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Future-oriented science education for agency and sustainable development

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Published in
Frontiers in Education

ISSN 1664-8714
ISBN 978-2-83251-936-3
DOI 10.3389/978-2-83251-936-3

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Future-oriented science education for agency and sustainable development

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Citation
Laherto, A., Levrini, O., Erduran, S., eds. (2023). *Future-oriented science education for agency and sustainable development*. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-83251-936-3

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frontiers | Frontiers in Education

TYPE Editorial
PUBLISHED 02 March 2023
DOI 10.3389/feduc.2023.1155507

OPEN ACCESS

EDITED AND REVIEWED BY
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SPECIALTY SECTION
This article was submitted to STEM Education, a section of the journal Frontiers in Education

RECEIVED 31 January 2023
ACCEPTED 16 February 2023
PUBLISHED 02 March 2023

CITATION
Laherto A, Levrini O and Erduran S (2023) Editorial: Future-oriented science education for agency and sustainable development. *Front. Educ.* 8:1155507. doi: 10.3389/feduc.2023.1155507

Editorial: Future-oriented science education for agency and sustainable development

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KEYWORDS

futures thinking, agency, Education for Sustainable Development, transformative education, science education

Editorial on the Research Topic
Future-oriented science education for agency and sustainable development

The gravity of the climate crisis, the United Nations' Agenda 2030 programme and the related aims of Education for Sustainable Development (ESD) call for a fundamental rethinking of values, aims and pedagogies of all education (UNESCO, 2017, 2021). Such developments pose new demands also for science education research and practice: taking responsible action and contributing to change have been taken up as important aims of school science (Hodson, 2003, 2020). The latest visions of science education and scientific literacy ("Vision III", Sjöström, 2017) stress that students should not only understand the role of science and informed decision-making in the society but also be able to question societal choices and values on the basis of ethical consideration and take action to bring about desirable change. While such agency connects to how one orients toward the future, research has shown young people perceiving the global and societal futures as hopeless and out of their influence (e.g., Cook, 2016; Kaboli and Tapio, 2018). To meet the emerging societal demands, science education should be *transformative* to the students and to the society.

In the field of science education, the themes of agency, anticipation, future and models of change and transformation have gained an increasing (but still too little) attention during the past decade. Some literature has been published in order to develop science education *for action* and to facilitate students' *action competence* in socio-scientific issues (Hodson, 2020). Several initiatives promoting futures thinking, foresight, imagination and future narratives in science classrooms have been reported (e.g., Lloyd and Wallace, 2004; Paige and Lloyd, 2016; Levrini et al., 2021; Laherto and Rasa, 2022; Rasa et al., 2022). A number of research publications and white papers have focused on a variety of competencies people need in the future (e.g., European Commission, 2015; European Commission Joint Research Centre, 2022). Such skills typically relate, at least implicitly, to an individual's agency and ways of perceiving the future. Besides the research on students' learning and transformation, some initiatives have focused on institutional level changes: the emerging objectives necessitate the exploration of alternative scenarios for schools, e.g., *open schooling* (European Commission, 2015).

Yet, more theoretical, empirical and practical work is needed to support transformation both at institutional and individual levels, and put into operation the potential of science education in fostering students' agency and futures thinking for sustainability. To this end, and to facilitate new syntheses of theoretical and methodological approaches, we undertook this Research Topic, *"Future-Oriented Science Education for Agency and Sustainable Development."*

The 33 authors in 10 peer-reviewed papers all considered the need to rethink the nature of science teaching and learning, and motivated this need by referring to the era of great uncertainty or the urgent need for climate action. Their papers set out to explore ways in which science education can support agency and/or futures thinking.

Laying the research-based groundwork for future-oriented education, one of the papers explores tensions in students' imagination of the future (Barelli et al.). Three papers focus on competencies that future-oriented science education should aim to develop in students. One of them investigates policy-makers views on what kind of competencies constitute 'future-oriented skills' (Ioannidou and Erduran). The two other papers focus on specific competencies and their mutual connections: the relationship between students' anticipatory competence and environmental awareness (Ratinen and Linnanen), and teachers' systems thinking competencies and the sense of personal and collective responsibility toward actions (Uskola and Puig).

Three papers deal with pedagogical approaches and concepts, all aiming to revitalize the connection of science education to teaching and learning of other subjects and domains of the world. The proposed approaches and concepts involve holistic science learning (Lloyd and Paige), transdisciplinary collaboration (Kubisch et al.) and, more generally, a *subject didaktik* model for embodied and relational science teaching and learning (Yavuzkaya et al.).

Finally, three papers set out to investigate the effect of more specific teaching-learning activities developing students' sense of agency and perception of the future: activities of fictional writing and scenario building (Hervé and Panissal), activities of analyzing real-world data and scientific argumentation (Rap et al.), and computational simulations on complex systems (Barelli).

The final outcome of this Research Topic provides a multifaceted collection of theoretical and practical initiatives for orienting science education toward the future in a research-based manner. Together they pave the way for building the response of science education to the "new social contract for education" proposed by UNESCO (2021).

Author contributions

The editorial was written by AL. Commented and revised by SE and OL. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers in Education

ORIGINAL RESEARCH
published: 08 March 2022
doi: 10.3389/feduc.2022.842252

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Writing Fictional Short Stories About the Anthropocene: Effects on Students' Futures Thinking

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This article deals with the identification of some general guidelines for teaching aimed at developing futures thinking about themes of the Anthropocene. For that, we estimate such teaching activities at the intersection of socioscientific issues, environmental education, and futures education. We describe two teaching contexts designed on this principle, and centered on pupils' writing fictional narratives, and analyze the effects on their futures thinking. The results show that it is important to design teaching activities that make it possible to think about the temporalities of processes and phenomena, and to invest in relational responsibilities. In order for the pedagogical activity to take temporalities into account, we propose that the backgrounds of the futures on which the stories take place be built using the scenario method. Writing short stories can also allow for a deeper understanding of relational responsibilities, based more on the framework of capabilities. One perspective is to integrate fictional short stories writing into the repertoire of possible activities to be conducted in an inquiry-based pedagogy about the Anthropocene.

Keywords: socioscientific issues, futures education, environmental education, futures thinking, Anthropocene, science fiction

Edited by:
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Specialty section:
This article was submitted to STEM Education, a section of the journal Frontiers in Education

Received: *23 December 2021*
Accepted: *08 February 2022*
Published: *08 March 2022*

Citation:
Hervé N and Panissal N (2022) Writing Fictional Short Stories About the Anthropocene: Effects on Students' Futures Thinking. Front. Educ. 7:842252. doi: 10.3389/feduc.2022.842252

INTRODUCTION

Within a few years, the term "Anthropocene" has become "a vivid yet informal metaphor of global environmental change" (Zalasiewicz et al., 2008, p. 7), even if the concept is not stabilized and the word is controversial. The prospect of human activities being responsible for a geological epochal shift marks a recognition of the extent of the human footprint on the Earth System. The Earth System is being propelled into an unprecedented phase of its geological history, one less conducive to maintaining biological diversity and stable living conditions for humanity.

The Anthropocene thus designates the emergence of a paradoxical era, because although the categories of thought and action of modernity make it possible to describe the biogeophysical evolution of the Earth System very precisely, they are nevertheless incapable of fully evaluating the changes underway and the actions to be undertaken. As Latour (2017) expresses it, "it is not speaking ill of humanity to recall the extent to which we are all ill-equipped—emotionally, intellectually, morally, politically, culturally—to absorb such news" (p. 45).

