 35.5% male. Most were primary school teachers (42.5%), followed by middle school teachers (35.8%), and high school teachers (21.7%).

Instrument

The study utilized the PACesd Scale, developed by Sass et al. (2022), to assess teachers' self-efficacy, perceived PCK, and willingness to implement ESD. The reliability analysis in the current study demonstrated excellent internal consistency (Cicchetti, 1994), with Cronbach's alpha values of 0.96 for self-efficacy regarding ESD, 0.98 for perceived PCK about ESD, and 0.97 for willingness to implement ESD.

Procedure

The PACesd data collection instrument was administered collectively to in-service teachers with the majority of participants completing the survey in approximately 10 minutes. Formal approval was obtained from the university's ethics committee prior to the start of the study. Participation was entirely voluntary and respondents were not required to provide their names or any other identifying information, ensuring anonymity.

Data Analysis

Both descriptive and inferential statistical analyses were conducted using SPSS 29. Descriptive statistics were employed to summarize and organize the study's data and to address the first research question. To address the second and third research questions, multivariate analysis of variance (MANOVA) was performed at a .05 alpha significance level. Before running the analysis, all necessary MANOVA assumptions were checked and fully met.

Results

The results of descriptive statistics are presented in Table 1. The maximum possible scores are 60 for self-efficacy, 66 for perceived PCK, and 60 for willingness. The total mean scores for the dimensions of PACesd are as follows: self-efficacy is 41.5, perceived PCK is 45.2, and willingness is 37.2. Additionally, among education levels, primary school teachers consistently scored higher than middle and high school teachers across three dimensions, with high school teachers having the lowest scores.

Table 1. Descriptive statistics.

Variable	*N*	*M*	*SD*	*M*	*SD*	*M*	*SD*
		(Self-efficacy)		(perceived PCK)		(Willingness)	
Discipline							
Primary	203	42.8	11.0	46.3	13.2	38.7	12.4
Science	82	42.0	9.6	46.7	11.5	37.7	11.3
Social Sciences	45	42.4	8.9	45.2	12.8	37.5	12.5
Physics	23	42.2	9.3	41.7	11.4	33.0	12.5
Biology	25	37.8	9.4	43.3	12.2	34.4	9.6
Chemistry	25	37.3	9.2	38.7	12.4	34.1	10.5
Geography	24	36.7	9.3	44.2	10.8	34.0	11.7
Visual Arts	17	38.5	11.5	43.5	13.4	32.7	9.2
Technology and Design	31	40.7	15.6	44.5	17.4	38.5	15.3
Education Level							
Primary School	203	42.8	11.0	46.2	13.1	38.6	12.3
Middle School	170	41.5	11.0	45.5	13.2	37.6	12.5
High School	102	38.8	9.5	42.5	11.9	33.8	10.7
Total	475	41.5	10.7	45.2	13.0	37.2	12.1

A one-way between-groups MANOVA was conducted to examine differences in PACesd across professional areas. The dependent variables included self-efficacy, perceived PCK, and willingness to implement ESD. The independent variable was in-service teachers' professional area. Preliminary assumption tests revealed no serious violations. Results showed a statistically significant difference among professional areas on the combined dependent variables, F(24, 1346) = 1.99, p = .003, Wilks' Lambda = .90, partial η^2 = .033. However, when analysing the dependent variables individually with a Bonferroni-adjusted alpha level of .017, no statistically significant differences were found as indicated in Table 2.

Table 2. MANOVA results.

Variable		Sum of Squares	*df*	Mean Square	F	Sig.	Partial Eta Squared
Discipline							
	Self-efficacy	1946.7	8	243.3	2.149	.030	.036
	PCK	1952.6	8	244.0	1.462	.169	.024
	Willingness	1972.5	8	246.6	1.692	.098	.028

A separate one-way between-groups MANOVA was performed to investigate differences in PACesd based on the educational levels where in-service teachers work (primary, middle and high school). The dependent variables were the same: self-efficacy, perceived PCK, and willingness to implement ESD. Preliminary assumption tests were satisfactory. A statistically significant difference was found among educational levels on the combined dependent variables, $F(6, 940) = 2.32$, $p = .031$, Wilks' Lambda = .97, partial η^2 = .015. As seen in Table 3, when considering the dependent variables separately with a Bonferroni-adjusted alpha level of .017, statistically significant differences were observed for self-efficacy scores, $F(2, 472) = 4.58$, $p = .011$, partial η^2 = .019. Post hoc analyses revealed that primary school teachers reported significantly higher self-efficacy scores ($M = 42.8$, $SD = 11.0$) compared to high school teachers ($M = 38.8$, $SD = 9.5$), $p = .007$. Significant differences were also found in willingness scores, $F(2, 472) = 5.52$, $p = .004$, partial η^2 = .023. Post hoc results indicated that primary school teachers ($M = 38.6$, $SD = 12.3$) reported significantly higher willingness scores than high school teachers ($M = 33.8$, $SD = 10.7$), $p = .003$. Middle school teachers ($M = 37.6$, $SD = 12.5$) also had significantly higher willingness scores than high school teachers ($M = 33.8$, $SD = 10.7$), $p = .033$.

Table 3. MANOVA results.

Variable		Sum of Squares	*df*	Mean Square	F	Sig.	Partial Eta Squared
Education Level							
	Self-efficacy	1042.3	2	521.1	4.583	.011	.019
	PCK	1002.7	2	501.4	3.006	.050	.013
	Willingness	1597.1	2	798.5	5.520	.004	.023

Conclusion And Discussion

This study has shown that although there were no statistically significant differences across professional areas in terms of self-efficacy, perceived PCK, and willingness to implement ESD, statistically significant differences were found across educational levels (primary, middle, and high school) in terms of self-efficacy regarding ESD and willingness to implement ESD. This study has demonstrated that primary education teachers tend to show higher self-efficacy, perceived PCK, and willingness compared to their peers in secondary education, similar to the findings of Isac et al. (2022). Previous studies have reported that secondary education teachers often exhibit lower levels of commitment and higher feelings of inadequacy concerning the knowledge and skills required for the implementation of ESD (Borg et al., 2012; Popova et al., 2016; Taylor et al., 2019). As Isac et al. (2022) point out, in the literature, these perceptions are attributed to the structure of secondary education which emphasizes subject-specific knowledge and provides limited opportunities for teacher training. This organizational framework restricts the adoption of interdisciplinary and holistic approaches which are essential for developing competences in ESD. Besides these, the lowest mean score for willingness might suggest a gap between teachers' capabilities and their motivation to implement ESD, highlighting the need to enhance their commitment and engagement.

Implications And Future Work

The study highlights key implications and future directions. To improve secondary teachers' self-efficacy, PCK and willingness in ESD, targeted professional development and curricular reforms promoting interdisciplinary and holistic approaches are needed. Future research should identify strategies for integrating interdisciplinarity in secondary education, assess the long-term impact of ESD training, and explore barriers and enablers of ESD adoption across professional areas. Moreover, efforts should prioritize enhancing teachers' willingness to implement ESD, as it emerged as the dimension with the lowest mean score within PACesd.

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Global Citizenship Education As A Transformative Framework For Reorienting Education Systems Towards Community Needs And Sustainable Development

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Global Citizenship Education (GCE) is increasingly recognised as a transformative educational approach that equips learners with the knowledge, skills and values required to address complex global challenges such as climate change, inequality and sustainable development. Grounded in critical pedagogy, transformative learning and systems thinking, GCE challenges conventional education systems characterised by rigid curricula, standardised assessment and hierarchical pedagogies. This paper explores how GCE reorients education systems towards inclusivity, critical engagement and community relevance while supporting the achievement of the Sustainable Development Goals (SDGs), particularly Goals 4, 11 and 13. Using a qualitative, document-based multiple case study approach, the study analyses selected examples from Africa, Europe and Asia, including Ubuntu-inspired education initiatives in South Africa, the Global Learning Programme in the United Kingdom and Japan's Education for Sustainable Development initiatives, with specific reference to RCE Okayama. The findings demonstrate how GCE is enacted through participatory, context-responsive and interdisciplinary pedagogies that connect local realities with global concerns. While GCE holds significant transformative potential, the study identifies persistent challenges related to resistance to change, Western-centrism and assessment practices. The paper concludes by proposing strategies for strengthening the integration of GCE through teacher education, policy alignment, community engagement and the use of digital technologies.

Keywords: Global Citizenship Education, Transformative Learning, Sustainable Development Goals, Community-Responsive Education, Education Systems Transformation.

Introduction

Global Citizenship Education (GCE) has gained prominence in the 21st century as globalization intensifies interconnected challenges such as climate change, migration and inequality. Traditional education systems often fail to prepare learners to navigate these complexities. GCE bridges this gap by fostering global awareness, critical thinking and collective responsibility (Duarte & Robinson-Jones, 2022; Pacho, 2020). It emphasizes cognitive, socio-emotional and behavioural dimensions to enable learners to critically engage with pressing global issues (Sun, 2020). GCE aligns with SDGs, especially Goal 4 (quality education), Goal 11 (sustainable communities) and Goal 13 (climate action) (Khoo & Jørgensen, 2021; Stein, 2021). Its interdisciplinary framework equips learners to address global challenges while fostering local resilience and action.

Aim And Research Questions

This study aims to explore how Global Citizenship Education is conceptualised and implemented as a transformative framework within science and sustainability-oriented education systems and how it responds to community needs for sustainable development.

Research Questions:

1. How is Global Citizenship Education conceptualised as a transformative approach within contemporary education systems?
2. How are GCE principles enacted in selected case studies across Africa, Europe and Asia?
3. What pedagogical and contextual features characterise these GCE initiatives?
4. What challenges and opportunities emerge in implementing GCE in diverse educational contexts?
5. What implications do these cases offer for strengthening science education for sustainable development?

Current Educational Practices

Traditional education systems emphasize standardized testing, rigid curricula and rote learning, which often marginalize critical thinking, collaboration and adaptability. These systems frequently reflect Western-centric methodologies, sidelining Indigenous and local perspectives (Silva et al., 2023). GCE offers an alternative by promoting interdisciplinary learning, global interconnectedness, and active problem-solving. It shifts the focus from knowledge retention to critical engagement with real-world issues (Pacho, 2020). However, implementing GCE faces hurdles such as resistance from traditional systems, resource limitations and assessment challenges (Bamber et al., 2018).

Case Studies

The implementation of Global Citizenship Education (GCE) differs across cultural and geographical contexts, mirroring various local challenges and opportunities. Analysing case studies from Africa, Europe and Asia provides important perspectives into the integration of GCE concepts into global education systems, promoting global citizenship while considering local contexts. These examples demonstrate the versatility of GCE in building connection, critical Thinking And Sustainability Within Several Cultural Contexts.

Africa: Ubuntu Philosophy In Education

The Ubuntu philosophy, rooted in African traditions, emphasizes communal responsibility and interconnectedness. In South Africa, Ubuntu-inspired programs address social and environmental challenges by promoting collaboration and collective accountability (Sipondo, 2025). These programs connect local cultural heritage with global perspectives, fostering a sense of belonging and environmental care.

Europe: Global Learning Programme (UK)

The UK's Global Learning Programme (GLP) integrates GCE values through activities such as model United Nations debates and sustainability seminars. These initiatives enhance learners' understanding of global challenges while fostering critical thinking and empathy (Huckle, 2015). However, critics highlight challenges such as curriculum overload and resource constraints (Collado-Ruano, 2016).

Asia: Education For Sustainable Development (Japan)

Japan's Education for Sustainable Development (ESD) integrates GCE principles into formal education, emphasizing learner-centered methodologies such disaster preparedness and environmental conservation (Ferguson et al., 2022). Programs such as RCE Okayama demonstrate how contextualizing GCE within local circumstances can empower learners to address both local and global challenges. RCE Okayama (Regional Centre of Expertise on

Education for Sustainable Development) is part of a global network recognised by the United Nations University. It functions as a collaborative platform linking schools, universities, local government, civil society and communities to advance Education for Sustainable Development. In Japan, RCE Okayama exemplifies how GCE and ESD principles are embedded within local contexts through place-based learning, disaster preparedness education and environmental stewardship. Its inclusion in this study highlights the importance of community-driven, context-sensitive approaches to global citizenship education.

Methodology

This study adopts a scoping qualitative, exploratory research design grounded in an interpretivist paradigm, recognising that educational practices are socially constructed and context-dependent (Creswell & Creswell, 2018; Pervin & Mokhtar, 2022). The study is based on secondary data and does not involve primary data collection at this stage. A document-based multiple case study approach was employed to explore how Global Citizenship Education is implemented in different geographical and cultural contexts (Yin, 2009). The cases were purposively selected from Africa, Europe and Asia to illustrate different yet comparable applications of GCE within formal and non-formal education systems.

Selection Criteria For Case Studies Included:

- Explicit reference to Global Citizenship Education or Education for Sustainable Development
- Clear relevance to science, sustainability or environmental education
- Availability of sufficient peer-reviewed or institutional documentation
- Representation of different socio-cultural contexts

The literature reviewed comprised peer-reviewed journal articles, policy documents and programme reports sourced from databases including Google Scholar, JSTOR, Semantic Scholar and IEEE Xplore. Inclusion criteria focused on relevance to GCE, sustainability and educational transformation. The selected documents were analysed thematically to identify recurring patterns, challenges and pedagogical strategies related to GCE implementation (Bryman, 2016).

Discussion

This section explores the potential for change of Global Citizenship Education (GCE) as a paradigm for overcoming the shortcomings that plague traditional education systems. This presentation clarifies the benefits, challenges and solutions for enhancing Global Citizenship Education (GCE), demonstrating its capacity to provide learners with the requisite skills, information and values to adeptly go through a progressively interconnected and complicated world.

Benefits Of GCE Integration

Through the development of critical thinking, multicultural awareness and global responsibility, GCE equips learners to engage substantively with real-world challenges, including climate change, socioeconomic injustice and global health crises (Bamber et al., 2018; Pacho, 2020). Its focus on multidisciplinary and interactive learning connects education with global citizenship, guaranteeing that learning aligns with society demands. GCE supports diversity by including multiple cultural perspectives and knowledge frameworks, especially those of Indigenous and underprivileged populations. This inclusive methodology facilitates learning and guarantees that education mirrors the actual experiences of numerous communities, promoting empathy, solidarity and an understanding of global interdependence (Dreamson, 2018; Smith, 2018). To attain genuine inclusion, GCE must transcend its dependence on Western epistemologies by integrating non-Western and Indigenous perspectives as equal contributors to its evolution (Dreamson, 2018). This strategy is consistent with coeducation principles, encouraging intercultural involvement and overcoming gaps in access to and quality of education worldwide (Ainscow, 2020).

An interdisciplinary approach to Global Citizenship Education amplifies its transformative capacity by addressing global systems of oppression and domination. Analytical categories such race, gender and class are employed to enhance learners' consciousness of their collective responsibility and culpability in these frameworks, thereby promoting political engagement and social justice outcomes (de Vries, 2020). This fundamental aspect of GCE corresponds with Freirean pedagogy, emphasising critical thinking, self-reflection and praxis as the basis for transformational action (Tarozzi & Inguaggiato, 2018). Ultimately, GCE improves learners' capacity for critical thinking and collaborative action, critical competencies for solving complicated global challenges demanding coordinated, interdisciplinary approaches. By emphasising active participation rather than passive knowledge absorption, GCE enables learners to become proactive problem-solvers and proponents of sustainable development (Khoo & Jørgensen, 2021; Santamaría-Cárdaba et al., 2021). Teacher education programs serve as crucial in this process, focussing on transformational methodologies that equip teachers to motivate and direct learners towards these objectives.

Challenges In Implementation

Although its revolutionary commitment, Global Citizenship Education (GCE) encounters major challenges in implementation across various contexts. A major challenge is the opposition from stakeholders established in traditional educational systems, such as policymakers, teachers and organisations that emphasise standardised testing and inflexible curricula. These systems frequently exhibit insufficient flexibility to support the transdisciplinary and participative nature of GCE, resulting in conflicts between traditional practices and transformational educational objectives. To overcome this opposition, systemic adjustments that emphasise innovation and adaptation are necessary.

A major challenge is the perception of GCE as Western-centric, especially given that its concepts and approaches are primarily sourced from Global North contexts. This perspective diminishes its significance and acceptance in various cultural contexts (Lauwerier, 2020; Akkari & Maleq, 2020). In West Africa, the external roots of GCE and inadequate local stakeholder engagement reduce its applicability (Lauwerier, 2020). Furthermore, South Korean teachers face challenges stemming from neoliberal and post-colonial proposals that marginalise Global Citizenship Education within the curriculum (Kim, 2019). Asian colleges experience supplementary barriers including financial constraints, inflexible curricula and challenges in maintaining cultural relevance (Sain et al., 2025). These examples emphasise the necessity for localised and context-specific strategies that integrate indigenous knowledge systems and culturally relevant behaviours (Ydo, 2023). The contested nature of GCE further hampers its execution. Various conceptions of global citizenship exist, frequently shaped by different cultural and ideological contexts (Akkari & Maleq, 2020). Certain teachers perceive GCE as a neocolonial construct, however others contend it may be adapted to address local challenges via customised strategies (Parejo et al., 2022). To maintain GCE's relevance and influence, it must acknowledge local contexts and question its dependence on Western frameworks.