Even if concerns about the evolution of the Earth System are shared, the social space is permeated by numerous visions of the future and divided on the actions to be taken to face it. Chateauraynaud and Debaz (2017) have shown that actors' reasoning in environmental and sociotechnical controversies is deeply structured by the futures images they are building.

They have identified four patterns in futures images about the Anthropocene that are circulating in society. First of all, there is the collapse scenario, which shows a catastrophic future that has the appearance of the end of the world. There is the technoprophetic scenario, that of a future technological breakthrough, with nanotechnology, artificial intelligence, Martian colonization and geoengineering as avatars. There is the scenario of regulation and policy-making, that of a controlled future, legislated by state or international institutions (in the Conferences of the Parties or at the UN), encouraging or forcing change. Finally, there is the scenario of the transition to sustainability, which is defined by new social and political assemblies, a focus on local experimentations and alternatives, for a systemic change in lifestyles.

To educate in the context of the Anthropocene is necessarily to question the sociotechnical trajectories of modern societies, to address environmental issues, and to evaluate possible and preferable actions with regard to their future consequences. This is why the educational currents of socioscientific issues (SSI), futures education (FE), and certain approaches to environmental education (EE) are currently converging, thus forming part of a critical and political tradition of the schooling of environmental issues (Sauvé, 2011).

In this article, we propose to investigate the characteristics of the futures thinking that French high school pupils use in learning contexts that confront them with the challenges of the Anthropocene. To this end, we are interested in two teaching sequences, whose design choices are based on SSI, FE and EE, and which have led pupils to write fictional short stories. By analyzing their productions, we can identify some guidelines for taking into account the temporalities of the Anthropocene in teaching.

EDUCATING IN THE ANTHROPOCENE, A FOCAL POINT FOR SOCIOSCIENTIFIC ISSUES, FUTURES EDUCATION, AND ENVIRONMENTAL EDUCATION

Three educational currents seem to be particularly interesting for constructing an educational point of view on the Anthropocene (**Figure 1**): they have in common the fact that they all consider the environment, science and technology, and the future as political issues that should be studied in school as such.

The SSI movement is a resource for thinking about education in the Anthropocene, as socioscientific, sociotechnical and socio-environmental controversies are seen as opportunities to politicize science education (Bencze, 2017; Simonneaux and Simonneaux, 2017; Sjöström et al., 2017; Bencze et al., 2018, 2020; Amos and Levinson, 2019; Chowdhury et al., 2020). Debating an SSI, mapping a controversy, playing a role-playing game, analyzing media, conducting a socioscientific inquiry are some examples of possible activities to be carried out with pupils. They aim to explore controversial, complex, interdisciplinary and value-laden issues (Sadler, 2011; Zeidler, 2015). They are also ways of getting pupils to consider the uncertainties that run through these issues, both in terms of academic knowledge and in terms of society and the media (because they are debated in society) (Sadler et al., 2017). The aim is a social transformation through the school sector (Simonneaux, 2014).

Environmental education is also a key educational research stream for thinking about the Anthropocene. The teaching of science, environmental protection or popular education approaches have played an important role in its development (Sauvé, 2005), in order to enable pupils to build knowledge and attitudes that are environmentally positive (Ojala, 2017). Environmental education constitutes a reservoir of educational practices that make it possible to politicize the challenges of the Anthropocene (Holfelder, 2019; Håkansson et al., 2019), even if its development in the form of education for sustainable development since the 2000s has been criticized for the importance given to the economic dimension to the detriment of the social and environmental dimensions (Jickling and Sterling, 2017; Kopnina, 2020). The themes studied (e.g., disagreements, controversies and conflicts in resource management), the ways of learning (e.g., collective action on a territory or deliberation on issues) and the learning objectives (in terms of knowledge or education for citizenship) all form part of an education in politics (Holfelder, 2019; Slimani et al., 2021).

Futures education is the transposition of practices and knowledge from futures studies (Hicks, 2001), and it is based on the analysis, the construction by the pupils, and the debate of futures images. This educational current considers that the future dimension is often forgotten in education, not questioned, implicit (Gough, 1990; Hicks, 2002). Its explicit integration into the curricula is necessary to promote futures that are responsive to major issues (Milojević, 2005; Hicks, 2012; Pauw, 2015). From the outset, futures education has been associated with issues of education for peace, citizenship and the environment (Gidley and Inayatullah, 2002; Gidley and Hampson, 2005), as well as the risks associated with scientific and technological development (Gidley, 2004; Hicks, 2012). It therefore also constitutes a resource for contemplating the school-based forms of education in the Anthropocene (Holfelder, 2019).

INTEGRATING FUTURE INTO TEACHING TO DEAL WITH SCIENTIFIC AND TECHNOLOGICAL DEVELOPMENT AND ENVIRONMENTAL ISSUES

There are a number of arguments to support a link between futures education and science education.

First of all, questioning economic, social and cultural development in Western societies inevitably leads to questioning science and technology because they are at the center of models of development. Many present and future world problems are based on scientific and/or technological foundations. Questioning scientific and technological development is thus one of the objectives of the SSI movement, and one way of approaching it is to focus on the future dimension (Jones et al., 2012; Buntting and Jones, 2015; Branchetti et al., 2018; Levrini et al., 2019, 2021). Researchers argue that science education with a

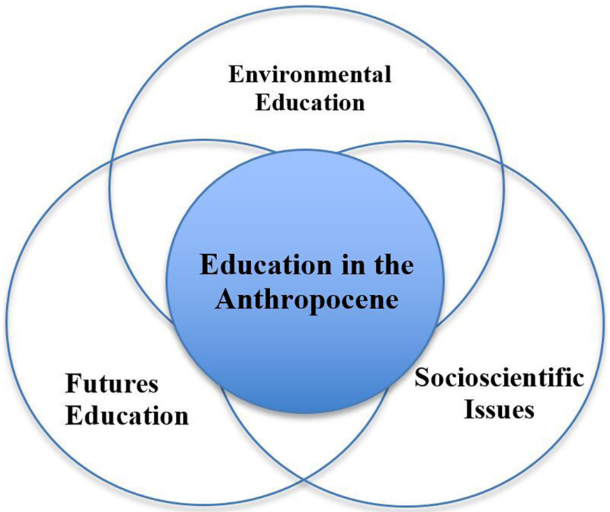

FIGURE 1 | Education in the Anthropocene, at the intersection of SSI, EE, and FE.

future perspective provides pupils with the means to examine and problematize their views and concerns about socioscientific issues, including environmental issues (Carter and Smith, 2003; Lloyd and Wallace, 2004). Futures education, integrated into science teaching, thus offers pupils the possibility of evaluating the impact of science and technology on society, constructing ethical dilemmas and exploring possible solutions or actions.

Numerous studies show that scientific and technological elements are very present in the futures images formed by individuals, and that they are often placed in tension with environmental issues (Hicks, 1996; Eckersley, 1999). For example, the quantitative study by Liu and Lin (2018) on students' futures images showed that "(1) students who believe that their preferred environmental futures will happen tend to hold a positive view about technoscience as an influencing factor; (2) students who are more positive about techno-science tend to be less concerned about the environment" (p. 1). Thus, the findings of this study "emphasize the importance of integrating a critical futures perspective into environmental education and science education programmes" (p. 14).

Lastly, teaching approaches that integrate the future dimension are likely to motivate pupils to learn about science, which is at times perceived as arduous (Lloyd and Wallace, 2004). It allows them to construct complex reasoning on problems that make sense to them: "science learning and a critical futures perspective, when used in combination, can assist students to use scientific ideas and processes to address current and emerging problems, and help them to anticipate possible consequences of applying scientific ideas" (p. 164).

The future dimension is considered central to the understanding of strong sustainability of lifestyles, it is also a key parameter for tackling "big problems" such as climate change, the loss of biodiversity, reducing inequality, etc., and it is a way of thinking about transitions and the changes they entail. Indeed, one goal of futures education is to keep the range of possible futures open (Voros, 2008), to work with pupils on the diversity of possible futures, to fight against the idea of a determined and threatening future, and to provide hope and alternative political projects. This is why futures education is promoted in the critical currents of environmental education (Hicks, 2012; Ojala, 2017; Holfelder, 2019).

Looking ahead to the future, identifying trends of change and their uncertainties, anticipating risks and consequences of decisions and actions, understanding emotions (e.g., hope, fear, or anger) related to the threats of the Anthropocene, imagining solutions or means of action, these are some of the educational objectives linked to the integration of the future dimension in education, and they represent several ways of using futures thinking.

It is because this thinking is essential to respond to the challenges posed by the Anthropocene that it is necessary to explore it further. A better understanding of futures thinking is to consider the means of articulating in action the temporalities of the social and bio-geophysical phenomena of the Earth System. It also means questioning these dynamics in the construction of the futures of the Anthropocene, in connection with scientific and technological development. To do this, it is important to understand the learning situations that enable its development.

FICTIONAL NARRATIVES TO DEVELOP FUTURES THINKING?

Futures Studies techniques inspire futures education, and the scenario method, for example, has been implemented in several educational contexts (Eckersley, 1999; Jones et al., 2012; Buntting and Jones, 2015; Pauw et al., 2018).

We are interested here in the possibilities offered by science fiction (SF), which is considered a "factory of futures images" (Rumpala, 2015). It is because science fiction extends or anticipates through the imagination the consequences of scientific and technological development in the material, social and cultural structures of societies that it has privileged links with futures studies. It thus constitutes a method in its own right. But if science fiction helps to conceptualize, to make certain imaginations come to life or to help understand what they imply, it is above all an artistic and creative expression. Its way of exploring times and alternatives can therefore be a help in making change concrete, accessible and sensitive (Lombardo, 2015).

First and foremost, science fiction narratives participate in the construction and dissemination of futures images, and as such, they can have a type of performative effect in feeding imaginations and preparing for future developments. Michaud (2017) thus makes science fiction an important element in the development of technoscience. He argues that cultural industries (e.g., cinema, literature, videogame) support industrial projects and maintain the desire for their development.

Fictional story writing is also used to raise awareness of environmental or scientific and technological development issues, and to encourage awareness of the need to act. It is seen as a means of influencing decision-making, imagining strategies for action and anticipating future changes. For example, the NESTA Foundation has funded an anthology of famous authors to warn of the consequences of antibiotic resistance[1], the University of Arizona publishes a collection of SF stories on the consequences of climate change every 2 years[2], and the Finnish Parliament has launched a short story writing competition open to all, to help identify possible unlikely events with extreme consequences, the so-called "wild cards" or "black swans" (Ahlqvist et al., 2015).

SF therefore refers to the possibility of creating fictional, meaningful worlds, which ultimately constitute simulations of our world, including "by pushing the boundaries" (Rumpala, 2016, p. 60), i.e., imagining endings or new worlds built on other civilizational premises, by investing in long-term issues. It is in this sense that we can speak of SF as a laboratory of thought experiments.

This is why SF productions are sometimes mobilized as material for the study of the relationship between science and society, and constitute research data that allow the social sciences to question the anthropological changes in the evolution of an increasingly technicized world. Miller (2015) goes even further, as she shows that SF works complement impact studies written in a rigorous and technical manner. In fact, by comparing the repertoire of SF and expert reports on two themes, namely nuclear power and artificial intelligence, she notes that certain dimensions (notably social, political and ethical) are not covered by the expert reports and that they are covered in SF. Thus, fiction and science are prolonged, fiction being a way to extrapolate the consequences of scientific results, adding emotions and feelings.

RESEARCH QUESTION

This article is aimed at identifying some general guidelines for developing futures thinking, based on analyzing singular teaching contexts dealing with Anthropocene issues and drawing on SSI, FE and EE trends. For this purpose, we are interested in evaluating and comparing the effect on futures thinking of two teaching contexts centered on the pupils' writing of fictional narratives. Following a training on SSI, two literature teachers decided to experiment with teaching about a SSI in their respective classrooms. Both wanted to innovate in their teaching, with the objective of developing their students' argumentative abilities regarding science-society issues. Having them write fictional narratives seemed to them a pedagogical means for articulating abilities related to the expression of language and thought, and abilities to reflect and question about SSI. In this article, we examine the nature of the futures thinking that students mobilize in their narratives.

METHODOLOGY

The work analyzed in this article was taken from two ordinary teaching situations, conducted by two French teachers who were trained in SSI during their initial formative year.

Teaching Contexts

We present here the teaching approaches designed and implemented by the teachers.

Teaching Context 1: The Human–Natural Environment Relationship in Fictional Narratives

This sequence was designed by a literature and philosophy teacher for pupils aged 15 to 16. It is divided into seven sessions. The teacher wanted the students to work on the following problem: how do the literature of ideas and the press invite us to rethink our relationship with nature? By addressing the issue of the relationship between human and nature at the time of the Anthropocene period through written production, she was able to meet the objectives of the curriculum, such as the development of judgment and critical thinking through the study of texts dealing with a controversy, or the analysis of different forms of argumentation. The work is based on fictional literature and requires the students to write a short story.

- Session 1: The aim of this 2-h session is to work on gathering information by studying the reasoning of different actors in their discourse on nature (for example Greta Thunberg's speech at Cop 24 or extracts from ecological SF short stories).
- Session 2: The argumentative purpose of a story is addressed through the study of *The Man Who Planted Trees* by Jean Giono. This is the story of a shepherd who decides to plant trees to bring the country back to life. At the end of the 2-h session, students are asked to write a 2-pages fictional short story, in the style of Giono, dealing with the relationship of human beings with the natural environment, and reporting on an action beneficial to nature taken by a character the narrator meets.
- Sessions 4–7 help students with their writing—drafting the short story, implementing the argumentative discourse, defending an opinion, building a character to serve the argumentative project.

Teaching Context 2: The Human–Technology Relationship in Fictional Narratives

This sequence was co-constructed by a literature teacher and a physics teacher, and addressed to students aged 14 to 15. It is divided into six specific sessions. The general objective of the sequence is to get students to think about the future of health technology with the development of nanotechnologies. It includes meetings with researchers (a lecture at the school and a visit at the researchers' lab), science lessons exemplified by the researchers' activities, and the writing of science fictional stories. We are interested here in the literature course in connection with which the writing activity took place.

- Sessions 1–4: a writing workshop with the literature teacher is set up, which consists of writing outlines of scenarios and snippets of stories.
- Session 5: a bionanotechnology researcher gives a lecture in the classroom, co-hosted by the physics teacher. At the end of this lecture, the pupils are given the task of writing a fictional story at home.