Strategies For Improvement

To address the challenges of implementing Global Citizenship Education (GCE) and fully utilise its revolutionary potential, many measures must be prioritised. Integrating GCE activities with broader global targets, specifically the Sustainable Development Goals (SDGs), especially SDG 4.7, guarantees consistency and expandability (Abazov, 2021; Longueira Matos & Vela-Eiden, 2020). Programs such as Bridge 47 reflect the value of collaborative efforts in advancing Global Citizenship Education and championing educational changes aimed at social transformation (Longueira Matos & Vela-Eiden, 2020). Policymakers must devise context-specific policies and nurture collaborations across governments, non-governmental organisations and educational institutions to overcome structural challenges especially for marginalised populations (Akkari & Maleq, 2020; Vindigni, 2024). Ongoing assessment and modification of policies is required to maintain relevance in changing global environments (Vindigni, 2024). Professional development programs must prioritise interdisciplinary learning, cultural proficiency and creative pedagogical approaches consistent with Global Citizenship Education concepts (Parejo et al., 2022). Effective professional development integrates experiential learning, critical thinking and chances for reflection and practice, addressing intellectual, affective and action-oriented domains (Darling-Hammond et al., 2017).

Technology plays an important role in broadening access to GCE and augmenting its effectiveness. Digital exchanges, digital tools and online resources facilitate worldwide collaboration and mutual understanding, producing holistic and interactive learning experiences that surpass geographical limitations (Abimbola Eden et al., 2024). Academic literacy facilitators can employ multimodal literacies, such as digital discourses, to successfully communicate GCE principles (Eybers & Muller, 2023). Teachers must synchronise technological tools with instructional objectives, promote digital literacy and stimulate critical thinking to optimise technology's positive impact (Abimbola Eden et al., 2024). These strategies facilitate the creation of more inclusive, egalitarian and sustainable learning environments that equip learners to confront the complicated issues of a connected world.

Conclusion

Global Citizenship Education represents a transformative shift in education. Along fostering critical thinking, global awareness and inclusive practices, GCE prepares learners to navigate and address the complexities of a globalized world. Despite challenges, its potential to create sustainable and equitable education systems underscores its importance.

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Assessing Students' Sense Of Responsibility In Chemistry Education: Development And Validation Of An STSE-Based Instrument

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Developing students' sense of responsibility is a central goal of contemporary science education, particularly in addressing Science–Technology–Society–Environment (STSE) issues. However, empirical tools for assessing students' responsibility in discipline-specific contexts remain limited. This study aimed to develop and validate an assessment tool for measuring the sense of responsibility among students in grades 9–12 within chemistry-related STSE contexts. A scale development and validation design was adopted. The assessment tool was constructed around three authentic chemistry contexts—hand warmers, global warming, and soda-making—selected for their curricular relevance and real-life significance. Based on a theoretical framework, students' sense of responsibility was operationalized into three dimensions: personal responsibility, social responsibility, and scientific responsibility. Items were developed using a storyline-based approach and refined through student interviews and expert review. The instrument was administered to 2,366 students, and its psychometric properties were examined using a Multidimensional Rasch Model. The results indicated satisfactory reliability, with Expected A Posteriori/Plausible Value (EAP/PV) coefficients ranging from 0.63 to 0.76. Item fit statistics (infit and outfit MNSQ) fell within the acceptable range, supporting the structural validity of the instrument. Students demonstrated the highest levels of performance in social responsibility, followed by scientific and personal responsibility. Furthermore, students' attitudes toward science and STSE issues, as well as their understanding of the nature of science, were positively associated with responsibility, whereas academic achievement alone showed a weaker relationship. This study provides a validated, context-based instrument for assessing students' sense of responsibility in chemistry education. The findings highlight the importance of integrating STSE issues into chemistry curricula to support students' ethical reasoning, decision-making, and engagement with real-world scientific challenges. The assessment tool offers practical value for both research and instructional design and contributes to ongoing discussions on responsibility-oriented science education.

Keywords: Sense of responsibility; Chemistry education; Instrument development; Multidimensional Rasch model

Introduction

One of the visions of science education is to nurture scientifically literate students who can make informed decisions and take responsible actions in their lives (Sjöström & Eilks, 2018). As future citizens, students will inevitably face modern scientific issues such as climate change, collectively referred to as science-technology-society-environment (STSE) issues (Kruse et al., 2024). To prepare students for citizen engagement, increasing their sense of responsibility is an effective approach for addressing STSE challenges (OECD, 2018). Adolescence can now be seen as a time of opportunity for developing a sense of responsibility. Science education can foster students' sense of responsibility, enabling them to apply their understanding of scientific concepts and processes to issues that affect their lives, culture, and the environment as a means of caring for themselves, others, and their community. It encourages them to take a critical stance towards the products of science and technology while empowering them to reduce potential harm these products may have on individuals, societies, and environments (Onwu, 2017). Previous research has indicated that various methods, including science identity, environmental identity, and citizen engagement, can be employed to assess the capacity for taking responsibility (Louros, 2022). However, there is little research focusing on identifying the most effective approach to evaluate students' capacity for taking responsibility. In this study, we designed an assessment tool to evaluate the attitudes and sense of responsibility of students in grades 9-12 when dealing with STSE issues. In addition, we investigated the relationship between scientific knowledge, nature of science, attitudes, academic performance, teacher support, school resources, and students' sense of responsibility.

Theoretical Framework

The Concept Of Take Responsibility

Science is a social enterprise that interacts with society in complex ways (Intemann & de MeloMartin,2010). Science should be described as a human activity that acknowledges the strengths of science and technology but also recognizes their limitations. In the specific topic we are discussing, we have the responsibility to ensure the conservation of resources, and to make students aware that we are accountable to society and will not destroy the environment. In science education, students should be encouraged to adopt a "critical thinking disposition" that allows them to investigate the pros and cons of any scientific and technological developments using their intellectual and ethical skills (Fuchs & Tan, 2022).

Existing literature categorizes responsibility into three types: personal responsibility, social responsibility, and scientific responsibility. Personal responsibility primarily revolves around individual consumption habits and lifestyle choices (Aygun et al., 2024; Louros, 2022). Social responsibility aims to promote social development and environmental conservation goals, involving the analysis, judgment, prediction, regulation, and decision-making of real-world issues in social contexts, including responsibilities for social development and environmental protection (Politi, 2024). Scientific responsibility is focused on advancing social development and reducing the negative impacts of science, encompassing scientific ethical responsibility and responsibility for the development of science (De Melo-MartíN & Intemann, 2023).

The capacity to take responsibility involves considering the future consequences of one's actions, evaluating risks and rewards, and accepting accountability for one's work. A performance of take responsibility is a person can reflect upon and evaluate his or her actions from the view of personal and societal goals. Acting ethically implies asking questions related to norms, values, meanings and limits, such as: What should I do? Was I right to do that? Where are the limits? Knowing the consequences of what I did, should I have done it? (OECD, 2018)

Assessing The Capacity Of Responsibility

Developing instruments to assess social responsibility is a complex process that requires careful consideration of cultural, ethical, and contextual factors. One notable example is the work by Dürten Röhm and Marissa Rollnick (2010), who developed an instrument to assess science students' views on the social responsibility of scientists. Their approach was based on the Views on Science-Technology-Society (VOSTS) instrument, which was originally designed to measure students' cognitive views on the interaction between science, technology, and society. The adapted instrument included multiple phases: interviews, open-response questionnaires, and fixed-response questionnaires. These methods were used to capture a comprehensive understanding of students' perspectives.

The development of social responsibility assessment tools typically involves both qualitative and quantitative methodologies. Qualitative methods, such as interviews and focus groups, are essential for capturing nuanced views and opinions. For example, Röhm and Rollnick used group interviews and open-response questionnaires to gather initial data, which were then analysed to identify key themes and dimensions related to social responsibility. This iterative process allowed the researchers to develop a structured questionnaire that reflected the authentic views of the target population.

Quantitative methods, such as fixed-response questionnaires, are used to validate and generalize the findings. The final instrument developed by Röhm and Rollnick included 20 statements with multiple-choice options, allowing for statistical analysis of responses. This approach ensures that the instrument can be used across larger populations while maintaining reliability and validity (González-García et al., 2019).

Factors Affecting The Capacity Of Take Responsibility

Previous research suggests that a lack of understanding of science content hinders one's ability to negotiate STSE issues (Fowler & Zeidler, 2016). Knowledge is the primary influencing factor. According to the Knowledge-Attitude-Behaviour (KAP) model, knowledge influences attitudes, which in turn affect behavioural awareness. Zoller (2013) argues that the "translation" of science and technology into actions that are responsible to society and technology depends on what the relevant personnel believe and what attitudes they hold when facing problems to be solved. Therefore, attitudes towards science and STSE issues are also important influencing factors. Understanding the nature of science helps students grasp what science is and how it works. Existing studies have shown that the nature of science enables students to be open-minded about scientific knowledge and STSE issues, rather than accepting them blindly (Abd-El-Khalick, 2013). The nature of science is an influential factor that cannot be ignored (González-García et al., 2019). In addition to this, factors such as students' academic achievement, the attitudes of teachers and parents, and other elements can also influence students' sense of responsibility.

Research Questions

In this study, we designed an assessment tool to evaluate sense of responsibility of students in grades 9-12 when dealing with STSE issues. Additionally, we investigated the relationships between scientific knowledge, the nature of science, attitudes, academic performance, the attitudes of teachers and parents, school resources, and students' sense of responsibility.

RQ-1：How can an assessment tool of students' sense of responsibility be developed within a chemistry context?

RQ-2: What are the relationships between scientific knowledge, the nature of science, attitudes, academic performance, the attitudes of teachers and parents, school resources, and students' sense of responsibility?

Research Method And Design

Study Design

This study adopted a scale development and validation design to construct an assessment tool measuring students' sense of responsibility within chemistry-related Science–Technology–Society–Environment (STSE) contexts. A mixed-methods approach was employed, combining qualitative data from student interviews with quantitative data from large-scale questionnaire administration, to ensure both content validity and psychometric robustness of the instrument.

Development Of The Responsibility Assessment Tool

This study independently designed an evaluation tool to assess students' sense of responsibility in chemistry-related STSE contexts. The development process followed three sequential stages: (1) contextual selection and framework construction, (2) item development and expert validation, and (3) large-scale pilot testing and psychometric analysis.

Context Selection And Framework Construction

The development of a social responsibility assessment tool specific to a chemistry context requires the selection of appropriate chemistry topics and the creation of authentic scenarios that can elicit students' responsibility-related reasoning. Through curriculum analysis aligned with national chemistry standards, three chemistry contexts were purposively selected: the chemistry of hand warmers, global warming, and the soda-making process.

These contexts were chosen because they involve core chemical principles familiar to students in grades 9–12, thereby minimizing cognitive load while maximizing opportunities for responsibility-related decision-making. The chemistry of hand warmers illustrates the application of oxidation reactions in daily life and highlights scientific responsibility for consumer safety. Global warming draws on energy-related chemical knowledge and emphasizes chemistry's role in addressing global environmental challenges. The soda-making process involves industrial chemistry and wastewater treatment, requiring students to balance economic efficiency with environmental protection and social responsibility.

Based on the theoretical framework, students' sense of responsibility was operationalized into three dimensions: personal responsibility, social responsibility, and scientific responsibility. Each dimension reflects progressively complex forms of responsibility, ranging from individual behavioural choices to collective decision-making and scientific innovation.

Item Development And Validation

The assessment tool was designed using a storyline-based approach, in which each chemistry context served as a coherent narrative stimulus embedding multiple decision points. As each storyline unfolded, 10–15 items were embedded within each context, resulting in a total of 30–45 items across the three responsibility dimensions.

Each item consisted of a multiple-choice question with four response options, representing increasing levels of responsibility. Responses were scored on an ordinal scale from 1 to 4, with higher scores indicating a higher level of responsibility.

To ensure content validity, extensive semi-structured interviews were conducted with students prior to item construction. Students were asked to explain how they would respond to each scenario and why. Their authentic responses were coded and used as the basis for constructing realistic and developmentally appropriate response options.

The initial item pool was reviewed and refined by two experts in chemistry education research and one Ph.D. researcher in chemistry education, focusing on clarity, relevance, and alignment with the intended responsibility dimension. Revisions were made iteratively until consensus was reached on item appropriateness and representativeness.

An example item from the assessment tool is presented below to illustrate the scoring logic and responsibility progression:

Consumers have reported that some heat packs may become too hot, posing a risk of burns. How do you think the research team should best respond? ( )

A. I would like to adjust the thickness of the heat pack packaging to prevent consumers from feeling it is too hot. (1 point)

B. I would like to analyse the cause of overheating and improve the heating mechanism to ensure it stays within a safe range. (3 points)

C. I would like to provide more guidance on preventing burns to help consumers use the heat packs safely. (2 points)

D. I would like to develop heat packs with a temperature regulation function that can automatically adjust the heating temperature to ensure safety. (4 points)

Assessment Of Influencing Factors

In addition to the responsibility assessment tool, a separate questionnaire was developed to measure factors potentially influencing students' sense of responsibility, including attitudes towards science, attitudes towards STSE issues, understanding of the nature of science, academic achievement, teachers' and parents' attitudes, and school resources.

This instrument was adapted from established scales reported in previous research (Hillman et al., 2016) and consisted of 30 Likert-scale items rated on a five-point scale ranging from "strongly disagree" to "strongly agree." Higher scores indicated more positive attitudes or greater perceived support.

Participants And Data Collection

A total of 2,366 students in grades 9–12 participated in the study. Among them, 44.4% were female and 55.6% were male. Data were collected through a 40-minute online assessment, administered during regular school hours.

Following the quantitative assessment, 10 students were purposively selected for follow-up semi-structured interviews, each lasting approximately 30 minutes, to explore students' perceptions of the assessment tool and their engagement with the chemistry contexts.

Ethical approval for the study was obtained from the relevant institutional review board. Informed consent was obtained from all participating students and their guardians prior to data collection, and all responses were anonymized to ensure confidentiality.

Data Analysis

To examine the psychometric properties of the responsibility assessment tool, a Multidimensional Rasch Model (a form of Multidimensional Item Response Theory, MIRT) was applied. This model allows for the simultaneous estimation of item difficulty and student ability across multiple latent dimensions while accounting for the interrelationships among dimensions.

The analysis was conducted using ConQuest Version 2.0 software, which is suitable for large-scale educational assessments. Model fit was evaluated using infit and outfit mean square (MNSQ) statistics, with acceptable values ranging from 0.7 to 1.3. Reliability was assessed using Expected

A Posteriori/Plausible Value (EAP/PV) Reliability Coefficients

To address Research Question 2, correlation and regression analyses were conducted to examine the relationships between students' sense of responsibility and influencing factors, including scientific knowledge, nature of science, attitudes, academic achievement, and perceived support from teachers, parents, and schools.

Findings

Psychometric Properties Of The Responsibility Assessment Tool

The psychometric quality of the responsibility assessment tool was examined using a multidimensional Rasch model. Overall, the model demonstrated satisfactory fit and reliability, indicating that the instrument was appropriate for measuring students' sense of responsibility across multiple dimensions.

The reliability coefficients (eap/pv), which indicate the stability and internal consistency of the measurement, ranged from 0.63 to 0.76 across the three dimensions of responsibility, suggesting acceptable reliability for an educational assessment tool. Specifically, social responsibility showed the highest reliability, followed by scientific responsibility and personal responsibility.

Item fit statistics further supported the adequacy of the model. Both infit and outfit mean square (mnsq) values for all items fell within the acceptable range of 0.7 to 1.3, indicating that the observed student responses were consistent with the expectations of the Rasch model and that no items exhibited substantial misfit.

These results provide evidence for the structural validity of the assessment tool and support the multidimensional conceptualization of students' sense of responsibility in chemistry-related stse contexts.

Differences Across Responsibility Dimensions

Analysis of students' performance across the three responsibility dimensions revealed statistically meaningful differences. Students demonstrated the highest levels of performance in social responsibility, followed by scientific responsibility, while personal responsibility scores were comparatively lower.

The consistently higher scores in social responsibility suggest that students are more inclined to recognize collective obligations and societal consequences of chemistry-related issues than to reflect on personal behavioural changes or engage in innovation-oriented scientific responsibility. No significant differences were observed across demographic variables in other dimensions.

Relationships Between Responsibility And Influencing Factors

To address Research Question 2, the relationships between students' sense of responsibility and influencing factors—including scientific knowledge, understanding of the nature of science, attitudes toward science and STSE issues, academic achievement, and perceived support from teachers, parents, and school resources—were examined.

The findings indicated that students' attitudes toward science and STSE issues were significantly associated with higher levels of responsibility, particularly in the social responsibility dimension. Understanding of the nature of science also showed a positive relationship with scientific responsibility, suggesting that students who possessed a more informed view of how science operates were more likely to engage in ethically and socially responsible reasoning.

In contrast, academic achievement alone did not emerge as a strong predictor of responsibility, indicating that responsibility-related competencies extend beyond traditional measures of academic performance. Perceived support from teachers and schools showed a moderate association with responsibility, highlighting the role of the educational environment in shaping students' responsibility-related attitudes.

Student Perceptions Of The Assessment Tool

Qualitative data from follow-up interviews provided complementary insights into students' experiences with the assessment. Participants reported that the assessment scenarios were engaging and closely connected to real-life situations, which increased their motivation to think deeply about the issues presented.

Several students noted that even when their chemistry grades were not strong, they felt capable of applying chemical knowledge to socially meaningful problems. This sense of relevance and usefulness contributed to a feeling of accomplishment and value, suggesting that the assessment tool successfully elicited responsibility-related engagement beyond rote knowledge recall.

Discussion And Implications

Interpretation Of Findings

This study aimed to develop and validate an assessment tool for measuring students' sense of responsibility within chemistry-related STSE contexts. The findings provide empirical support for conceptualizing responsibility as a multidimensional construct comprising personal, social, and scientific dimensions, consistent with prior theoretical frameworks (OECD, 2018; De Melo-Martín & Intemann, 2023).

The higher levels of social responsibility observed among students may reflect the increasing emphasis on collective action and societal challenges, such as climate change, within contemporary science education and public discourse. In contrast, scientific responsibility—which involves innovation, ethical reflection, and long-term technological decision-making—may require more explicit instructional support to develop fully in secondary education contexts.

The significant relationships between responsibility and attitudes toward science and STSE issues underscore the importance of affective and epistemic dimensions in responsibility development. These findings align with the Knowledge–Attitude–Behaviour (KAB) framework, suggesting that responsibility is not solely driven by content knowledge but is strongly shaped by students' values, beliefs, and perceptions of science's role in society.

Educational Implications

The validated assessment tool developed in this study offers several implications for chemistry education. First, it provides educators and researchers with a practical instrument for diagnosing students' responsibility-related competencies in authentic STSE contexts. Such diagnostic information can support curriculum design that intentionally integrates responsibility development alongside conceptual understanding.

Second, the findings suggest that embedding chemistry instruction within meaningful socio-scientific scenarios can enhance students' engagement and sense of purpose, particularly for students who may not excel in traditional academic assessments. This highlights the potential of STSE-based instruction to promote educational equity by valuing diverse forms of competence beyond test scores.

Third, the observed influence of teacher and school support emphasizes the need for learning environments that encourage discussion, reflection, and ethical reasoning. Professional development for teachers should therefore focus not only on content delivery but also on facilitating dialogue around responsibility, ethics, and societal implications of chemistry.

Limitations And Future Research

Several limitations of this study should be acknowledged. First, although the sample size was large, the participants were drawn from a limited educational context, which may constrain the generalizability of the findings to other regions or educational systems. Second, the assessment relied primarily on self-reported responses to hypothetical scenarios, which may not fully capture students' actual behaviour in real-world situations.

Third, while the Multidimensional Rasch Model provided strong evidence for structural validity, future studies could further examine the external validity of the instrument by comparing responsibility scores with observed behaviours or longitudinal outcomes.

Future research should explore how students' sense of responsibility develops over time and how different instructional interventions influence each responsibility dimension. Cross-cultural validation of the assessment tool would also be valuable to examine how responsibility in chemistry is shaped by cultural, social, and educational contexts.

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From Instrumental To Communicative Rationality: Reimagining Science Education For Sustainability In Socio-Political Conflicts

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We present the early stages of an interdisciplinary research aimed at promoting future-oriented agency competencies to support upper secondary school students in participating in the public debate on the energy transition within their communities. As a case study, the research focuses on Sardinia (Italy), where renewable energy policies have triggered strong social tensions: while national energy policies assign a strategic role in Italy's decarbonization efforts to the island's renewable energy capacity, local activists denounce renewable energy projects as speculative ventures, with severe impacts on landscapes and land ownership. This research is structured in three phases. The first step was ethnographic fieldwork, focusing on the social movement that opposes new energy infrastructures, addressing its historical, cultural, and economic background. As a second step, we will adapt an MGA (Modelling to Generate Alternatives) energy-system model as a tool for enabling students to understand the complexity of the energy transition and to critically explore alternative energy scenarios. Finally, we will test the developed educational tools directly in the schools of the communities involved in the study. As a preliminary conclusion, we propose to interpret the tensions between the local communities' lifeworld and the development of new energy infrastructures as a conflict between communicative rationality and instrumental rationality, according to Habermas' theory of communicative action. From this perspective, the use of an MGA energy-system model within an interdisciplinary education framework appears as an attempt to rethink science education for sustainability in line with the ideal of communicative rationality.

Keywords: sustainability, communicative rationality, future-oriented science education.

Premise

In line with the Paris Agreement of 2015, the European Union aims to reach climate neutrality by 2050 through an ambitious energy transition program known as the European Green Deal. The objective of climate neutrality by 2050 became legally binding in 2021 with the adoption of the European Climate Law and the legislative package Fit for 55, which sets the intermediate target of a 55% reduction in greenhouse gas emissions by 2030.

Although the European Green Deal formally claims to reconcile environmental sustainability, economic growth, and social cohesion (European Commission, 2018), the energy transition has generated significant social tensions (Eichenauer & Gailing, 2022; Sovacool et al., 2022). European energy policies operate within a neoliberal framework (Laes & Bombaerts, 2022), as evidenced by the use of market-based instruments such as the Emissions Trading System (ETS) (Verbruggen et al., 2019). Within this framework, procurement procedures that favor large-scale capital over local actors can contribute to strong power asymmetries in electricity system governance (Kirkegaard et al., 2021). Especially in Southern Europe, a predominantly top-down approach to energy governance, characterized by massive investments in large-scale power plants and limited engagement of local communities, has triggered widespread social opposition to the energy transition (Osti, 2018; Wolsink, 2007). In Italy, energy policies have been marked by pronounced inequalities in the distribution of the costs and benefits of the transition (Albulut, 2026). These social tensions have been further exacerbated by the significant acceleration of the energy transition promoted under the RePowerEU plan in 2022 (Pavlenko, 2025), particularly as a result of land grabbing associated with the expansion of wind farms.

In the coming years, tensions between local communities and renewable energy projects are expected to increase due to upcoming commitments to the transition.

Research Question

According to the social science literature, the engagement of local communities in decision-making processes is effective in supporting the development of energy policies with broader social support, thereby reducing social opposition to renewable energy facilities (Wolsink, 2007). Our research aims to explore the potential role of schools, as sites of science education and critical citizenship, to increase the capacity of local communities to participate in public debate in an informed and effective way, in contexts where energy policies have already triggered social opposition. In this context, a key question is whether science education for sustainability, by equipping high school students with future-oriented agency competences, can foster their participation in the decision-making processes – thereby contributing to identifying just transition policies supported by broader social consensus.

From this perspective, science education for sustainability cannot be reduced to simply explaining the rationale for – and advocating the urgency of – decarbonization, without criticizing the power asymmetries implicit in current energy policies. This is especially true in a context where public education was long used as a tool of cultural colonization, enforced assimilation, and eradication of local languages (Bandinu et al., 2003; Sorge, 2015). Rather than dismissing local movements' concerns by labelling them as irrational and excluding them from public debate – a rhetoric aimed at legitimizing asymmetric access to decision-making spaces in many conflicts over the appropriation of resources – this research aims to develop educational practices and tools that create space for polyphonic dialogue, recognizing the legitimacy of these voices.

Case Study

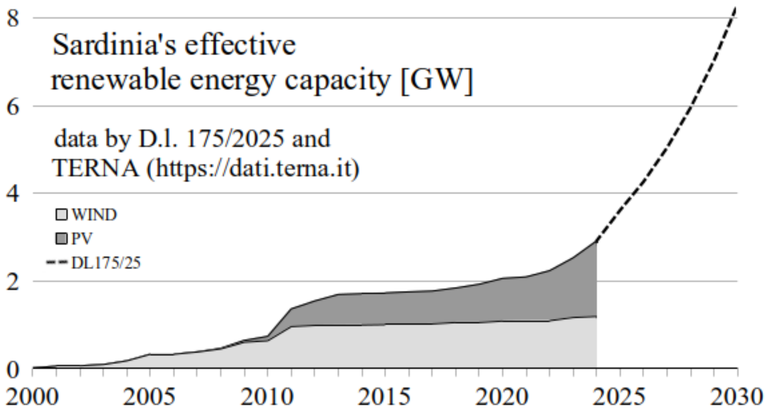
This research focuses on social tensions triggered by renewable energy policies in Sardinia (Italy). Sardinia, the second largest island in the Mediterranean, has a distinctive cultural identity and strong territorial rootedness. It is recognized as a highly suitable territory for renewable energy development (Politecnico di Milano, RELab, 2020), not only because of consistent wind patterns and high solar exposure, but also due to extensive grassland areas with little human presence. The most recent legislation (D.l.175/2025) establishes the target of 8.3 GW of effective renewable energy capacity in the region by 2030 as legally binding. At the beginning of 2023, it amounted to 2.5 GW. By late 2024, Italy's grid management company had received authorization applications exceeding 50 GW in Sardinia alone, against a national target of about 70 GW (TERNA, 2023a, 2023b, n.d.).

Since 2023, an increasing number of local committees have emerged in response to the surge in permit applications for wind and photovoltaic projects, denouncing this as a speculative strategy. Protests peaked between the summer and autumn of 2024, culminating both in a broadly supported citizens' initiative bill against new energy infrastructures and in a jurisdictional conflict between regional and national authorities over the allocation of decision-making authority (ANSA, 2024a, 2024b).

Structure Of The Research

The research unfolds in three phases. The first phase involved ethnographic fieldwork focused on the social movement opposing new energy infrastructures. The second phase will be devoted to developing educational tools to engage students in the public debate on the energy transition. The final phase will consist of implementing and evaluating these educational tools directly in the schools of the communities involved in the study.

Figure 1. Sardinia's effective renewable energy capacity.



Fieldwork

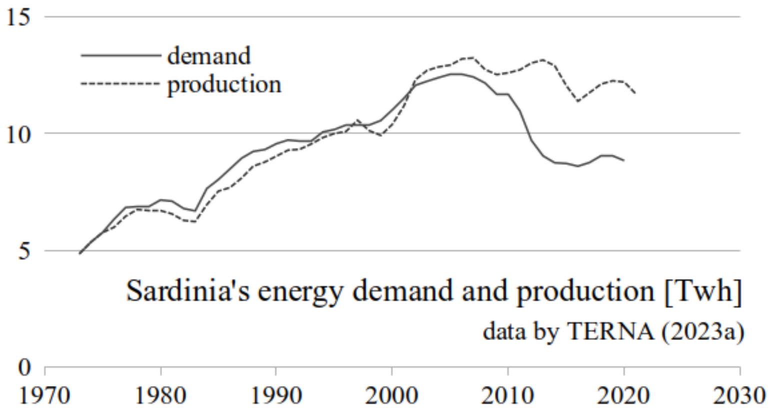
The first step of the research consists of ethnographic fieldwork on social opposition to energy policies. The aim of this inquiry is to provide a qualitative description of these tensions – with attention to the historical, cultural, and economic drivers of the opposition – so that these findings can be brought back to students through interdisciplinary teaching activities.

The fieldwork took place during 2025, over ten months. It was conducted using standard ethnographic methods, primarily participant observation and qualitative interviews. We conducted more than 40 hours of interviews with activists against *energy speculation* (using the movement's own definition), climate activists, teachers, local administrators, and journalists. Interviews followed an open-ended approach, starting from the central theme of the movement and concluding on the role and possibilities of younger generations in the decision-making process. Where possible, interviews were recorded. Conversely, when recording was likely to generate mistrust between the researcher and informants, conversations were summarized in field notes. We also conducted participant observation during street demonstrations and public assemblies, visited various energy infrastructures, and analysed local press and social media communication.

The movement is characterized by the demographic predominance of older adults. It is politically heterogeneous and has gained broad social support, without ideological cohesion but unified by a strong demand for self-determination – and specifically for self-determination in Sardinian energy policies. Criticism is related to a conflict over resources: land as a resource disputed between local farmers and external energy enterprises; similarly, the need to protect landscape and cultural heritage as resources for tourism; and the export of locally generated energy, judged as not sufficiently compensated by essential state services and compensatory schemes. But it goes well beyond this, involving deep symbolic factors tied to Sardinia's historical subordination to the central state, which long acted as a colonial force on the island.

For these reasons, decarbonisation policies are denounced by broad segments of the population as a new form of extractivism – one that, in Sardinia, has left a legacy of environmental degradation, public health issues, slow economic development, and demographic decline (Sorge, 2015). It is not only about the expropriation of material resources: the systematic exclusion of local communities from decision-making processes erodes spaces for dialogic debate and, in turn, leads to the collective expropriation of future-oriented agency, exacerbating social opposition.

Figure 2. Sardinia's energy demand and production.



Theoretical Framework

To support the design of the educational tools, we propose a framework grounded in Horkheimer's critique of instrumental rationality (1947/1974) and its further elaboration in Habermas's theory of communicative action (1981/1984).

In archaic Greece, a society marked by a strict hierarchy, myth held authoritative power over truth. When collective participation in the life of the polis expanded, driven by an emerging bourgeois class, new linguistic practices became necessary. The term logos – which in Homer still denoted a beguiling tale – now came to mean the common ground of discourse, where citizens could voice their demands and deliberate in pursuit of the common good, recognizing their shared belonging to the polis. Throughout its development, philosophical reflection tried to clarify the criteria for good argumentation, a process which culminated in the development of formal logic (Perelman, 2010). This can be understood as a calculative system aimed at determining an argument's validity, so as to arrive – at least ideally – at a unique conclusion to the debate, thereby closing the common ground of discourse.

As Horkheimer observes (1947/1974), when reason is reduced to mere calculation, it ceases to deliberate purposes – evaluating their legitimacy or desirability – and simply focuses on selecting the most efficient means to achieve them. It becomes instrumental rationality, aimed at pursuing goals withdrawn from public debate. Under this perspective, scientific knowledge, rather than guiding social actions toward shared values, offers legitimacy to a technocratic society where democratic dialogue loses influence on social life – a condition that can fuel violent reactions by groups excluded from decision-making processes.

Habermas (1981/1984), building on the early Frankfurt School's critique yet moving beyond it, reworks the notion of rationality into an explicitly communicative framework. Alongside purpose-oriented rational action (instrumental or strategic), he introduces the concept of communicative rational action, defined as linguistic practices aimed at mutual understanding. According to Habermas, the central conflict in contemporary society is no longer the class struggle but the conflict between instrumental rationality and communicative rationality, that is, the tendency of systemic rationality to colonize the communicative actions of a community, which he terms the lifeworld (adopting Husserl's terminology).

Instrumental And Communicative Rationality In Science Education

We propose to interpret the tensions between local communities and the development of new energy infrastructures as a conflict between communicative rationality and instrumental rationality. If we accept this interpretation, it has significant implications for the design of teaching activities.

A science education entirely limited to instrumental rationality necessarily excludes students from any reflection on purposes, allowing only the calculation of efficient means to achieve predetermined goals as legitimate educational practice. Nevertheless, teleological reflection – such as critical inquiry into future scenarios – is essential to cultivate a future-oriented agency, which in turn is a prerequisite for addressing the current global crisis (Laherto & Rasa, 2022). Moreover, such an approach can degenerate into a form of strategic action, treating students as means to predefined ends – for example, the promotion of a specific energy policy. Thus, the same tensions driving social conflict may manifest within the school community, resulting in a biased rejection of scientific discourse.

We therefore ask whether science education practices can be oriented toward the ideal of communicative rationality, useful for deliberating on ends and not only for calculating more efficient means. We will explore this line of research by providing educators with tools to represent the complexity of the social issues involved in the conflict.

Future Steps

Engaging local communities in decision-making remains challenging, as it requires not only public spaces for collective deliberation, but also analytical tools accessible to non-specialists to evaluate alternative transition pathways. The next stage of the research will involve developing a computational model, adapted for educational use, to represent the range of possible decarbonization pathways available to policymakers.