[1]https://www.nesta.org.uk/blog/we-need-to-talk-about-antimicrobial-resistance/
[2]https://climateimagination.asu.edu/

The pupils are assisted with their writing in the various disciplines involved in the educational experiment (technology, biology, physics, chemistry, literature). Each teacher initiates a discussion in their class about these stories in relation to their teaching subject, they address, for example, certain consequences, notably from an ethical point of view, of the possible applications of carbon nanotubes in physics chemistry, information storage in technology, health in biology. The pupils continue and complete their stories at home.

– Session 6: Volunteer pupils read the stories created, and there are interpretative debates based on the stories read (2 h) with the literature teacher.

The Data Collected

The data corpus is made up of the pupils' productions during the two sequences:

For teaching context 1: 16 individual short stories (two to six pages). Only one story was removed because it did not fit the general theme. **Supplementary Appendix 1** lists the themes addressed by the students in their stories. The stories highlight an extraordinary action by an individual confronted with an environmental problem.

For teaching context 2: 12 individual short stories (four to ten pages). These are the ones that were published in a book named *Nanorecits*[3]. **Supplementary Appendix 2** lists the themes addressed by the students in their stories, which can be grouped into three categories: (1) human enhancement is explored through the downloading of a dead person's human consciousness into a robot (story n°2) (2) geopolitical issues concern power struggles between nations and population control (stories n°6, 8, 9, 12). (3) The theme of nano-health is approached from the perspective of healing, preventive treatment, clinical trials and regeneration (stories n°1, 3, 4, 5, 7, 10, 11).

Framework for Analyzing Data

In order to analyze the mobilization of futures thinking by the students in the fictional stories, we employ a psycho-social model built by Ahvenharju et al. (2018) from a bibliographic synthesis involving various disciplinary backgrounds. According to this model, futures thinking is characterized by five dimensions:

Time perspective is the set of configurations that an individual or a group constructs to situate past, present or future events or situations in time. It can be more or less extended in time (time horizon) or preferably oriented toward the past or the future. It therefore differs between individuals, for example according to their age, living conditions, social status and culture. This dimension also refers to people's understanding of the future consequences of their actions.

Concern for others is an individual's ability to incorporate the wellbeing of others as a condition for one's own well-being. In this respect, it is in line with the idea of "world consciousness." Futures thinking involves a sensitivity to the axiological valence of futures, some of which are valued and desired, while others are rejected or disliked. The question of valued, hierarchical futures is therefore inherent to that of an ethical positioning. The "others" can be humans, animals, plants, etc. The preferred future scenarios are thus often linked to claims of sustainability, ecology or rights for future generations (Thompson, 2017).

Systems perceptions is the ability to think about situations in a comprehensive way, taking into account the relationships between the elements of a situation or the interdependence of systems. As such, the adoption of the synthetic or holistic viewpoint is valued over a purely analytical perspective. It integrates the way an individual perceives, combines and articulates different temporalities, for example those of human and natural phenomena.

Openness to alternatives is the ability of an individual to imagine open possibilities. In this way, it is deeply linked to creativity. It is also critical thinking, as it questions preconceived, prevailing ideas, in particular the idea of a determined and irreversible future. It is also an acceptance of the uncertainties inherent in futures and the consequences of actions, and thus values risk-taking.

Agency beliefs allow people to have a direct control over their actions according to the goals and objectives they have set for themselves. It implies a sense of self-efficacy that makes the individual believe in their ability to act upon the future to achieve their goals. It is also related to the way the future is perceived (open or determined future, optimistic or pessimistic views), and to the attitudes of individuals toward action (passive, active, proactive, etc.).

A content analysis in the form of key words (Krippendorff, 2004) associated with each dimension of futures thinking was used as criteria to categorize the pupils' productions (**Table 1**).

RESULTS

The results of the mobilization of futures thinking are, respectively, described below for each teaching context (human-living relationship, and human-living technologized relationship) according to the criteria outlined in **Table 1**.

Teaching Context 1: The Human–Natural Environment Relationship

Time perspective: We observed that 10 stories (out of 16) do not identify the action of the main character in time, while for the other six writings, this action extends from 5 years (construction of an animal shelter for example) to 20 years (the fight against deforestation). The action takes place in a cumulative manner, by successively adding together micro actions that ultimately give shape to an action that is part of time, without the links between the micro actions having been formalized or argued. Thus, for example, a story about the protection of caribou in Canada involves a number of successive actions, which are not specifically dated, but which add up to 20 years: observation of the animals' behavior, counting in the area, study of their diet,

[3]*"Nanorécits: un monde imaginaire insoupçonné. Fictions des élèves de la classe 304 du collège de Carbonne."* "Nanorecits: an unsuspected imaginary world." Fictions of the students of the class 304 of the college of Carbonne. Toulouse: Messages sas, sponsored by les Nouvelles Éditions Loubatières.

TABLE 1 | Criteria for identifying futures thinking dimensions in pupils' productions.

Dimensions of futures thinking	Criteria
Time perspective	Presence of chronological markers (dates, etc.) Presence of chronological connectors (after, then, during, etc.) Isolated events or continuous temporal process Causal links between events or processes
Concern for others	Caring, attention to others (human or non-human) Social or emotional connection Continuation or repair of the world
Systems perceptions	Taking into account the multifaceted aspect of a situation Taking into account the relationships between individuals, things and situation Taking into account the overall nature of a situation
Openness to alternatives	Imagination of one or more possible worlds Multiplicity of possibilities envisaged Optimism/pessimism of visions
Agency beliefs	Link between knowledge and empowerment Suggested courses of action Focus on political, economic, etc. powers

construction of a rescue center, which then extends to a center for the protection and study of the ecosystem.

Concern for others: Nine stories (out of 16) focus on efforts to save or care for wild animals living in forests. The other stories focus on a more complex entity, such as the "forest" or the "living environment," by evoking an interrelation between wildlife, flora and human social activities. This is the case, for example, in the story of the transition to agroecology of a farmer who is working to spread her ideas of "love for the land." The character whose actions are described in the stories is in most cases a person who lives in isolation from other humans (13 of 16). The production of the stories leads the pupils to question what should be done at the local level.

Systems perceptions: It is in the students' argumentation that we find elements of the systemic dimension, however, they are not elaborated upon. It comes in the form of a questioning of the relationship between human activities and their consequences on the forest or the environment, and constitutes the background against which most of the stories unfold. These contextual elements are most often expressed in the form of catastrophe: deforestation, industrial pollution, intensification of agricultural practices, climate change causing fires, and are described by the pupils as the causes of a decaying environment. This oppressive context is present in all but two of the writings, which show the importance of the natural environment for human health (sylvotherapy) or social resilience (restoration of a village following a storm).

Openness to alternatives: The actions described by the pupils are seen as realistic utopias set against a pessimistic background. Various relationships between human and the environment are thus made possible. Firstly, human action allows "nature to regain its rights." This idea is expressed in several ways according to the stories: creation of a natural area or a protection center for wildlife, repopulation. They also insist on the sustainable use of artificial objects (such as recycling, plastic Christmas trees). Finally, some writings show a more integrated social and natural world, especially in terms of land-use planning or shifts in agricultural production methods. However, these utopias are mostly conceived as local alternatives. Only one story tells of the national extension of a transition to agroecology.

Agency beliefs: Students write about different ways of changing the world. Some writings focus on the political dimensions of environmental issues, in the form of collectively organized resistance, sabotage of industrial plants, demonstrations and boycotts of consumer products. Others focus on the economic dimensions, for example, access to property is a way of settling conflicts over land use. It is through the commitment of an individual inhabited by the cause he or she defends that students consider the possibility of taking action. The type of relationship between the person and the narrator, which is mostly found in the stories, is one of mutual aid and transmission of knowledge.

Teaching Context 2: The Human–Technology Relationship

Time perspective: The long-term temporal dimension is barely addressed in the students' narratives. The short stories on the theme of nanohealth are anchored in the present or near-future and are focused on the search for solutions to treat incurable diseases. The temporal aspect focuses on the process of medical treatment or experimental protocol to develop treatments. The anchoring in the present and the non-questioning of the world mark the narrative on human enhancement, through the downloading of the consciousness of a deceased person into a robot to extend human exchanges beyond death. The stories about geopolitical competition between nations are also rooted in the resolution of present-day conflicts with a very Manichean representation of the protagonists. Here again, time is not questioned, only the victor is glorified. One story, about a researcher who has developed an anti-cancer treatment that allows people to live to be 160, questions life on earth and its temporality, and pushes the reader to question the opportunity to postpone old age and death. In sum, the chronological structure of the narratives is mainly in the present, with rapid time steps.

Concern for others is varied according to the themes of the stories. Thus, geopolitical narratives consider others only through international competition and the goal of world domination. It is a vision of dominance that drives technological research and the arms race. By contrast, the narratives of nanohealth are imbued with this concern for others. They all deal with human vulnerability through disease, clinical trials, care, and the fight against epidemics. Benevolence is therefore emphasized in these stories, which does not prevent the pupils from developing a critical distance from the applications of scientific research on living beings, in particular by addressing the themes of toxicity or the possible misuse of techniques.

Systems perceptions: The students' stories are focused on the character(s) in their narrative. As a result, they do not identify the totality and complexity of the situations and backgrounds in which the stories develop. The narratives related to nanohealth and human enhancement are confined to the enclosed spaces of the home, laboratory or hospital, and do not mention relationships with the outside world. The perseverance and dedication of researchers or doctors are central themes in the stories. The pupils do not consider the threat of exploitation of the care contract and the dangers of reification of the patient that can arise in increasingly molecularized medicine. They have complete confidence in the practitioners and the new technologies. This state of absolute confidence is not surprising. Indeed, the media discourse on nanohealth means that young people are certainly aware of it, but are focused on its promising effects. The same is true for topics related to geopolitical perspectives, which, as we have already mentioned, are caricatured in a Manichean approach between good and bad, stemming from the ideologies of the Cold War. Geopolitical complexity is not addressed by young people, nor is it included in the school curriculum for this age group.

Openness to alternatives: Optimism emerges from the analysis of the stories. The authors highlight particular qualities such as dedication, self-sacrifice, tenacity, perseverance, kindness and a sense of justice. Even if the outcome of the fictional story is not a happy one (such as the death of a volunteer patient in a clinical trial), it is the confidence in human beings that emerges through the emphasis on the virtues of the heroes of the stories. The future can thus be envisaged with serenity because humans are fundamentally good. Several relationships between humans and technology are thus made possible: the human who sacrifices himself to make technology more efficient, the human who devotes himself to technology to save others, the human who takes irrational risks. For all these students, technology is a means and not an end, it remains a tool to save humanity and improve lives, they do it for the wellbeing of humanity.

Agency beliefs: In their stories, the students show several ways of changing the world. The stories on the theme of nanohealth feature dedicated heroes focused on caring for others (curing diseases, restoring sight, ending a pandemic, finding a drug, improving a diagnosis). These narratives reflect the reliance on experts to change the medical world and continually push the boundaries of pathology. They ignore the collective work of teams and laboratories. The fictions that we have previously described as Manichean reflect a desire for commitment and an optimism in these young adolescents to face up to the adversities of life. When the community is envisaged, it is uniform and subject to a competitive military philosophy. The political dimensions of agentivity are almost absent, with only one story about population control showing this reflection. A young hero, aware of the use of technology to alienate people, investigates the toxicity of products and their use by the government with his sister. He creates a small network of resistant allies thanks to which he will thwart the manipulation and free the oppressed people.

Summary of Results

Results are closely linked to the specificity of each teaching context (architecture of the sequence, work instructions given, etc.). We have summarized them in **Table 2**.

TABLE 2 | Futures thinking in the two teaching contexts.

	The human - natural environment relationship	**The human - technology relationship**
Time perspective	Little consideration of temporalities	
Concern for others	The environment as a commons	Ambivalence of the human - technology relationship: the vulnerable individual who must be helped–the collective who must be dominated
Systems perceptions	Global dimension present but little explored (setting of the story)	Little explored global dimension, stereotyped technical social spaces
Openness to alternatives	Desirable future in a worrying background	A desirable future marked by trust in human beings and dedication to the service of others and technology
Agency beliefs	Different ways of acting, often individual initiatives	Different ways of acting, guided by the figure of the hero or the expert

DISCUSSION: GUIDELINES FOR THE DEVELOPMENT OF FUTURES THINKING

Thinking About the Temporalities of Processes and Phenomena

The analysis of the temporal dimension in the two teaching contexts shows that the students have difficulties in differentiating the temporalities of the phenomena or situations. Thus, differences in the temporality of tree growth, the rhythms of climate or social change, or innovative technological developments are not distinguished by pupils, nor are those constituting the different actions that are described in the narratives.

Temporalities are most often thought of in the short term, in the near future, and cannot give impetus to futures thinking as it should be solicited to think about the challenges of the Anthropocene. We can make the hypothesis here of considering them as a specific obstacle for the design of teaching situations. It is then a question of emphasizing a pedagogical support that allows pupils to pay attention to the proper time of the phenomena, processes or living beings, in order to inscribe their reflection in a temporal ecology (Grossin, 1996) that is not reduced to the measured social time of humans.

To do this, building scenarios of the future can be complementary to writing fictional stories. The scenario method consists in imagining the evolution of a system (for example, a socio-technical system such as the social deployment of a technology, or a socio-environmental system such as the development of a city or the transformation of an ecosystem). It is based on the identification and temporal monitoring of key trends and relevant drivers to simulate different changes according to the constraints applied (Amer et al., 2013). Scenario building leads students to explain changes by articulating not only different scales, local or global, individual and collective, but also different temporalities, because not everything changes at the same speed (Eckersley, 1999; Jones et al., 2012; Buntting and Jones, 2015; Pauw et al., 2018). We therefore propose here a few guidelines for the pedagogical framework of an activity involving the production of fictional narratives. First of all, it seems necessary to us to assume an explicit anchoring of the produced narratives in the sub-genre of near-future science-fiction. Indeed, a characteristic of near-future science fiction is its ability to set fiction in a familiar reality, but different from ours by introducing elements that do not exist (e.g., scientific and technological developments, social events, environmental changes). These fictional elements make possible changes in the forms of socialization even though the background is familiar. This created strangeness permits problematizing societal preoccupations (around nature, technology or science, society). Explicit teaching on the societal or environmental background is therefore important so that a coherent and strange story can develop and incite reflection or debate. One way of getting students to construct this background and its temporalities may be to have them identify the consequences of social, technological or environmental changes by building scenarios, whose evolutionary trends and drivers make it possible to grasp the temporalities at play. The writing of stories can thus be organized in a second step, taking place within the constructed background, and giving to see a more familiar futures image, coherent, and embodied in a narrative.