Previous work has shown that the use of complex systems simulations in educational contexts can enable students to critically explore alternative future scenarios (Barelli, 2022; Fabbri, 2021; Miani, 2025). Building on this line of research but seeking specific tools to address issues related to the low-carbon transition, we have focused on a particular type of energy system model.

Planning a decarbonized electricity system involves complex choices due to multiple technological options and sociopolitical constraints. Energy-system design typically relies on cost-optimal models, which may neglect other viable system configurations and overlook social factors essential for political feasibility. The Modelling to Generate Alternatives (MGA) approach, rather than identifying a single cost-optimal solution, explores the space of sub-optimal solutions to generate qualitatively different configurations. This wide range of energy alternatives provides a deliberative space for policymakers and local communities (Lombardi, 2020).

Our aim is to adapt these tools for educational use, allowing students to engage in energy-system design, acquire knowledge repertoires, and support debate among peers, within families, and ideally within their communities.

In the final step, we will test the developed educational tools directly in the schools of the communities involved in the study. Social tensions triggered by the energy transition will be framed as topics for interdisciplinary inquiry, drawing on ethnographic findings and the energy-system model. On this basis, students will be asked to elaborate sustainable and desirable future scenarios and to participate in the public debate within their communities, according to the future-oriented science education approach (Laherto et al., 2023; Levrini, 2019)

Conclusions

Finally, we will evaluate the reception, outcomes, scalability, and potential for further development. We will also assess to what extent these educational experiences contribute to redefining how scientific knowledge becomes embedded in local social life. If these experiences prove capable of fostering students' engagement in the public debate on the energy transition, they will be consistent with the ideal of communicative rationality.

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Greek Chemistry Teachers' Perspectives On The Integration Of Green And Sustainable Chemistry Practical Activities In Secondary Education

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Green and sustainable chemistry, aimed at minimizing environmental impact and supporting resource efficiency, has gained significant attention in recent decades. This shift has promoted a strong global community of practitioners and advocates, and increased interest in integrating these principles into school and university education. While various strategies have been developed to incorporate green and sustainable chemistry into curricula, there is limited data on the extent of its integration across different countries. This study examines the integration of green and sustainable chemistry into secondary education in Greece, with a focus on practical activities conducted by chemistry teachers. Data were collected from 92 teachers via an online questionnaire, developed for an international survey by the International Union of Pure and Applied Chemistry (IUPAC). Participants reported that averagely 29,9% of their practical activities incorporated green and sustainable chemistry. Moreover, they highlighted the importance of such activities in promoting critical thinking and problem-solving skills, and introducing green chemistry and sustainability through hands-on activities. However, some teachers reported not incorporating such activities, reflecting challenges in integration. Our findings highlight the increasing role of green and sustainable chemistry in education and underline the need for further research concerning its integration into curricula and teaching practices.

Keywords: Secondary education, sustainability, teacher beliefs

Introduction

In an era of growing environmental concern, green and sustainable chemistry has gained substantial interest, leading to the establishment of a robust community of practitioners and advocates within the global chemistry field. Green and sustainable chemistry adopts a holistic perspective through life-cycle analysis and systems thinking, ensuring that sustainability is considered at every stage – from raw material sourcing to product disposal. This comprehensive framework not only advances scientific innovation but also aligns with broader global goals, such as dealing with climate change, conserving resources, and enhancing economic development in harmony with environmental protection (MacKellar et al., 2020).

Green and sustainable chemistry refers to the concept of designing processes and products that improve the way natural resources are used to meet the needs of present and future generations, without causing harmful impacts on humans and ecosystems. It is guided by specific principles that emphasize environmentally friendly methods for conducting chemical reactions and producing chemical products. These principles promote practices such as using environmentally friendly auxiliaries like solvents for reactions and separations and streamlining processes to reduce the number of steps. These ideas form the core of green chemistry, focusing on more sustainable and efficient chemical production (Anastas & Zimmerman, 2019; Clark, 2016).

Over the years, various strategies have been employed to incorporate the principles and practices of green and sustainable chemistry into the chemistry curriculum in secondary education and undergraduate studies. Concerning the latter, some universities have developed independent, stand-alone green chemistry elective courses, others have fully integrated green chemistry principles throughout their entire chemistry curriculum, and some universities have incorporated green chemistry laboratories as substitutes in laboratory courses (MacKellar et al., 2020). Concerning school education, four basic models of integrating green and sustainable chemistry have been developed: (a) integrating green and sustainable chemistry practices into school chemistry practical activities, (b) integrating green and sustainable chemistry practices as core content within the chemistry curriculum (c) using socio-scientific issues related to sustainability and chemistry as a foundation for learning chemistry and understanding the relevance of green and sustainable chemistry to sustainable development, and (d) using sustainability as a driver for school reform, transforming school life in alignment with sustainability principles, including aspects related to chemistry and its applications (Burmeister et al., 2012).

Focusing on school education, we note that despite the various strategies that have been developed to incorporate the principles of green and sustainable chemistry into the curriculum, it seems that there are not enough data concerning the extent of this integration across different countries. The present study was conducted as part of a global survey coordinated by the International Union of Pure and Applied Chemistry (IUPAC) (Delaney et al., 2024) and aims to investigate the integration of green and sustainable chemistry practices into chemistry practical activities within secondary education in Greece. The research questions addressed are the following:

RQ1: What percentage of the chemistry practical activities that teachers conduct is connected to green and sustainable chemistry approaches?

RQ2: Which factors do teacher consider important when choosing chemistry practical activities to do with their class?

RQ3: Where do teachers normally obtain their chemistry practical activities related to green chemistry and sustainable chemistry?

Methodology

The data of this study were collected through an online questionnaire created within an international IUPAC project (Delaney et al., 2024) and translated into Greek by the authors of this paper. The questionnaire included items concerning the integration of practical activities into teaching of chemistry in general, the integration of green and sustainable chemistry practical activities into teaching of chemistry in particular and demographic questions. The questions included were open and closed ended. Here we are concerned with the part of the questionnaire that deals with the integration of green and sustainable chemistry practical activities into chemistry teachers' practice. More specifically, we report on three closed ended items that concern (a) the percentage of practical activities implemented by teachers that are related to green and sustainable chemistry approaches, (b) the factors that teacher consider important when they choose chemistry practical activities to do with their class, and (c) the sources that the teachers use to obtain green and sustainable chemistry practical activities.

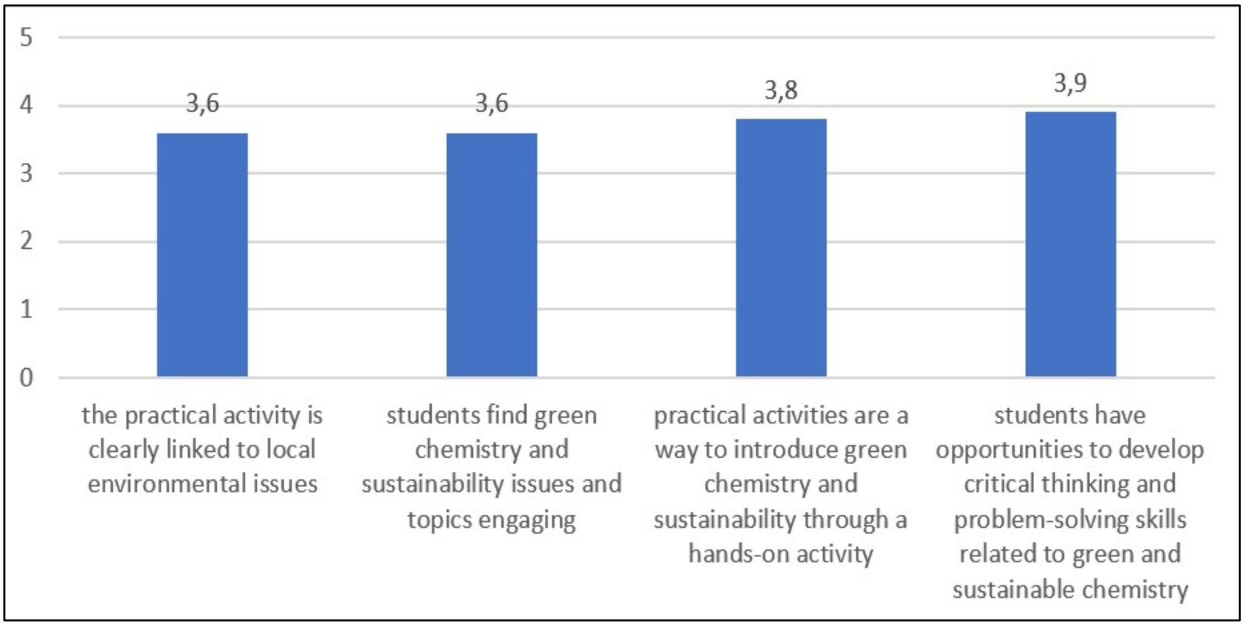
For the first item, participants had to choose the percentage of practical activities they did with their class which was related to green and sustainable chemistry approaches using a slider. For the second item, participants had to answer about the importance of four factors when choosing chemistry practical activities to implement into their teaching using a 5-point Likert scale. More specifically, they had to answer whether the following factors were "not at all important" (1), "slightly important" (2), "moderately important" (3), "very important" (4) or "extremely important" (5) when choosing practical activities to use in class: (i) the practical activity is clearly linked to local environmental issues, (ii) students find green chemistry and sustainability issues and topics engaging, (iii) practical activities are a way to introduce green chemistry and sustainability through a hands-on activity, and (iv) students have opportunities to develop critical thinking and problem-solving skills related to green and sustainable chemistry. Finally, for the third item participants had to answer how they obtain green and sustainable chemistry practical activities among the following choices: (a) learned from other teachers, (b) learned during university studies/teacher training (pre-service), (c) learned during professional development after starting teaching career (in-service), (d) read about in a magazine or online, (e) heard about at a conference, (f) designed myself, (g) other, (h) I do not consider green or sustainable chemistry activities in my teaching.

The part of the questionnaire that concern us in this paper was filled in by 92 teachers teaching chemistry in secondary education in Greece. They were selected by convenience sampling (Bryman, 2012) and they agreed to participate in the study after receiving (i) detailed information about the study's objectives, and (ii) confirmation that their participation would remain anonymous. Concerning their experience in teaching chemistry, 7 teachers answered that it was their first year, 13 teachers had 2-5 years of experience, 25 teachers had 6-15 years of experience, 38 teachers had 16- 30 years of experience, and 9 teachers had more than 30 years of experience. Finally, 12 teachers stated that they were currently teaching in Grade 7, 33 teachers were currently teaching in Grade 8, 35 teachers were currently teaching in Grade 9, 56 teachers were currently teaching in Grade 10, 52 teachers were currently teaching in Grade 11, and 59 teachers were currently teaching in Grade 12. It should be noted that in most cases the participating teachers were teaching in more than one Grade in order to complete the required schedule.

Results

The mean percentage mentioned by participants concerning the implementation of green and sustainable chemistry practical activities was 29,9. It should be noted that the standard deviation was quite large (26,9) indicating that there was a high level of variability within their answers.

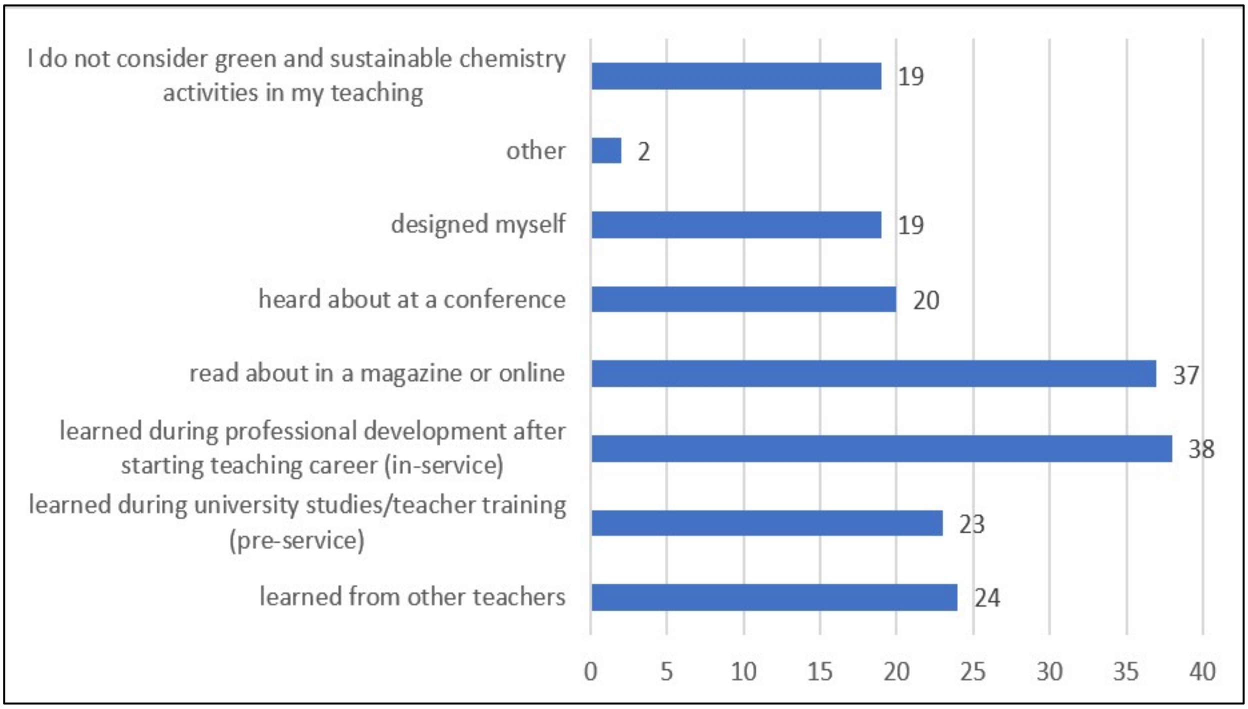
Figure 1. Average importance of factors concerning selecting practical activities for classroom use.



Regarding the factors that the participants considered important when choosing practical activities, it seems that the most important factor was that through them students have opportunities to develop critical thinking and problem-solving skills related to green and sustainable chemistry. We noticed that averagely all factors that had to do with green and sustainable chemistry were considered rather important by the participating students concerning selecting practical activities for their teaching (Figure 1).

Finally, concerning the sources that teachers use in order to obtain green and sustainable chemistry practical activities, it seems that the most popular ones are continuing professional development programs (38) and magazines/online sources (37). It is worth noticing that several teachers answered that they do not consider green or sustainable chemistry activities in their teaching (19) (Figure 2).

Figure 2. Frequencies of sources that teachers use in order to obtain green and sustainable chemistry practical activities.



Discussion

Green and sustainable chemistry has gained significant attention in the last decades, enhancing the development of a strong community of practitioners and advocates in the global chemistry landscape. Moreover, it seems that a strong interest in ways to integrate the approaches of green and sustainable chemistry into education has also been developed (Dicks & Bastin, 2019). Green and sustainable chemistry education has been present in educational research and practice already from 1990s. Zuin et al. (2021) researched the number of papers that concerned green and sustainable chemistry education and reported that more than 500 papers were available in the literature spanning a period from 1998 to 2021. Most of them focused on developing curricular materials and evaluating student learning outcomes and attitudes. Discussing their results, the authors concluded that various institutions have created tools and resources to facilitate the integration of green and sustainable chemistry into high school and even elementary education.

While several strategies have been developed to embed the principles of green and sustainable chemistry into curricula, there appears to be a lack of sufficient data on the extent of this integration across various countries. In this study we investigated Greek chemistry teachers' practice and ideas concerning green and chemistry practical activities and some interesting results arose. For example, it seems that a considerable percentage of the practical activities conducted in their class concerns green and sustainable chemistry approaches. Moreover, participants seem to find the dimension of green and sustainable chemistry rather important when they choose practical activities to implement into their teaching. For instance, they averagely assigned a 3,9 score (ranging from 1 "not at all important" to 5 "extremely important") to the importance of practical activities offering students the opportunity to develop critical thinking and problem-solving skills related to green and sustainable chemistry.

Finally, regarding the sources that participants use in order to obtain green and sustainable chemistry practical activities, it seems that the most popular one was continuing professional development programs. This may not agree with relevant literature at certain level, since chemistry teachers around the world seem to mention the lack of in-service training as a main barrier to integrating green and sustainable chemistry content into their teaching (MacKellar et al., 2020). Other popular source of green and sustainable chemistry practical activities were magazines and online sources, while fewer participants stated that they obtained a practical activity by attending a conference or they designed it themselves. We should note that some teachers reported not incorporating green and sustainable chemistry practical activities in their teaching, reflecting challenges in integration.