Our results show that the exercise of writing an anticipation story is relevant to address the themes of the Anthropocene with students. The stories have a familiar air, they can be close to the interests of young people. The writing can thus allow students to pay attention to what is happening now, to build on contemporary events in order to methodically explore what could happen in a more or less distant, but not strictly imaginary, future.

Investing in Relational Responsibilities

The narratives produced by the students, in both teaching contexts, consider vulnerabilities, they highlight the importance of relationships (e.g., human-animal, or human-landscape in teaching context 1; patient-doctor, patient-kin, or military-country in teaching context 2). However, these relationships are most often privatized within the confined space of the story character and his or her adventures, and do not allow for an exploration of responsibility beyond this local relationship. The narratives produced generally involve ethical questioning related to concern for others. It is initiated, for example, when students propose to think of the environment as a commons (in the sense of Ostrom, 1990), or highlight the benevolence of a doctor or researcher triumphing over disease, but it is not pursued through the examination of the relationships between actors, technologies, the links that all actors (human and non-human) can build with each other, and the impacts of these links. Relational responsibilities are not thought of in the service of the social contract that allows the perpetuation of society. The vulnerability of living beings is entrusted to the good will of superheroes, and the ordinary individual is deprived of his power to act. However, to take care of the environment, and by extension of the living, is to highlight the importance of particular relations and to institute them as the roots of our responsibilities. Indeed, the Anthropocene is not only a way of describing the degradation of natural systems as an effect of the modernization of human societies, it is also a sign of the need to renew the modes of attention between humans, living non-humans, and technology (Haraway, 2016). Therefore, it is about fostering social and cultural transformations that establish new relationships between humans and non-humans.

It is therefore necessary to explicitly invest educational work on relational responsibilities that problematize the impacts on environment and future generations. Nussbaum (2010) suggests building a social imaginary, based on everyday life, to construct moral emotions capable of considering vulnerability and combating feelings of omnipotence and domination. The aim is to stimulate emotional and cognitive reasoning in citizens in order to develop a moral imagination of the suffering of others (human and non-human) and of the relationships of social interdependence. Writing fictional narratives is thus appropriate to engage students in questioning human vulnerability. Nevertheless, our results show that agency beliefs are a weak point in the sequences studied in this article. It is one thing to give learners the opportunity to create ethical reasoning to probe the gray areas that our current perceptive and intellectual capacities are not able to perceive, it is another to develop in them capabilities, predispositions to action. Capability goes beyond competence, it encompasses what the person can do, but also what he or she can achieve in his or her environment. Capability thus implies the possibility that a person has to make choices between several possibilities that are presented to him or her, by judging what is estimable. It is therefore exercising a freedom of choice, the choice itself and the possibility to express this choice. Capabilities thus convey issues of social justice and the good life and could be a source of inspiration for the implementation of curricula for the development of agency beliefs.

Nussbaum (2000) proposes a base of ten capabilities as the foundation of a just society: life (being able to lead a life of normal length), bodily health (being able to be healthy), bodily integrity (being able to move around, being protected), senses, imagination and thought (being able to use one's senses, to imagine, to think, to be informed), emotions (being able to attach, to love, to associate), practical reason (being able to form a conception of the good and to participate in a critical reflection on the organization of one's life), affiliation (being able to live with and toward others, having the social bases of self-respect), relations with other species, play (being able to laugh, play, have fun), and control over one's environment (political: being able to participate politically, material: being able to own, have a job). These capabilities are a reserve of power to act from which each person can draw according to the circumstances, and we believe they can serve as a reference point for examining the narratives of a future world through the imagination. In concrete terms, this means structuring the narratives around one or more capabilities, which constitute dimensions that the students must explore. In the same way that the scenario method relies on trends and drivers to produce futures images, the capabilities could serve as key elements to be mobilized in futures images that stories present. To do this, building a fictional narrative could involve, for example, describing the forms of attachment that the characters have with each other, the forms of attention that they develop toward living beings or technology, the emotions that they express, or the forms of collective organization necessary to solve an environmental or socioscientific problem. It is thus a question of integrating into the pedagogical scenario a reasoning on a society of power to act, and of denouncing the attempts of reification of the living and the logics of domination, in order to envisage different ways of extending the possibilities of right action for individuals and collectives.

It is in fact a whole work of politicization that it is necessary to organize so that the students' narratives can provide opportunities to reflect on the means of collective action for change, and thus to encourage agency beliefs. The posture of author that is proposed to the students allows for fictional explorations that feed the construction of a futures thinking. The act of writing allows students to question what is important, what matters, for themselves and for others. In this sense, writing contributes to the moral development of the subject.

CONCLUSION

Our study shows that futures are perceived as worrisome by students and that their ability to change the world seems limited to them. Agency beliefs are low, many students seem to place their hopes in singular individuals or "superheroes."

The two teaching contexts presented are stemming from ordinary teaching practices, they were not conceived to develop futures thinking as we defined it from the model of Ahvenharju et al. (2018), but they have the interest to problematize the relations of the human being with the living and the technology by the writing of fictional narratives. It is therefore conceivable that the combination of different rationalities offers the possibility of opening up to different ways of thinking, acting and feeling about issues in the Anthropocene. Two guidelines for the design of teaching devices have been identified: the attention to be paid to the temporalities of processes and phenomena, and to consider responsibilities as relational. In order for the temporalities of the phenomena to be taken into account more in the fictional narratives, we recommend that the writing work be done after having built evolutionary scenarios (for example in the manner of Jones et al., 2012). In order for relational responsibilities to be explored, we suggest structuring the narratives around Nussbaum's capabilities; the students should then put into their narratives and question the quality of humans' life in the imagined futures.

Our study allowed us to show the feasibility of teaching context focused on the development of futures thinking, in connection with SSI and EE, and to understand some of their effects. Our results therefore allow us to consider these teaching contexts as being able to be integrated into the inquiry approach advocated in SSI pedagogy (Simonneaux et al., 2017; Amos and Levinson, 2019). Indeed, the inquiry pedagogical process proposed by Simonneaux et al. (2017) consists in putting students in a position to problematize and explore socioscientific issues. To this end, the inquiry is conceived as an iterative, interdisciplinary process, consisting of several stages: the gathering of information, the taking into account of the subjectivity of the investigators, the analysis of the information, the testing and selection of solutions, the proposal, and even the implementation of solutions and actions. The integration of didactic devices aiming at the development of futures thinking can thus make it possible to enrich the process of inquiry, which until now has been studied rather from the point of view of systemic and critical thinking. From this perspective, the writing of fictional narratives is interesting, but more research is needed to understand how it can be articulated with other pedagogical approaches (such as the scenario method) and how it can contribute to developing the agentivity of individuals and groups in the Anthropocene context. The two markers identified in this article can therefore also constitute points of vigilance for teachers, both in their conception of teaching-learning situations and in the pedagogical support of students' inquiry.

Complexity is at the heart of futures thinking, it is not only a capacity to anticipate the probable, but also to project oneself in time, to simulate the possible temporal effects of actions, to feel the articulation present-past-future, which leads to questioning all the participations of the actors, the sharing of responsibilities and interdependencies. As such, futures thinking is constitutive of a political thought, necessary for education in the Anthropocene.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

NH and NP wrote sections of the manuscript. Both authors contributed to manuscript revision, read, and approved the submitted version.

ACKNOWLEDGMENTS

The authors thank the teachers who contributed to this research by having their students write fictional stories.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2022.842252/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers in Education

ORIGINAL RESEARCH
published: 23 March 2022
doi: 10.3389/feduc.2022.838135

Rethinking Quality Science Education for Climate Action: Transdisciplinary Education for Transformative Learning and Engagement

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OPEN ACCESS

Edited by:
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Rosemary Hipkins,
New Zealand Council for Educational Research, New Zealand

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Specialty section:
This article was submitted to STEM Education, a section of the journal Frontiers in Education

Received: *17 December 2021*
Accepted: *08 February 2022*
Published: *23 March 2022*

Citation:
Kubisch S, Krimm H, Liebhaber N, Oberauer K, Deisenrieder V, Parth S, Frick M, Stötter J and Keller L (2022) Rethinking Quality Science Education for Climate Action: Transdisciplinary Education for Transformative Learning and Engagement. Front. Educ. 7:838135. doi: 10.3389/feduc.2022.838135

Latest findings of the IPCC highlight the fact that there is an urgent need for climate action on both individual and societal levels, because political regulations and technical advances just would not be enough to counter climate change. Acknowledging young people's role as present and future decision-makers, their engagement is absolutely imperative in order to achieve Sustainable Development Goal 13, "Climate Action." Therefore, new methods of teaching and learning are necessary, and they need to encourage transformative learning, which, it is assumed, will lay foundations for transformative engagement. Research in the field of science education credits scientific literacy vision III as fostering transformative learning and engagement. In this study, transdisciplinary education is analyzed as a promising concept that enables exchange of knowledge, experiences, and perspectives between students and scientific partners while they jointly complete research on real-world issues. A quantitative analysis capturing scientific literacy and transformative engagement for climate action of Austrian and German secondary school students (N = 162) is carried out alongside a literature review. This study reveals that the didactical concept of transdisciplinary education notably contributes to the implementation of scientific literacy vision III as well as vision II. According to the results, the three visions of scientific literacy are predictors for transformative engagement for climate action, assuming to be preceded by a transformative learning process. These encouraging findings need to be replicated by further scholars in other contexts.

Keywords: climate action, quality (science) education, sustainable development goals, transdisciplinary education, scientific literacy, transformative learning, transformative engagement

INTRODUCTION

Anthropogenic climate change (CC) is one of the Grand Challenges of the 21st century and the most prominent Planetary Boundary world society has to tackle (Steffen et al., 2015, 3–6; IPCC, 2018, V–VI). Visible CC consequences like increase of extreme weather events, such as drought and extreme heat in North America and Siberia, and heavy rains and flooding in Asia and Europe during summer 2021, demonstrate that CC is not only a future issue (Ciavarella et al., 2020, 21;

Schäfer et al., 2021, 14; Philip et al., 2021, 1–2). Increase of human interference with nature has become so intense that the age we live in has been designated the "Anthropocene," the age of mankind (Crutzen, 2006, 13; Zalasiewicz et al., 2017, 56). Nevertheless, world societies not only share responsibility for the climate crisis but also have a significant role in mitigating and adapting to CC (IPCC, 2018, V; O'Brien, 2018, 154). Young people, in particular, hold an important position, since they are the ones who will be increasingly affected by CC consequences during their lifetime. Their role as decision-makers of today and tomorrow, as well as their active engagement is critical to sustainable development (Corner et al., 2015, 523). In order to "limit global warming to well below 2, preferably to 1.5 degrees Celsius," the aim of the community of states in the Paris Agreement 2015 (UNFCCC, 2015), political regulations and financial investments, as well as scientific and technological breakthroughs, are necessary, but they alone are not enough (UNFCCC, 2015; Barnosky et al., 2016, 1). To maximize the success of meeting all these requirements, there is an urgent need for change, a transformation within the personal sphere, including beliefs, values, world views, and, more than anything, individual and collective actions for a climate-friendly future (Rockström et al., 2017, 1,269; O'Brien et al., 2018, 155–57).

Recently, there has been yet another call for education to not only produce knowledge but to also raise awareness on today's challenges and sustainable actions as well as to empower learners to develop key competencies like critical thinking, systems thinking, integrated problem-solving, and collaboration competency, as well as values to engage for sustainable development (WBGU, 2011, 352–58; UNESCO, 2017, 2021, 17). In this context, the role of transformative learning, which can be defined as "learning that transcends habitual thought patterns and behavior through deep learning that changes frames of reference, assumptions, and habits of mind" (Klein, 2018, 13) or, in Mezirow's words, learning "that transforms problematic frames of reference—sets of fixed assumptions and expectations [. . .]—to make them more inclusive, discriminating, open, reflective, and emotionally able to change" is discussed (Mezirow, 2003, 58). Consequently, this kind of learning is considered to be a powerful tool to create change and to promote individuals' transformative engagement (Mitchell et al., 2015, 88 and 92–93; Klein, 2018, 21). Transformative engagement, in this study, is understood in a more comprehensive understanding of Barnes et al.'s (2020, 824) definition of *transformative* and Grabau and Ma's (2017, 1,046–47) definition of *science engagement*, as being a fundamental change in individuals' cognitive, emotional and behavioral characteristics encouraging alteration of social-ecological relationships toward a climate-friendly future.

Sustainable Development Goal (SDG) 4, "Quality Education," plays a significant role in fostering this type of learning for achieving SDG 13, "Climate Action" (Boeren, 2019, 279; UN, 2021, 27). In this regard, the potential of science education with its major goal of raising scientific literacy (SL) has been thoroughly discussed (Laugksch, 2000, 84; Yacoubian, 2018, 308–9). However, can teacher-centered, knowledge-based science education really fulfill these challenges? A growing body of literature claims that traditional pathways of teaching have to be rethought in order to foster transformative learning and engagement, enabling participation, integration, and reflection (Singer-Brodowski, 2016, 15–16; Balsiger et al., 2017, 359; Hindley and Wall, 2018, 263–66; Kyle, 2020, 1; Leichenko and O'Brien, 2020, 1). Leichenko et al. (2021, 1), for example, stated that most climate change education (CCE) programs pay attention to the physical dimension of CC and evaluation of political, technological, and behavioral solutions without practically supporting students to adopt and sustain their active role in the necessary transformation. Kyle (2020, 4–5) argued that students frequently experience a kind of science education disassociated from real-world topics. He suggested that science education should empower students to actively deal with societal issues in their lifeworld. Moreover, many approaches fail to consider the relevance of emotions, values, and worldviews, which are important in provoking personal change (Leichenko et al., 2021, 2–3) [for more details, see Verlie et al. (2021) and O'Brien and Sygna (2013)]. In a literature review about effective CCE strategies, Monroe et al. (2019, 804–6) pointed out the importance of personal meaningfulness and engaging teaching methods by means of field trips, community action projects, or collaboration with scientists or affected persons. These claims were also addressed by the concept of SL vision III (Sjöström and Eilks, 2018, 67; Valladares, 2021, 581–82).