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Science Teachers' Democratic Assignment: A New Vision Of Scientific Literacy And Civic Engagement For A Futuristic, Fair And Sustainable Europe

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There are calls today from several directions, including from UNESCO 2021 for a new social contract for education, and by implication science education. This begs the question what this might mean for the framing of scientific literacy and civic engagement in a futures-oriented Europe, aspiring for fair and sustainable green and digital transitions. This newly desired subjectivity, centred on repairing former colonial injustices, requires reimagining a new vision of scientific literacy and civic engagement, one that is attentive to human emancipation, and to the knowledge(s), cultures, ethical values, care and justice needs of a fair and sustainable economy, society and environment. Here I draw from Mooney Simmie and Edling's (2019) theorisation of Teachers' Democratic Assignment (TDA), Giroux (1988/2024) and Hordern's (2024, 2022) theorisations of teachers' identities and knowledge base, and Bang's (2017) assertion of the ontological indeterminacy embedded in science education. I use these theoretical perspectives to critically scrutinise the mainstream framing of scientific literacy and civic engagement, and to consider the exponential growth in the literature of an alternative emancipatory framing of science TDA for learning to live well with others in pluralistic democracies. The study reveals a reframing of science TDA in the direction of a knowledgeable, care-based, critically reflexive and activist citizenry in a highly complex, scientific and technological world. The emerging critical insights reveals that reframing science TDA needs to move beyond evidence and externally provided norms and to include the interruptive power of the arts, humanities and the deliberative traditions.

Keywords: *scientific literacy, civic engagement, science teachers' democratic assignment*

Introduction

Since the start of this century, and the policy imperatives embedded in a fast-globalising education reform movement, the education and training of science teachers, their identities and knowledge base, are often defined within reductionist views of science teacher's responsibilities in relation to the preparation of young people for a life of active engaged citizenship. While citizenship, and becoming a citizen, rests on a political concept of membership of a nation state, the concept in general education today, and in science education is more often framed as a neutral and apolitical concept unrelated to power and privilege and whose interests are being served. It may well be that, working within the boundaries of the nature of science, and scientific pedagogies, science teachers' task is confined to primarily providing a scientifically literate population, for the ever-changing qualification and socialisation needs of the economy and society (e.g. the pipeline of talent) and within an appreciation of science-in-society and real-world applications.

Levrini et al. (2025) argue the this mainstream framing of science education is underpinned by a rather naïve positivistic framework, where there appears to be little or no requirement for science teachers to engage young people with the messiness of real world ethical, scientific and political dilemmas and/or to build capacities to interplay with other knowledge(s) and ways of knowing (e.g. cultural and historical memory) in order to critically question, debate and debunk issues of public interest values (e.g. climate change) so pertinent today for the successful future of democratic societies and the planet.

There is already a pressing need recognised by the European Commission in Europe to reframe education and skills, and by implication the relations between scientific literacy and civic engagement for a futures-oriented fair and sustainable green and digital transition (Mooney Simmie, 2025b). How this is to be done in theory, policy and practice remains an open question and one this is increasingly complicated by the neoliberal imaginary underpinning science education, including scientific literacy and science teachers' work practices (Mooney Simmie, 2025a, 2023). Neoliberalism continues to act as a highly successful and hybridised project of governance in science education today. Sant (2019) reveals that this political project of governance relies on an ideological governing form that is anti-democratic at heart and based on the normalisation of elite ruling by (scientific) experts and market leaders. Neoliberalism therefore frames science teachers' knowledge base and practices in the direction of evidence-based and standardised practices, all known in advance, manageable and measurable (Mooney Simmie & Tolbert, 2025).

This neoliberal framing of science education is taking place at a time of unprecedented change in Europe, a time of marked increase in the rise of injustices and fascist ideologies. The historian, Gerstle (2024) argues that the neoliberal social order, rising to prominence in the 1980s nowadays reveals serious fault lines, especially since, the global recession in 2008-2009, the rise of technoscience and the unprecedented threats to the western economy and democratic politics by the Trump administration in the US (Tolbert, 2025).

UNESCO's *Reimagining Education Report* (2021) asserts a new urgency for general education, and science education, to arrive at a new social contract and to build capacities to repair past injustices of colonisation. The UN Sustainable Development Goals act as a blue print for this social contract that aspires, amongst others, to end poverty, secure climate justice and digitisation through empowering new transformative social partnerships. The American philosopher of education, John Dewey, asserted that democracy is remade with each new generation and that education, and science education, always acts as the mid-wife of democracy (Dewey, 1916/2024). This begs the question how democracy is discerned in science education, and in science teachers' felt sense of obligation to democracy, in a future-oriented science education and its relation to scientifically literate and activist citizens.

Theoretical Perspectives

Here I draw from critical and feminist perspectives to frame the problem of *Science Teachers' Democratic Assignment* (STDA) as a sociological problem connected to the teachers' obligation for a humanising and (re)constructivist discourse of science education embedded in a relational ethic of care and justice, in theory and in practice (Mooney Simmie & Edling, 2019). From this way of reasoning democracy is positioned as an ever-changing politics in the wider society whose purposes, principles and practices change as change is needed in the economy, society and the environment. Unlike systems of majority rule, democracies by design are always in the political direction of equality, diversity and justice, with stated protections for the rights of minorities.

A feminist perspective places the human subject (subjectivity) at the heart of science education as a relational and dialogical practice that pays attention to the situational and the interplays between knowledge(s) and different ways of knowing, In this way, a critical and feminist framework for science education positions science teachers' identities, knowledge base, and work practices more as a cultural problem – with science teachers as public intellectuals with cultural responsibilities and obligations rather than as clinicians, technicians and/or as mere delivers of instruction for a system of compliance (Giroux, 1988/2024; Howie, 2020).

While Levrini et al. (2025) reveal the naïve positivism underpinning the mainstream framing of science education and scientific literacy today, the science educator Lars Bang draws on the postmodern work of Deleuze to reveal the necessary ontological indeterminacy and crack at the heart of science education (Bang, 2017). This way of reasoning is further supported by the theorisation of the science educator, Jesse Bazzul, who starts from the paradoxical premise that the purposes of science education are multiple and contradictory, that can be grasped as a perpetually open ethical question that seeks to, on one hand conserves culture and heritage, and on the other, leaves the way open for the new to emerge.

What might this mean for science teachers' knowledge base today and for a future of uncertainty? Will it be sufficient for science teachers to have access to constant upskilling and reskilling in content knowledge (e.g. knowledge of science and science pedagogies), and externally provided norms and values, or will something else be needed? Given that feminist perspectives foreground intersectionality, the human at the centre and the relational capacity for teacher-student dialogue, and critical theories highlight the need to develop critical consciousness, for the affective equality needed for the greater good of society and public interest values (Lynch & Crean, 2019), then policies of content knowledge and externally provided norms, while necessary will be far from sufficient to assure scientific literacy works for a futures-oriented citizenship tasked with human emancipation, and the greater good of fair, sustainable and care-based pluralist democracies and eco-friendly environments.

In teasing out teachers' knowledge base today, drawing for the concept of teaching as an advanced professional practice, Hordern (2022, 2024) presents a three-dimensional concept that aligns well with the argument above. Hordern theorised that (science) teacher's knowledge base is nuanced and sophisticated and calls on knowledge(s) and different ways of knowing that needs access to three distinctive sources: (1) the sciences (2) the arts and humanities and (3) the deliberative traditions.

This three-dimensional concept of science teachers' knowledge base accepts the premise that science teaching needs access to the sciences for sense making practices, to the foundational disciplines in the arts and humanities - such as, philosophy, history and sociology – for strange making practices, such as, interruption of the discourse to leave spaces open enough to think otherwise, for the not-yet-thought, to sap power, and finally, access to the deliberative traditions, so that science education is understood as a holistic and dynamic practice for a desired subjectivity that is considered to be more than the sum of the parts.

Aims And Research Questions

This contested literature opens new spaces for reclaiming and reframing scientific literacy and civic engagement, and especially for consideration of what it means to be a desired human subject today (subjectivity) in a complex and highly scientific and technological society. The study therefore aimed to conduct a critical scrutiny of a select literate, albeit a limited and small scale study of the contemporary literature to better understand how fresh calls for a new social contract today in science education for a fair and sustainable Europe need to play out differently from a neoliberal imaginary and what this might mean for science teachers' knowledge base and for a new and different vison of science teachers' democratic assignment (STDA).

Findings

The framing of the purposes of science education in the life of the young person in schools today, and its relation to the journey of human becoming (subjectivity) as a scientifically literate, engaged and active, if not fully an activist, citizen is deeply contested in the literature of science education. What started off in the 1950s, as a desire for a scientifically literate general population, with a positive disposition toward science, and to support publicly funded scientific research has changed, even if not dramatically, to different visions of 'scientific literacy', and also found in such concepts as contextualised images of Science-in-Context, and Science-in-Society and more recent notions of 'citizen science', 'transformative science' and 'argumentation'.

The concept of scientific literacy itself has gone through multiple iterations since the 1950s (Bybee & Mc Crea, 2011, Roberts, 2007). The rationale behind the concept was to develop an uncritical appreciation of science and science research and to identify a pipeline of elite talent (abstract thinkers) to enter career pathways in the sciences, and as researchers connected to economic competitiveness and national security. The first vision, Vision I centred on propositional knowledge, while the more recent vision, Vision II while connected to contexts and to real world applications was largely confined to a notion of human becoming that Bang (2017) identified as a 'Cartesian understanding of knowledge and Cogito, the Dogmatic Image of Thought' (p.810). More recently, a third vision, Vision III seeks to reclaim science education as a human centred and socio-cultural endeavour, a sociological project whose rationale in concerned with supporting a transformative view of science education. Sjostrom & Eilks (2021) present Vision III as a *Critical Reflexive Scientific Literacy,* drawing from the Northern European concept of *Bildung* and its connection to holistic traditions for an expansive notion of education for human development in the wider world rather than confined to curriculum studies.

Ast the same time as the ongoing development of scientific literacy for a new vision of a scientifically literate citizenry, Bencze et al. (2020) reveal the forty year history of struggle in the science education literature and in globalising reforms, reframing a rich variety of constructs seeking to connect school science to society and the wider world, such as *Science-in-Context*, *Socio-Scientific Issues* (SSI) and *Critical Science Questioning*.

More recently, the science education literature and policy reforms are framing new notions of 'citizen science' and 'argumentation' as novel ways of reconnecting science and scientific literacy to new notions of engaged citizens, often apolitical notions of what it means to be a citizen in a nation state and/or in the wider global world today. For example, a study by McNew-Birren & Gaul-Stout, 2022) taking pace in an urban research centre in Milwaukee, Wisconsin in the US constructed 'citizen science' and positioned citizen volunteers as additional place-based 'data gatherers' for the research centre, provided with the necessary resources of equipment and technical training, rather than any collectivist (political) notion of citizenship in relation to how ethics, science, and politics plays out for the greater good of society, economy and the environment. In a similar, and related construct, a notion of 'argumentation' in science education is currently employed for debating socio-scientific issues while drawing only from science, analytical thinking, data and empirical evidence. Kim & Roth (2018) reveal the process involved when children and young people are coached in higher order thinking to support these domain specific skills of argumentation. In this way, the concept of 'argumentation' appears tightly confined to Bang's (2017) 'dogmatic image of thought' where right answers are valued, dialogue with other ways of knowing are closed down, and there is no recognition of the necessary ethical and political dilemmas and/or struggles with multiple knowledge(s) and different ways of knowing. In this regard, the diversity of new constructs seeking to connect scientific literacy to the development of engaged citizens today, largely disappoints given that they are often under-theorised and assume a normative consensus (Mooney Simmie & Tolbert, 2025).

A New Social Movement Reimagining Science Education

At the same time, there is also a deeply contested science education literature, and a growing global social movement, involving science education researchers in the US, New Zealand, Australia, UK and Canada with advocacy for Reimagining Science Education in the Anthropocene – the term given to the geological footprint in the planet largely coming from manmade exploitation of the Earth's natural resources (Tolbert et al., 2024; Wallace et al., 2022). This fast-globalising social movement reveals inherent dangers in viewing science education and its relation to society and the planet in reductionist ways. Instead, they advocate for a philosophically grounded and problem-posing approach to science education which can humanise the discipline and leave sufficient open spaces for scientific, critical and reflexive literacies and futures thinking about the importance of scepticism in science education and its ethical and political relation to personal, social and planetary justice.

Critical pedagogy researchers in science education, such as Hodson (2003), and feminist thinkers in science education, such as Colucci-Gray (2014) reveal how novel concepts in science education, scientific literacy and civic engagement are all hampered in different ways by the rather naïve positivistic framing of science education that continues to persist in mainstream policy and research in neoliberal times (Bang, 2017; Bazzul, 2023; Levrini et al., 2024). Howie (2020) a school principal in Australia shows how this political project frames education and teaching for compliance and self-imposed responsibility rather than agency:

In closing down dialogue and setting normative standards, an evidence hierarchy is inherently anti-democratic, as it closes the public space, so to speak, reducing social relations to obligation. The barriers of the political-administrative establishment go up around the public educational research space. What should be open to question and not reductively represented as self-evident, including research methodologies and outcomes, are standardised and ranked (p.683).

Discussion And Conclusions

The selected theoretical lens used here became a powerful explanatory framework for interrogating the contemporary problem of how to reframe scientific literacy and civic engagement in ways that are actively connected to the socio-scientific, ethical and socio-political issues of the moment, and for a futures-oriented, fair and sustainable Europe. Based on the critical insights emerging, albeit from what was a small scale study of a select literature, a number of key research questions emerged that can guide this new framing of STDA in a future of uncertainty, where science will need to play out in a futures-oriented science classroom in ways that are problem-posing, philosophically grounded, and connected to the critical consciousness needed for the greater good of a desired subjectivity, society and planet (Mooney Simmie & Moles, 2025)

Starting with Hordern's (2022, 2024) rubric, any reframing of STDA will clearly need to draw from the three-domains of science teachers' knowledge base in ways that are inclusive of the meaning-making and interruptive power of the sciences, arts and humanities respectively, as well as the deliberative tradition that secure the holistic and dynamic nature of science education. Besides, any new framing of scientific literacy and its connectivity to civic engagement will need to offer affordances for critical appraisal of the power and limits of evidence and rely on an interplay with a rich variety of literacies found, for example, in the sciences, ethics, politics and in ways that can release the transformative potential of the learner for care based, fair and just sustainability (Colucci Gray 2014).

In conclusion, the following key questions emerged from the study as a preliminary way of distinguishing between a neoliberal framing of STDA for compliance with the contemporary social order (status quo), or for affordances for human emancipation and a futures-oriented fair, just and sustainable economy, society and planet:

How are science teachers' democratic assignments (STDA) framed - as a problem-solving exercise or as a philosophically grounded problem-posing exercise?

Are science teachers expected to interplay with other literacies, values, cultures, knowledges and different ways of knowing in relation to the necessary (scientific, ethical and political) struggles with contemporary issues in the wider world?

Are science teachers expected to engage in the deeply personal work of critical reflexivity to improve their self-awareness and justification of selections?

Are science teachers required to challenge and to move ('affect') their students to action (affectivity) in relation to socio-scientific issues of injustice in the wider world?

Are science teachers expected to develop students' capacities for an appreciation of science-in-society and/or for a critical appraisal of the power and limits of science?

The critical insights emerging suggest that a problem-posing and transdisciplinary approach is needed in any new reframing of science teachers' democratic assignment (STDA), a framing that will need to be inclusive of the sciences, the arts and humanities for the necessary productive clashes between their sense-making and interruptive powers, and the deliberative traditions. This supports Bang's (2017) assertion of ontological indeterminacy and the need to hold any new framing of scientific literacy and civic engagement open to scrutiny and problem posing while providing productive pedagogical spaces in the science classroom and school for dialogue, critical debate, and provocation for eliciting self-awareness, agency and action to occur.

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Empowering Children As Agents Of Climate Action: A Case Study Of A Teacher's Enactment Of Socio-Scientific Inquiry-Based Learning In A Kindergarten

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Kindergarten-aged children, although often considered to be too young, have the right to know about the uncertain world they are living in and to have their voices heard in climate action. Climate change education equips students with the knowledge, skills and values of climate change, and empowers students for climate change mitigation and adaptation. However, children in kindergartens tend to receive less education in climate change compared to other school periods, and teachers often lack the subject knowledge and teaching skills needed to address climate change with kindergarteners. To explore how early childhood teachers can enact climate change lessons in age-appropriate ways, we implemented a teacher professional development programme, which supported teachers to enact four climate change lessons based on the socio-scientific inquiry-based learning (SSIBL) approach consisting of three stages (Ask, Find out, and Act). In this proposal, we present a qualitative case study focusing on how one teacher enacted her lessons in a kindergarten in Shanghai, China. Semi-structured interviews, lesson video recordings and teacher's reflection journals were collected and analysed qualitatively. The findings of instructional strategies the teacher used in each SSIBL stage are: (1) Ask - the teacher created a need to know with personally and locally relevant topics about climate change; (2) Find out - the teacher used iconic representation to help children concretise their reasoning process in personal inquiry, and used a sensory approach in scientific inquiry to teach abstract scientific knowledge; (4) Act - the teacher encouraged children to take indirect climate action through family or community stakeholders.

Keywords: climate change education; early childhood science education; socio-scientific inquiry-based learning

Introduction

For the sake of addressing climate change urgently and promoting sustainable development, the United Nations (2017) proposes to empower climate action through education such as curriculum inclusion and teacher education. Climate change education (CCE) entails equipping students with knowledge of the concepts, causes, impacts and solutions related to climate change, as well as the skills, values and attitudes needed to empower them for climate change mitigation and adaptation at local and global scales (Hung, 2014; Kavanagh, Waldron and Mallon, 2021). Young children are more likely to act in a pro-environmental way than they are in later life (Collado et al., 2015), making this period critical for CCE by developing their knowledge and attitudes and building the foundation for future learning. However, the challenges posed to young children by complex and abstract knowledge (Copple and Bredekamp, 2009) and the lack of teachers' relevant background knowledge (Kavanagh et al., 2021) might be reasons that inhibit CCE in early childhood education.

Climate change as a socio-scientific issue (SSI), involves controversial opinions on how it impacts society with a connection to scientific concepts and applications (Zeidler, 2014). In this research, the pedagogical framework of socio-scientific inquiry-based learning (SSIBL) (Levinson, 2018) is adapted by teachers to enact climate change lessons. SSIBL has three practical stages: (1) Ask - asking authentic questions and creating a need to know related to SSI; (2) Find out – finding the evidence for answering the questions through inquiry-based learning, which includes scientific, social and personal inquiry; (3) Act – taking action to address SSI.

SSIBL involves integrating SSI into classroom teaching that leads to action-oriented CCE where children are empowered to make informed decisions and take action.

To address the scarcity of CCE studies in early childhood, this research explores the strategies of teaching about climate change used by a kindergarten teacher, with support from a teacher professional development (TPD) programme that included the subject knowledge of climate change and the teaching skills aligned with SSIBL. The overall research question was: What strategies do an early childhood teacher use to enact climate change lessons based on the SSIBL approach?

Methods

Teacher Professional Development Programme

In accordance with Desimone's (2009) five core features of the effective TPD programme - content focus, active learning, collective participation, coherence and duration - we developed a TPD programme that consists of four workshops, to prepare teachers with the subject knowledge of climate change (Workshop 1) and the SSIBL pedagogy (Workshop 2) for enacting the climate change lessons. Workshops 3 and 4 facilitated teacher's reflection on what they had done and for improving lessons. Teachers attended Workshops 1 and 2 before they selected teaching topics related to climate change and then co-designed the four lesson units. Following that, teachers enacted Lessons 1 and 2 before they attended Workshop 3 and enacted Lessons 3 and 4 before Workshop 4. The programme spanned four months, from March to June 2024.

Participants And Data Collection

This study is a qualitative case study. Four teachers participated in the TPD programme, but in this proposal, we focus on one teacher's experience for an in-depth analysis. The teacher had been teaching in kindergarten for 11 years and was working with children aged 5-6. This teacher had been living in Shanghai for 39 years and had some familiarity with the impacts of climate change that Shanghai experiences. The research context was a public kindergarten in Shanghai, China, that follows the governmental kindergarten educational policy of enacting inquiry-based science learning.

Data were collected through semi-structured interviews, lesson video recordings, and the teacher's reflection journals to explore how the teacher enacted the action-oriented climate change lesson with the SSIBL approach in kindergarten. Three semi-structured interviews were conducted. The initial interview was conducted before the TPD programme, to find out about the teacher's background and her understanding of climate change and inquiry-based learning, so that the workshops can be designed to better support their subsequent lesson enactments. The mid-interview was conducted after Lesson 2, focusing on the teacher's rationale for choosing teaching topics and enacting certain instructional strategies of Lessons 1 and 2. At the end of the programme, the teacher's rationale for certain instructions of Lessons 3 and 4 was explored in the final interview. Four lessons were video-recorded to observe what and how the teacher enacted in the classroom. The interviews conducted after observing the teacher's lesson enactment can improve the reliability of interpretation (Desimone, 2009). Teacher reflection journals were recorded throughout the TPD programme and focused on her experience and feelings about lesson enactments and participation in workshops.

Data Analysis

The interviews and teachers' reflection journals were analysed by thematic analysis (Terry et al., 2017). The lesson video recordings were first segmented into episodes based on activity, and then the activity contents were summarised. Secondly, the lesson recordings were transcribed into written documents, and the classroom discourse was coded based on two frameworks. One framework focuses on the dimensions of SSIBL, such as the codes ‘Contextualise the controversy to a locally/personally relevant experience’ ‘Encourage action taking through indirect action’ etc. The other framework is about accountable talk (Michaels et al., 2008). The teachers’ talk moves were coded deductively from this framework to represent the functions of the discourse and how it interacts with SSIBL. Sequentially, the codes were categorised by the three stages of SSIBL (Ask, Find out and Act), to explore what strategies the teacher used for each SSIBL stage in CCE within a case. The rationales for the teacher’s use of the strategies were compared with the data from interviews and reflection journals.

Findings

The analysis revealed the teacher’s strategies for CCE in early childhood based on the SSIBL approach. We present the strategies of how the teacher enacted each SSIBL stage (Ask, Find out and Act) for teaching climate change to her 5-6-year-old class of 15 children.

(1) Ask stage: Creating the need to know by contextualising locally and personally relevant controversy related to climate change

The teacher asked the children to survey the local neighbourhood regarding the changes of green spaces being replaced by car parks before the lessons. As shown in Table 6.1, the teacher illustrated the dilemma that existed in the neighbourhood with pictures (turn 5), and raised an open question ‘Should we build car parks or green spaces in the community?’ (turn 7) to invite children’s ideas for further inquiry activities. She introduced the issue from real life that is personally and locally relevant to young children, to create a need to know related to climate change.

Table 1. The Ask stage in Lesson 1 was implemented by the teacher.

Turns	Speaker	Lesson discourse	Codes
5	T	Oh, this is the community being renovated, right? The neighbourhood committee issued a notice. This notice, said that the neighbourhood was going to be renovated. What was being renovated? Some parents of children said that there are not enough parking spaces in the neighbourhood, and they want to add more parking spaces. Some people said that they like greening, right?	Contextualise the controversy to a locally/personally relevant experience; Raise authentic/open questions; Invite students to express personal opinions;
6	T	So let’s have such a voting [activity].	
7	T	Hey, do you think we should add more parking spaces or increase green spaces?	

The teacher elaborated on the importance of personal experiences when discussing her rationale for choosing this topic and designing such an activity in her mid-interview:

> ‘Neighbourhood conversion is something this area has been going through recently, so I think that personal experience is more useful to inspire children to learn more about this [climate change] topic.’

(2) Find out stage: Iconic representation (e.g. drawings) serves as a communication tool, helping young children concretise their reasoning process in personal inquiry

The teacher gained additional information about children's opinions through their drawing, in terms of their choice of keeping car parks or green spaces, to press for further reasoning, as shown in the example in Table 2.

Table 2. Analysis of the teacher's lesson discourse in personal inquiry in Lesson 1.

Turns	Speaker	Lesson discourse	Codes
38	T	Which child drew this point of view [in the picture]? I will invite him to talk about it.	Iconic representation Encourage reasoning
39	S7	My family has a car, so I want to draw a parking garage. There are always many parking spaces in my community, but they are all taken by other people, so I want to build a parking garage.	Invite students to express personal opinions (say more)
40	T	Well, she built a parking garage here, so why is there green on it [car park -the bottom right part of Figure 6.2.2]?	Support students in deepening their reasoning drawing on everyday life
41	S7	I think the parking garage is pretty hot. I'm going to make some vines to cover it so it won't be that hot.	

The teacher encouraged Student 7 to share her reasons for supporting increasing the car parks with the picture (turn 38). From the student's response, the teacher realised that the viewpoint expressed in Student 7's spoken language did not entirely correspond to the one she sought to represent in her drawing (turn 39, Figure 1), so she pressed further reasoning by asking what the green stuff above the car park in her drawing (turn 40). From Student 7's response in turn 41 about how to keep the car park while keeping green spaces, the teacher then better understood that Student 7's choice was not only in support of the car park drawing on her family experience in turn 39, but also seeking a balanced solution to the issue. In the teacher's lesson, the drawing represents the child's complete ideas that helped the teacher identify the child's additional unarticulated personal thoughts and made the child's reasoning process visible.

Figure 1. Student 7's picture visually represents her personal opinions on whether to keep green spaces or build car parks.

(3) Find out stage: Using a sensory approach in scientific inquiry to teach abstract scientific knowledge as evidence for climate action

In Lesson 2, the teacher taught children to learn about the cooling effect of the trees. The children felt different temperatures under the trees and in the places without the trees, by touching different materials (i.e. floor, tile, soil), as shown in Figures 2 & 3, during the extreme hot weather in Shanghai at the end of May. The teacher simplified the complex principles behind the cooling effect produced by trees through transpiration and shading into a scientific phenomenon that could be used as evidence for making informed decisions by using a sensory approach.

Figure 2. Children were feeling the temperature under the trees..

Figure 3. Children were feeling the temperature in places without trees

The teacher used the senses to make the scientific knowledge accessible to young children, such as why planting trees contributes to reducing the temperature, and adapted to the hot weather caused by climate change in Shanghai. The teacher discussed that the young children can learn about science by using a sensory approach in her reflection journals:

> 'It is easy for students to learn through feeling and touching, but when knowledge is taught in the form of abstract theory, it is difficult for children to understand.'

(4) Act stage: Encouraging young children to take indirect climate action through family or community stakeholders

In Lesson 4, the teacher led children to draw posters in relation to protecting the trees, put up their posters at the school gate, and encouraged children to introduce their solutions to their families when they go back home (Figure 4).

Figure 4. Posters drawn by children advocating for tree protection as a climate action.

The teacher believed that because children's ability is limited, what they can do is to take indirect climate action by encouraging their family and others to take direct action. She said in her final interview:

> 'The ability of children is to encourage the adults, that is, the adults in their family, and then go on to contribute more to society. Their ability is only to change a small part of the people around them and to change their own mind first before they can help more people.'

Discussion And Conclusions

The teacher's instructional strategies in this case study indicate more possibilities of having CCE in early childhood with the SSIBL approach. Although the knowledge of climate change is often claimed to be too complex and abstract for kindergarten children, this study suggests that the teacher is capable of teaching climate change to children through everyday experiences (Ginsburg & Audley, 2020) that are personal and locally relevant to them, by being immersed in a contextualised learning scenario related to climate change, and inquiring through iconic representation and sensory appraoch. These strategies can help young children develop their conceptual understanding and empower them as agents of action.

This research contributes to the theoretical knowledge on how SSIBL can be enacted as an action-oriented approach for CCE. The implications for teachers and teacher educators will involve guiding them in adopting age-appropriate approaches to teaching climate change and enacting SSIBL.

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Facing Scenarios Of Ontological And Epistemic Uncertainty In Science Teaching: Perspectives On Agency In The Literature In The Field

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Advances in science and technology have intensified social and educational challenges in which uncertainty shapes how individuals and collectives are able to act. In science education, this calls for approaches that promote students' agency, understood as the capacity to participate meaningfully in knowledge construction and to act in uncertain contexts, rather than merely acquiring established knowledge. This study examines how the literature has conceptualised and promoted agency in situations and scenarios of uncertainty within science education. A systematic literature review was conducted using the ERIC and Web of Science databases, resulting in the selection of 15 relevant articles. The analysis identifies two main macro-trends. One, predominantly associated with European research, conceptualises agency in future-oriented educational approaches that emphasise collective and projective forms of action, using narratives, simulations and interdisciplinary practices to engage with ontological and epistemic/epistemological uncertainty. The other, largely linked to studies from the United States, focuses on agency as students' participation in scientific practices, highlighting epistemic and consequential agency in contexts of epistemic and conceptual uncertainty. Although distinct, these approaches are complementary in showing how different forms of agency emerge in response to different types of uncertainty. The findings suggest that science education should integrate these perspectives to support students in developing agency to act, decide and take responsibility in complex and uncertain worlds.

Keywords: agency / uncertainty / literature review

Introduction

The world we live in has become increasingly complex as advances in science and technology have confronted us with challenges whose outcomes are ever more uncertain. New challenges such as climate change, artificial intelligence, food security, genetic engineering, and energy transition, among others, have required action under conditions of risk and uncertainty that do not lend themselves to simple solutions, since neither accumulated knowledge nor our projections are capable of providing the certainties, we seek (Giddens, 1990; Beck, 1992, 2009; Rosa, 2020). Schools face the challenge of preparing students to deal with problems of this kind, while simultaneously attempting to reinvent themselves in order to position their practices within this changing world.

Historically, determinism has constituted the foundation of science and, consequently, of science education (Levrini et al., 2024), sustaining the idea that, once the initial conditions and governing laws of a system are known, its future behaviour can be predicted with precision. This epistemological environment contributed to the construction of an image of science as a producer of certainty, control, and predictability. However, social and scientific developments have shown this view to be limited and insufficient. Contemporary understandings of complex systems reveal that natural and social phenomena are frequently non-linear and composed of multiple interacting variables (Prigogine & Stengers, 1984; Funtowicz & Ravetz, 1994). Moreover, uncertainty has become an inseparable element of the scientific process of knowing and acting in the world, including in its various forms of appearance, such as epistemic, ontological, scientific uncertainty, *etc.* (Kirch, 2012; Njå et al., 2017). Recognising complexity and uncertainty in natural and social processes is therefore fundamental to a more comprehensive understanding of the world we inhabit and of the role attributed to scientific knowledge in the education of citizens (Pietrocola & Souza, 2019).

The OECD (2019), in the report *The Future of Education and Skills 2030*, states that students must be prepared for "the mobilisation of knowledge, skills, attitudes and values to meet complex demands in situations of uncertainty" (p. 25). Accordingly, science education must move beyond the transmission of deterministic knowledge and incorporate explicit engagement with uncertainty and with ways of acting in contexts marked by its presence. Scientific education must acknowledge that we live in an increasingly volatile, uncertain, complex, and ambiguous world, requiring the construction of an ethical stance towards scientific knowledge that assigns responsibility to students as agents in the construction of desirable futures (Bell, 1998). This calls for progress towards a more transformative conception of scientific literacy, one capable of fostering participation, social activism, and agency in response to contemporary challenges (Valladares, 2021).

Within the literature, particularly in approaches that mobilise socioscientific issues, decision-making occupies a central place in the analysis of students' actions. While this emphasis has contributed to shifting science education beyond the mere transmission of content, understanding formative processes exclusively through the lens of decision-making proves conceptually limited, especially in complex situations. Such an approach tends to capture only isolated moments of action, often conceived as discrete rational choices, while overlooking the temporal and social conditions that structure the very possibility of deciding (Emirbayer & Mische, 1998).

It is within this context that the notion of agency offers a more robust analytical framework for thinking about action in socioscientific situations. Some studies have addressed how agency can be promoted in educational contexts where students encounter complex and uncertain problems. However, to date, there has been no work synthesising these contributions in a way that supports reflection on science education in a world marked by uncertainty, where traditional school knowledge was not designed to prepare citizens capable of acting and making decisions under such conditions. Although there is a broad body of literature on uncertainty, not all of it engages with the question of how, in uncertain scenarios, students' agency can be fostered. Accordingly, this study seeks to address the following research question: how has the literature proposed the promotion of agency in situations and scenarios of uncertainty within the context of science education?

Methodology

To achieve the defined objectives, we conducted a systematic reviews search (Pollock & Berge, 2018) in two databases: ERIC (Educational Resources Information Center) and Web of Science, during the second half of 2024. ERIC is aimed specifically at publications in the field of education, while Web of Science covers a broader spectrum of areas of knowledge. The combination of these two databases allowed for a comprehensive reach, guaranteeing a more detailed and complete review of the topic in the educational context. This method also enabled us to understand how the topic is approached from different perspectives, enriching the analysis and broadening the possibilities for contributions to the field.

In both databases, we used the keywords "uncertainty" and "agency" together, without restricting the period of publication, evaluating all titles and abstracts to identify articles relevant to the scope of the study. In ERIC, we limited the search to "peer review" studies, which resulted in

122 articles, of which 27 were considered relevant. On Web of Science, as it is a broader database, we applied filters to articles in English and within the “Education Educational Research” category, obtaining 133 articles in total. Of these, 31 were relevant, but 11 were already present in the ERIC search, resulting in 20 relevant articles to be added in the base. In all, we came up with 47 articles. We didn't make a specific selection of journals in order to obtain a more robust sample, but one that took into account the selection criteria. For this work, we cut out these 47 articles, analysing only those that fell within the field of science teaching or that investigated central themes of interest to this area (such as climate change, agriculture, *etc.*). As a result, 15 articles were selected and analysed in detail.

Results And Discussion

Table 1. Future-orientated articles in science education.

<table>
<tr><th>Title</th><th>Authors</th><th>Year of Publication</th><th>Nature of the article</th><th>Journal</th><th>Author's institutional country</th></tr>
<tr><td>Facilitating transformative science education through futures thinking</td><td>Laherto, A.; Rasa, T.</td><td rowspan="5">2022</td><td>Theoretical</td><td>On the Horizon</td><td rowspan="2">Finland</td></tr>
<tr><td>Futurising science education: students’ experiences from a course on futures thinking and quantum computing</td><td>Rasa, T.; Palmgren, E.; Laherto, A.</td><td rowspan="6">Empirical</td><td>Instructional Science</td></tr>
<tr><td>Imagining the School of the Future Through Computational Simulations: Scenarios' Sustainability and Agency as Keywords</td><td>Barelli, E</td><td rowspan="4">Frontiers in Education</td><td rowspan="2">Italy</td></tr>
<tr><td>Making sense of youth futures narratives: Recognition of emerging tensions in students' imagination of the future</td><td>Barelli, E; Tasquier, G; Caramaschi, M; Satanassi, S; Fantini, P; Branchetti, L; Levrini, O</td></tr>
<tr><td>Scientific Literacies for Change Making: Equipping the Young to Tackle Current Societal Challenges</td><td>Tasquier, G; Knain, E; Jornet, A</td><td>Italy; Norway</td></tr>
<tr><td>Enhancing relevance and authenticity in school science: design of two prototypical activities within the FEDORA project</td><td>Cassina, FD; D'Orto, E; Tasquier, G; Fantini, P; Levrini, O</td><td>2023</td><td>Italy</td></tr>
<tr><td>Quantifying and communicating uncertain climate change hazards in participatory climate change adaptation processes</td><td>Müller, L; Döll, P</td><td>2024</td><td>Geoscience Communication</td><td>Germany</td></tr>
</table>

Table 2. Articles focusing on scientific uncertainty in science teaching.

Title	Authors	Year of Publication	Nature of the article	Journal	Author's institutional country
Enlisting Supervised Machine Learning in Mapping Scientific Uncertainty Expressed in Food Risk Analysis	Rona-Tas, A.; Cornuéjols, A.; Blanchemanche, S.; Duroy, A.; Martin, C.	2019	Empirical	Sociological Methods & Research	USA; France
Explicit Instruction of Scientific Uncertainty in an Undergraduate Geoscience Field-Based Course	Bateman, K.; Wilson, C.; Williams, R.; Tikoff, B.; Shipley, T.	2022		Science & Education	USA
The glue that makes it hang together: A framework for identifying how metadiscourse facilitates uncertainty navigation during knowledge building discussions	Ko, MLM; Luna, MJ	2023		Journal of Research in Science Teaching	
Course-Based Undergraduate Research Experiences in a Chemical Engineering Laboratory Promote Consequential Agency	Wilson-Fetrow, M.; Svihla, V; Burnside, B.; Datye, A.			Journal of Chemical Education	
Student Uncertainty as a Pedagogical Resource (SUPeR) approach for developing a new era of science literacy: practicing and thinking like a scientist	Chen, Y.; Jordan, M.			Science Activities	
Cultivating a higher level of student agency in collective discussion: teacher strategies to navigate student scientific uncertainty to develop a trajectory of sensemaking	Chen, Y.	2024		International Journal of Science Education	
Navigating student uncertainty for productive struggle: Establishing the importance for and distinguishing types, sources, and desirability of scientific uncertainties	Chen, Y.; Jordan, M.; Park, J.; Starrett, E.		Theoretical	Science Education	

The articles were read in full and some information about them can be seen in Table 1 and 2. Only one of them was published before 2020, which appears to be a timely cut-off, as the COVID-19 pandemic seems to have spurred researchers worldwide to reflect on the issue and propose interventions in science education. More than half of the articles analysed cite the pandemic in their text, corroborating this trend. What's more, a large proportion of the articles are empirical - around 80% - based on analysing data collected in practical applications in the classroom or analysing educational materials. Although the publications are distributed across several journals, *Frontiers in Education* stands out, hosting ⅓ of the articles, probably due to its focus on global challenges in education, as pointed out in its scope. In addition, 80% of the authors of the articles in this journal are Italian, reflecting an influence from the researchers' country of origin. The other journals are varied, without repetition.

It was noted that there are two macro-trends in the articles analysed. The first is linked to authors from European institutions and focuses on future-oriented education, on the one hand looking exclusively at climate threats and their uncertainties (Müller & Döll, 2024) and, on the other, those that focus on the application of Future Studies in science teaching, as can be seen in Table 1, with many of these studies associated with I SEE and FEDORA project, further corroborating their similarity in focus. If you look at the keywords in the articles, you'll notice that the words “agency” and “future” appear a lot, but this isn't a rule. However, the word ‘uncertainty’ does not appear. These articles use methodological strategies such as the use of narratives, simulations, interdisciplinary practices and others to work with futures and their uncertainties.

The second macro-trend is linked to US authors and is focused on understanding how students deal with scientific uncertainty (conceptual and epistemic) during teaching and learning processes and how they construct knowledge, as can be seen in Table 2. If you look at the keywords in the articles, you'll notice that the word ‘uncertainty’ is the most common and has three forms, while ‘agency’ only appears once. The last article on this list (Ferguson & White, 2023) does not fit into any of these macro-trends, as it brings a theoretical perspective on addressing socio-ecological challenges, in this case climate change, through student action and community involvement.

These macro-trends are not arbitrary; they reflect ways of addressing different types of uncertainty. Studies on scientific uncertainty in the classroom focus on epistemological uncertainty, examining what we know about a subject and how that knowledge is constructed and validated. Such approaches confront the limitations of current knowledge, where uncertainty can be reduced through new data collection or alternative models and theories. Categorising uncertainty types clarifies their distinct origins, characteristics, and implications, helping to determine the most appropriate response. By differentiating them, researchers propose strategies to equip students and educators with critical adaptation and action skills.

Within these studies, agency is understood not merely as an individual capacity to act, but as a sociocultural process through which students assume authority and responsibility both for their own learning and for the collective construction of knowledge within the school community. This perspective distinguishes different levels of agency, contrasting low-level forms, typical of transmissive teaching models, in which students act as passive recipients, with high-level forms, in which learners position themselves as knowledge producers and active participants in scientific practices. In such contexts, agency becomes visible when students identify gaps in their own understanding, formulate guiding questions and collaborate with peers to deepen their comprehension, thereby shifting from a relationship of knowledge consumption to one of authorship and production.

This conception is further expanded through specific forms of agency that emerge in scientific and inquiry-based practices, particularly epistemic and consequential agency. Epistemic agency refers to students’ opportunities to participate meaningfully in knowledge-building practices, contributing to the formulation, evaluation, and direction of investigations, while consequential agency is expressed through decision-making processes that directly shape the course of work and learning. In learning environments marked by scientific uncertainty, this agency is strengthened, as engagement with the unknown creates conceptual and epistemic demands that motivate action. Agency thus becomes visible not only in students' choices, but also in discursive interactions and in the opportunity, structures afforded by instructional design, especially when students engage in authentic practices and move from peripheral positions towards more central roles within communities of inquiry. In this sense, agency emerges when learners move beyond merely "learning about" science and begin to "figure out how" explanations are produced, mobilising their own ideas, intuitions and experiences to address real-world problems.

Future-orientated work approaches uncertainty in a different way. Although epistemological and epistemic uncertainty are present, arising from the limitations inherent in the methods and frameworks used to think about the future, ontological uncertainty appears to be central. Ontological uncertainty is recognised as inherent to the future, as it involves phenomena that are, by nature, unpredictable, chaotic or emergent. This uncertainty cannot be eliminated, even with perfect information or better models, because it is embedded in reality itself. An example of this is the construction of desirable future scenarios, with the intention of thinking about what, through agency, can be done to reach a desirable future, even if we don't know everything. In this context, the two types of uncertainty are connected in the epistemological reflections on the limits of projections, which can touch on ontological uncertainties, especially when dealing with chaotic or emerging phenomena, with climate change being addressed more than once.

Overall, in this macro-trend, agency is conceptualised as the capacity to intentionally influence and transform social and material worlds, extending beyond a strictly individual notion of action to include shared and collective forms. This conception is strongly grounded in Emirbayer and Mische's framework, in which the projective dimension of agency occupies a central position. By enabling subjects to momentarily disengage from limiting assumptions and to imagine desirable futures guided by values, this dimension underpins educational practices oriented towards futures thinking. In this sense, students are positioned as protagonists capable of constructing pathways of action towards preferable scenarios, shifting from an adaptive stance towards the future to an active and intentional engagement with it.

This understanding of agency is further articulated through models of transformation that integrate personal, practical, and political dimensions, highlighting that action involves connecting values, everyday choices, and broader institutional structures. Agency thus emerges as the capacity to move across these spheres, shifting from a condition of being "objects of change" to that of "subjects of change". In the contexts analysed, science and technology play a fundamental role in this process, particularly through non-deterministic approaches that emphasise the social construction of technology and the role of individuals and collectives in shaping global dynamics. In scenarios marked by uncertainty, agency is understood as the ability to act without guarantees, planning action in relation to multiple possible futures. Strategies such as back casting and the use of complexified narratives reinforce this perspective by framing the future as an open field of possibilities, in which action does not eliminate uncertainty but is constituted precisely through it.

Conclusion

This review identified two main macro-trends in the literature addressing agency and uncertainty in science education, which offer complementary but distinct ways of conceptualising both uncertainty and agency. One macro-trend, largely associated with studies from the United States, focuses on scientific uncertainty within classroom practices, particularly epistemological and epistemic uncertainty arising from the limits of current knowledge. In these studies, uncertainty is treated as a pedagogical resource, and agency is understood as a sociocultural process through which students assume authority and responsibility for inquiry and knowledge construction. Agency emerges through participation in authentic scientific practices, where epistemic and consequential forms of agency are central: learners identify knowledge gaps, formulate questions, make decisions that shape investigations and collaborate within communities of inquiry. Instructional designs that provide meaningful structures of opportunity are therefore crucial in supporting students' transition from passive reception to active authorship of knowledge.

A second macro-trend, predominantly associated with European research, approaches uncertainty through a future-oriented perspective in which ontological uncertainty occupies a central position. Rather than focusing solely on what is not yet known, these studies recognise uncertainty as an inherent feature of future realities shaped by complex, emergent and unpredictable phenomena, such as climate change. Within this framework, agency is conceptualised as the capacity to intentionally influence and transform social and material worlds, extending beyond individual action to include shared and collective forms. Grounded in the projective dimension of agency, these approaches position students as protagonists capable of imagining desirable futures and constructing pathways of action towards them, even in the absence of certainty.

Taken together, these macro-trends point to the need for science education to integrate epistemological, epistemic and ontological dimensions of uncertainty while foregrounding agency as a central educational outcome. Whether through engagement in knowledge-building practices or through futures-oriented pedagogies, the literature converges on the importance of preparing students to act without guarantees in complex and uncertain contexts. At the same time, the strong geographical concentration of the analysed studies highlights the need for broader contributions from contexts in Latin America, Africa and Asia, where uncertainties may take different forms and educational priorities and resources differ significantly. Expanding this body of research is therefore essential for developing more diverse and globally informed perspectives on agency and uncertainty in science education.

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Expanding Perspectives on Agency within Climate Change Education Debate

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As global challenges intensify, science education is uniquely positioned to bridge knowledge and action by fostering agency in learners. However, traditional approaches often only focus on individual behavioural change, neglecting the collective and political dimensions essential for systemic transformation. This symposium examines the multifaceted nature of agency and its role in empowering learners to navigate the complexities of the Anthropocene through interdisciplinary, transformative education. The symposium integrates insights from environmental psychology, philosophy, futures studies, and science education to explore the idea of collective and political agency as crucial educational outcomes. It highlights three key contributions: a systematic review of the conceptual landscape of agency in climate change education, an interdisciplinary framework that proposes a three-lens model (epistemic, ethical, pragmatic) to conceptualise agency, and an empirical case study applying futures literacy in teacher education to strengthen collective and political agency. By connecting theory and practice, this symposium contributes to the ongoing dialogue about the transformative potential of science education in the context of sustainability and the climate crisis.

Keywords: Agency, Climate change education, Transformative science education

Introduction

Climate change, biodiversity collapse, and socio-environmental injustice increasingly challenge the adequacy of traditional models of science education. In the context of the Anthropocene, education is called upon not only to equip learners with scientific knowledge but also to prepare them to engage meaningfully and responsibly with complex, uncertain, and contested socio-ecological realities (Levrini et al., 2024; Latour, 2018; Sjöström et al., 2018). As such, the concept of *agency* has gained prominence in recent educational discourse. However, it remains far from clear what is meant by *agency* in the context of science education, how it can be fostered, and why it matters.

Although frameworks such as GreenComp (Bianchi et al., 2022) and the PISA 2025 Science Framework (White et al., 2023) conceptualise agency as a multifaceted competence, educational practices, particularly in the context of science education, tend to emphasise individual dimensions, such as behaviour change or personal responsibility. This may limit attention to broader systemic and collective dimensions of agency that are crucial for transformative engagement (Kranz et al., 2025). Particularly in climate change education, the dominant orientation tends to privilege personalised responses and lifestyle choices, while overlooking the more systemic, collective, and political dimensions that underpin the potential for effective social transformation (Kranz et al., 2022; O'Brien, 2015; Otto et al., 2020).

Within the field of science education, the concept of agency is frequently invoked but rarely subjected to rigorous theoretical scrutiny. As highlighted in prior literature (e.g., Marsh et al., 2019; Schubatzky et al., 2026), the concept of agency is often invoked using a variety of related terms, which are not always clearly defined or theoretically distinguished. This contributes to a degree of conceptual ambiguity that may hinder coherence in both research and practice. This lack of clarity risks undermining both research coherence and pedagogical design, as it becomes uncertain which capacities science education is meant to develop and why. At the same time, a growing body of research – initially from social sciences and humanities (e.g. Emirbayer & Mische, 1998) and more recently within science education research - has highlighted the need for a relational collective and political understanding of agency (e.g. Tasquier et al., 2022; Kranz et al., 2022; Levrini et al., 2019). While not entirely new, this view has often remained underdeveloped in science education, particularly in relation to climate change.

Against this backdrop, the ESERA 2025 symposium titled "Expanding perspectives on Agency within Climate Change Education debate" presented aims to advance a theoretically grounded and empirically informed dialogue around the role of climate agency in science education. We argue that science education must not only acknowledge agency as a learning outcome but also expand how agency is conceptualised, operationalised, and supported across curricula, pedagogical practices, and teacher education. More specifically, we contend that collective and political forms of agency, understood as the capacity to act with others to influence structural and systemic conditions, should receive the same attention as the individual dimension, sincethey are essential goals of science education in the Anthropocene (Kranz et al., 2025a).

The symposium brings together three complementary studies that address a shared research problem: *How can science education develop ways to conceptualise, support, and assess agency in light of the scale, complexity, and socio-political nature of the climate crisis?* The first contribution examines this question by mapping how agency is conceptualised in current climate change and sustainability education research, identifying dominant framings and theoretical blind spots. The second contribution develops a theoretical framework that reconceptualises agency through three interrelated lenses, epistemic, ethical, and pragmatic, articulating a normative and multidimensional perspective. The third contribution presents an empirical case study illustrating how futures literacy–oriented pedagogical practices in teacher education can support agentic engagement with uncertain futures and make collective and political dimensions of agency more visible.

Together, these contributions articulate a coherent yet pluralistic effort to reimagine agency beyond individualistic and behavioural paradigms. The symposium thus seeks to strengthen the theoretical foundations of agency in science education while offering practical directions for designing educational experiences capable of fostering the forms of collective engagement and transformative capacity that are urgently needed for a just and sustainable future.

Problematizing The Concept Of Agency In Climate Change Education

In recent years, agency has become a prominent yet theoretically unstable concept in climate change and sustainability education. Across science education research, policy frameworks, and curriculum documents, agency is frequently invoked as a key educational aim, often framed as essential for enabling learners to respond to the climate crisis (White et al., 2023; UNESCO, 2021). However, this growing prominence has not been accompanied by conceptual coherence across different research traditions (e.g., Priestly et al., 2015). Instead, agency is used in markedly different ways, ranging from psychological readiness and pro-environmental behaviour to civic participation and action.

The first contribution to this symposium addresses this problem through a systematic scoping review of agency in climate change and sustainability education research. Analysing 110 peer-reviewed studies published between 2004 and 2024, the review maps how agency is defined, theorised, and operationalised in school-level science education. A central finding is the widespread absence of explicit definitions: fewer than one third of the reviewed studies provide a clear theoretical definition of agency, while the majority use the term implicitly or without clarification. This pattern exemplifies what Marsh et al. (2019) describe as a jingle–jangle fallacy, where the same label refers to different constructs, or different labels describe overlapping phenomena.

This lack of definitional clarity has concrete consequences. Studies labelled as fostering "agency" often pursue fundamentally different educational goals: some focus on strengthening students' hope, motivation, or self-efficacy; others aim at developing sustainability-related competencies; still others foreground participation, identity work, or civic engagement. Without explicit conceptual positioning, it remains unclear which forms of agency are being aimed to be supported, how they relate to one another, and which are adequate for addressing the systemic and political nature of the climate crisis. From a pedagogical perspective, one might argue that this diversity is of secondary importance, as the central concern of climate change education is to support students in doing something in the face of the climate crisis, rather than remaining passive or disengaged. In this sense, different pathways to agency may appear equally legitimate.

However, precisely because agency is increasingly framed as a key educational response to a systemic and political crisis, it is not trivial which forms of agency are being promoted. Without explicit conceptual positioning, there is a risk that agency becomes reduced to individual coping, lifestyle choices, or isolated actions, thereby obscuring questions of collective responsibility, power, and structural change. Clarifying how agency is conceptualised is therefore not a purely theoretical concern, but a prerequisite for aligning educational aims with the transformative demands of the climate crisis.

To bring analytical structure into this fragmented landscape, the review identifies five recurring conceptualisations of agency in the literature. These include (1) agency as a psychological resource, emphasising hope, self-efficacy, and emotional resilience; (2) agency as competence, framing agency as a set of learnable and assessable knowledge–skill–attitude configurations aligned with policy frameworks such as PISA 2025; (3) critical-emancipatory agency, rooted in Freirean and critical science education traditions, foregrounding empowerment, justice, and collective struggle; (4) temporally embedded sociocultural agency, highlighting identity, participation, and the integration of past experiences and imagined futures; and (5) action-oriented or problem-solving agency, focusing on concrete participation and locally situated sustainability actions.

Importantly, these conceptualisations are not mutually exclusive. Rather, they emphasise different clusters of attributes and rest on distinct theoretical traditions. The review therefore proposes conceptualising agency as a family resemblance concept (Podsakoff et al., 2016), characterised by overlapping features rather than a single defining essence. Across traditions, several central attributes recur, including a perceived capacity to act, situatedness in socio-cultural contexts, participation with others, and a future-oriented perspective. At the same time, each conceptualisation foregrounds distinctive elements—such as psychological resources, competencies, empowerment, identity work, or local problem-solving—that shape how agency is enacted and studied.

This diagnosis sets the stage for the subsequent contributions in the symposium. Building on the conceptual mapping provided by the review, the second contribution advances an interdisciplinary framework that reframes agency through epistemic, ethical, and pragmatic lenses. The third contribution presents an empirical case study illustrating the role of futures literacy in shaping agency-related orientations in teacher education, including collective and political dimensions of agency. Together, these contributions respond to the conceptual challenges identified here by moving beyond individualistic and behavioural paradigms toward a more robust understanding of agency suited to science education in the Anthropocene.

Reframing Agency Through Interdisciplinary Perspectives

Building on the need for greater conceptual clarity, the second contribution proposes a theoretical framework that redefines agency as a multidimensional educational construct. Tasquier, Pongiglione, and Ricci (2026) argue that science education must be expanded through the integration of insights from philosophy and economics to address the ethical, epistemic, and pragmatic dimensions of agency.

Their model, developed in the context of the ENCOMPASS research programme, moves beyond conventional notions of agency as primarily psychological or behavioural. It aims to capture the complex and situated nature of agency as it manifests in the climate crisis, where action must often be taken despite uncertainty, structural constraints, and conflicting values. Through a theoretically grounded synthesis of three disciplinary perspectives - science education, philosophy, and economics - the model proposes an educational response that recognises the plurality and interdependence of the competencies required for transformative engagement (Tasquier et al. 2026; Sezen-Barrie et al., 2026).

Central to this model is the articulation of three interwoven lenses through which agency can be rethought. First, epistemic-driven agency refers to the capacity to critically engage with scientific knowledge. In the context of climate science, this entails grappling with complex systems, probabilistic models, and the provisional nature of evidence. Students must be able to navigate contested knowledge claims, evaluate the reliability of sources, and understand how scientific knowledge interacts with political and social interests. This epistemic engagement is essential to avoid both naïve scientism and paralysing relativism.

Second, ethical-reflective agency foregrounds the importance of moral reasoning in contexts characterised by uncertainty and normative pluralism. Climate change raises profound ethical questions about responsibility, justice, and intergenerational equity. Philosophical reflection offers tools for deliberating about what is at stake, for whom, and according to which values. By integrating ethical reflection into science education, learners are not merely trained to know or to act but to judge. This form of agency requires sensitivity to others, awareness of ethical complexity, and the capacity to live with ambiguity.

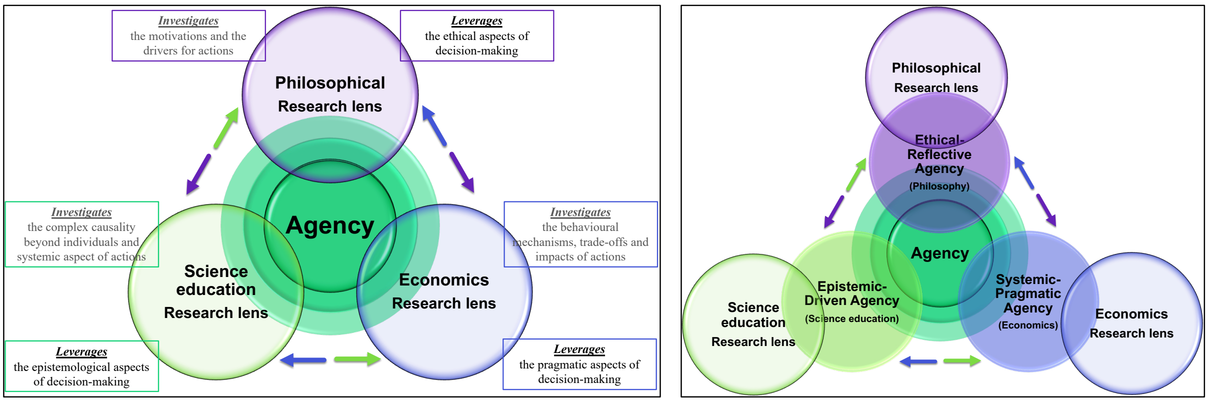
Third, systemic-pragmatic agency refers to the ability to understand and act within real-world constraints, considering trade-offs, opportunity costs, and institutional limitations. Drawing on economic reasoning, this dimension of agency attends to the feasibility and effectiveness of climate actions. Students are invited to think strategically, acknowledging that ideal solutions may not always be viable and that action requires negotiation and compromise. Systemic-pragmatic agency thus aligns action with context, enabling learners to move from aspiration to implementation.

Taken together, these lenses offer a reframing of agency as a distributed and educable capacity. Rather than treating agency as a fixed trait or an individualised outcome, the framework situates it within learning environments that scaffold deliberation, judgement, and action. It calls for science education to be reimagined as a site of public reasoning, where students engage not only with scientific content but with the socio-political and ethical dimensions of science-in-society.

This perspective resonates with Vision III of scientific literacy (Sjöström et al., 2017), which advocates for the development of critical and transformative competencies that enable students to participate in shaping more just and sustainable futures. It challenges the epistemological reductionism of traditional curricula and calls for an expansion of educational aims to include the cultivation of political imagination, collective responsibility, and civic engagement.

Importantly, the framework is not merely theoretical. It has informed the development of design principles that guide the creation of pedagogical environments where these forms of agency can emerge (Sezen-Barrie et al., 2025). These environments are characterised by exposure to uncertainty, authentic problem contexts, deliberative dialogue, and opportunities for situated action. They invite students to encounter complexity not as a barrier but as a condition of responsible engagement. By positioning agency at the intersection of epistemic, ethical, and pragmatic reasoning, this contribution offers a powerful vision for rethinking science education in the Anthropocene.

Figure 1. *ENCOMPASS Three-Lens Model of Climate Agency. (Adapted from Tasquier, Pongiglione & Ricci, 2026).*



Futures Literacy And Agency In Teacher Education

The third contribution examined how futures literacy is related to the development of agency in the climate crisis, with a particular focus on pre-service teachers (PSTs). In contrast to the conceptual plurality highlighted in the other symposium contributions, this study deliberately adopts an explicit working definition of agency to enable empirical analysis. Here, agency is understood as the capacity for autonomous social action through which individuals intentionally transform their social and material worlds (e.g., Biesta & Tedder, 2007). It is further viewed as inherently future-oriented, as people's anticipations and visions of the future shape how they act in the present (Lombardo, 2016; Ojala, 2012).

Two interrelated conditions described in the literature motivated this focus. First, research on young people's future thinking points to a lack of constructive future perspectives, often characterised by dystopian and fixed visions of the future (e.g., Miller, 2018). Second, studies in science education on climate change suggest that educational approaches frequently remain passive with regard to agency, prioritising individual agency or knowledge acquisition rather than fostering learners' capacities to shape social and material conditions (Kranz et al., 2022; Kranz, 2024), including collective and political forms of agency. Together, these patterns risk constraining both how the future is imagined and how agency is perceived. This gap is particularly consequential in teacher education as PSTs can be understood as future change agents whose own sense of agency and future imaginaries are likely to shape how they later engage students with the climate crisis (Winter et al., 2022). Yet, there is still limited research on how science teacher education can deliberately support the development of futures literacy and agency. Building on these motivations, the contribution addresses the guiding question of how a climate-focused intervention can support the development of agentic, sustainability-oriented future thinking in PSTs. To this end, an interdisciplinary teaching module named (*FULit - Shaping the Future in Times of the Climate Crisis*) was implemented in the physics teacher programme at Freie Universität Berlin (Germany), integrating futures studies methods with transformative action-oriented approaches (Kranz et al, 2025b). The study involved 15 PSTs and followed an exploratory qualitative pre–post design. Focusing, among other data sources, on patterns in PSTs' future narratives, the analysis was structured along three dimensions: (1) the perceived quality of the future, (2) the perceived agency to shape the future, and (3) sustainability-related agency.

Regarding the perceived quality of the future, pre-intervention future narratives were predominantly articulated as ambiguous and uncertain. Rather than clearly dystopian or utopian visions, many accounts emphasised uncertainty, for example with respect to how climate change might develop or how societal responses could unfold. Dystopian elements were present but did not dominate, while utopian visions were rare. Post-intervention analyses indicate a slight shift: dystopian future visions declined, while ambiguous and uncertain futures became more prominent. The prevalence of ambiguity did not decrease and explicitly utopian futures remained rare.

With regard to the perceived agency to shape the future, pre-intervention narratives were equally distributed between active and passive orientations. Following the intervention, a slight shift toward agentic framings was observed (e.g., *'We redesign school life'*), more often positioning participants as potential actors capable of contributing to change. This shift was particularly visible in the combination of ambiguous future scenarios with agentic orientations. In contrast, utopian futures, when present, were more often paired with passive framings, indicating that positive visions did not necessarily coincide with a stronger sense of agency.

Finally, analysis informed by the EU GreenComp framework showed additional qualitative changes. Post-intervention narratives more frequently articulated, for example, acting for sustainability. While references to collective action remained rare, political agency became more visible. Participants more often framed the climate crisis as a socio-political challenge and referred to systemic or policy-related solutions rather than exclusively to individual behaviour.

Overall, the findings suggest that futures-oriented, transformative approaches hold the potential to support agentic engagement under uncertainty in the context of the climate crisis. Participants' future visions remained largely ambiguous rather than optimistic but were more frequently paired with agentic orientations. This pattern may be interpreted as a form of constructive hope (Ojala, 2012), oriented toward navigating uncertainty and reflecting on multiple possible futures rather than striving for idealised outcomes. The study followed an exploratory qualitative approach focused on identifying patterns rather than assessing intervention effectiveness. It examined prerequisites of agency, such as future imaginaries and perceived possibilities for action, rather than agency as an outcome per se. The findings point to the need for more structured opportunities for collective action and inform future comparative and longitudinal research on how different pedagogical elements support distinct dimensions of agency.

Discussion

Together, the three contributions in this symposium articulate a coherent and multilayered response to the central research problem: How can science education conceptualise, support, and assess forms of agency that are adequate to the scale, complexity, and socio-political nature of the climate crisis? Each study illuminates distinct facets of this problem, yet they also converge in affirming the need for a paradigmatic shift in how agency is understood and cultivated within science education.

The first contribution offers a panoramic diagnosis of the current conceptual landscape, highlighting the conceptual fragmentation and the risk of a dominance of individualistic framings in empirical research. This mapping underscores the importance of developing and using theoretically robust and pedagogically meaningful definitions of agency that transcend behavioural models and foreground relational, collective, and political dimensions. It provides the groundwork for understanding why existing approaches often fall short in addressing the systemic nature of the climate crisis.

The second contribution builds on this diagnosis by offering an interdisciplinary model that reconceptualises agency through epistemic, ethical, and pragmatic lenses. Rather than viewing agency as a static competence, it frames it as a dynamic and educable process embedded in deliberation, judgement, and strategic action. This model provides a normative vision of what agency *should* entail in the context of climate change, anchoring educational goals in democratic reasoning, moral complexity, and institutional awareness. Crucially, it affirms that science education must not only transmit knowledge but also scaffolded forms of agency that enable learners to navigate and shape contested socio-ecological futures.

The third contribution translates this vision into pedagogical practice through the integration of futures literacy into teacher education. It offers an empirical illustration of how futures-oriented educational approaches can be associated with shifts in learners' future imaginaries and perceived agency, including greater attention to collective and political dimensions of climate action. In doing so, it illustrates the pedagogical viability of the theoretical claims advanced in the second contribution. Taken together, the three studies advance the proposition that science education must be reoriented to explicitly cultivate agency not only as individual agency but also as a collective and political practice. Addressing agency in science education therefore requires conceptual clarity about which forms of agency are being invoked (Contribution 1), a theoretical reframing of agency as an epistemic, ethical, and pragmatic educational capacity (Contribution 2), and an empirical illustration of how these conceptual insights can be taken up in futures-oriented pedagogical practice (Contribution 3). Rather than being treated primarily as a by-product of knowledge acquisition or an individual trait, agency can be conceptualized as a central educational aim that is intentionally designed for. The three contributions in this symposium do take important steps to contribute to this aim. Rather than prescribing a singular model of agency, they point to the need for science education to become a space where different forms of agency can be recognised, interrogated, and deliberately cultivated, through research, curriculum design, and teacher education. This, we argue, is essential if science education aims to play a meaningful role in shaping responses to the climate crisis.

Conclusion And Outlook

This symposium contributes to an emerging educational discourse that seeks to reimagine science education as a site for cultivating transformative forms of agency. By interrogating how agency is defined, theorised, and enacted, the three contributions collectively make the case for a shift away from narrow, behavioural models toward more expansive and politically engaged framings. They argue for the design of educational environments where students are equipped to challenge, critique, and change the conditions that produce it.

Importantly, the symposium also points forward. It lays the conceptual and empirical foundations for future research and innovation in science education, particularly in the context of the newly funded EU Erasmus+ project TRACE (Transformative Agency in Climate Education), coordinated by the University of Innsbruck. TRACE builds directly on the theoretical and pedagogical advances discussed in this symposium, aiming to foster teachers' capacity to design and implement climate education that cultivates collective and political agency. Through a transdisciplinary, practice-based approach, TRACE focuses on supporting students and teachers in exploring how collective and political dimensions of agency can be addressed through climate education. It does so by involving them in the design and implementation of teaching scenarios that integrate other perspectives beyond science education, while also developing tools for self-reflection in regard to agency in the climate crisis.

The work presented here thus represents both a reflection on current limitations and an invitation to envision what science education towards agency could become in the Anthropocene. It affirms that agency is not a peripheral theme but a central challenge, one that demands conceptual precision, interdisciplinary imagination, and pedagogical innovation. Responding to this challenge means creating educational spaces where science is not merely learned but lived, where learners become co-authors of their futures, capable of engaging with complexity not with resignation, but with constructive hope and collective intent.

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