Moving beyond traditional pathways of (teaching and) learning, we argue that transdisciplinary education (TE) is a promising concept in science education, enabling students to perform research together with out-of-school (scientific) partners in real-world learning settings (Kubisch et al., 2021b, 3–5). TE is assumed to raise students' SL and transformative learning, foster personal meaningfulness and generate competencies *via* active engagement and exchange of experience as well as different perspectives and forms of knowledge (Thomas, 2009, 245; Mitchell et al., 2015, 86), and, finally, contribute to a climate-friendly future by transformative engagement (Kubisch et al., 2021b, 1). TE should not be considered as an isolated approach but rather a frame for active and constructivist learning approaches like inquiry-based learning (Riemeier, 2007; Pedaste et al., 2015).

The objective of this publication is fourfold:

(1) To provide an insight into the scholarly discussion about science education and SL for transformative engagement for climate action.
(2) To point out the relevance of TE by means of a literature review and good practice examples, addressing demands on science education in the field of CC.
(3) To quantitatively evaluate the change of predictive quality of the three dimensions of SL (vision I to III) on transformative engagement for climate action and assessing the single contribution of the visions (*via* pre-post comparison of secondary school students' answers in a TE project).
(4) To derive from the findings how and in which form TE can contribute to scientific literacy and transformative learning for transformative engagement for climate action.

The study is structured as follows: first, we give a brief insight into the role of science education, its limitations and visions, and significance of student's scientific literacy; this is followed by a literature review and good practice examples of transdisciplinarity (in education), and is continued by study design and results. We finish with discussion and conclusion.

VISIONS AND LIMITATIONS OF TODAY'S SCIENCE EDUCATION AND THE ROLE OF SCIENTIFIC LITERACY

In contrast with the broad consensus among scientists that anthropogenic CC is happening and that there is an urgent need for more actions (IPCC, 2018, V–VI), doubts about and denial of CC still exist in societies (Maibach et al., 2014, 295; Corner et al., 2015, 529; Jylhä, 2018, 487; Hahnel et al., 2020, 16). Since awareness of CC causes and consequences is critical for engagement and action (Poortinga et al., 2019, 25), there is still lack of individual and collective engagements (Maibach et al., 2014, 295–96; Jylhä, 2018, 487). Literature reviews of young peoples' CC awareness, knowledge, and action found that vague knowledge and concepts, as well as misconceptions about CC causes, impacts, and solutions persist among young people aged between 8 and 19 years (Corner et al., 2015, 529; Lee et al., 2020, 7–9). According to Lee et al. (2020, 7–9), scientifically accurate knowledge of the causes of CC tended to increase with age. The need for climate protection was proposed without the acknowledgment of personal responsibility or awareness of time lags of the usefulness of measures (Lee et al., 2020, 7–9). These findings are in contrast to the ongoing Fridays For Future movements (Hagedorn et al., 2019, 79) and general high levels of CC concern among young adults (Corner et al., 2015, 529).

Against the backdrop of findings pointing at various possible manifestations of young people's knowledge, awareness, and action, the importance of science education becomes apparent. Liu (2013, 26) states, that formerly mentioned challenges are also reflected in school, culminating in students' disinterest in science and decreasing interest in science careers. According to an international group of scholars, school science is disconnected from reality, failing to address the role of science in students' everyday lives (Linder et al., 2007, 2–3). Moreover, relevant topics like CC and the role of science for social, economic, and political actions are neglected. Consequently, recent calls from scholars state the need for transformative science education– moving away from simply teaching and learning disciplinary knowledge to "science-in-context" (Bencze and Alsop, 2014, 827–29). This is captured by the concept of socioscientific issues (SSIs) (Zeidler et al., 2005, 357; Zeidler et al., 2019, 1), contextualizing science knowledge and connecting science knowledge to issues of social significance (Bencze and Alsop, 2014, 833). This kind of science teaching and learning tends "to mold sustainable development education by developing general educational skills in the area of an individual's actions as a responsible member of society" (Eilks, 2015, 154–55). Thus, SSIs are part of an educational philosophy that is built on moral intelligence and social responsibility (Bencze and Alsop, 2014, 833). Moral intelligence and social responsibility also reflect in Valladares's (2021, 582) requests of a type of science education "that broadens the agency capacity of individuals and communities to take advantage of science in the generation of adaptative, resilient, and sustainable responses to unpredictable changes of today." Valladares (2021, 581) further states that in order to achieve transformative science education, students need to experience education that allows them to "understand, value, and relate to the world differently in their everyday lives, not only through canonic scientific ideas, but also through a dialog exchange of different perspectives (1), of alternative forms of knowledge (2) and by fostering student's engagement with science and with their community and culture (3)."

This notion is captured by the concept of SL, which is considered to be one of the major goals of science education, which is backed by scholars of science education, science curricula, and policy documents, as it is considered to be equally beneficial for both individuals and societies as a whole (Laugksch, 2000, 84; OECD, 2017, 21; Yacoubian, 2018, 308–9). According to science educationists, a scientifically literate person should be able to make informed decisions that are based on scientific knowledge, which requires factual and procedural knowledge of science. Scientifically literate people know about the benefits of science while simultaneously taking a critical perspective on science (Norris and Phillips, 2003, 225; OECD, 2017, 21; Yacoubian, 2018, 308). In particular, SL vision III, which can be designated as science for transformation (Sjöström and Eilks, 2018, 78) or critical SL (Hodson, 2011) in Sjöström and Eilks (2018, 66), touches on this idea, targeting to encourage critical engagement with science (Liu, 2013, 25) and sociopolitical actions (Hodson, 2003, 645). While aiming to contribute to critical citizenship and sustainability (Sjöström and Eilks, 2018, 78), vision III is closely associated with transformative learning (Mezirow, 2003, 58–59) and transdisciplinarity, fostering student's dialogical emancipation and participation (Sjöström and Eilks, 2018, 77; Valladares, 2021, 557). According to Simonneaux (2014, 51), critical reflexivity, participation, and action in scientific activities are significant for transformative science education. According to Choi et al. (2011, 681), a concept of SL for the 21st century is required, which includes competencies, which echo the competencies demanded by Education for Sustainable Development (ESD) (UNESCO, 2017, 10). Wiek et al. (2011, 204) propose a definition of competencies contributing to sustainability as "complexes of knowledge, skills, and attitudes that enable successful task performance and problem solving with respect to real-world sustainability problems, challenges, and opportunities." Besides SL vision III, their definition also highlights the importance of visions I and II of SL. While vision I is focused on knowledge of scientific content and processes, vision II creates a link to students' lifeworld, focusing on the relevance of scientific knowledge and processes in society (Roberts, 2007, 2011). Consequently, vision I, "within science," is focused on pure science learners aiming to develop mental capacity and preparing for a science career, whereas vision II targets bridging science and society. Meanwhile, vision III, "science within society," aims at encouraging students to engage in complex SSIs for seeking informed and responsible solutions (Liu, 2013, 29). Liu (2013, 31) argues that “focusing on one vision while ignoring others is undesirable” (Liu, 2013, 31), since the three visions of SL are interdependent and reinforce each other. Balanced didactical implementation of the three visions of SL might also face challenges similar to those encompassed in the concept of ESD. ESD is now an educationally well-justified concept (Burmeister and Eilks, 2012, 93–94; Burmeister et al., 2013, 169), however, its implementation in formal school education still remains rare (Eilks, 2015, 156). Despite the demand for competencies, educating responsible and critical citizens, which is significant for achieving SL vision III, teaching and learning, in many cases, still remains content-driven (Eilks, 2015, 156). According to Burmeister et al. (2013, 173–74), reasons for this are lack of teacher’s knowledge of the ESD philosophy and pedagogy and limited resources. However, Sjöström and Rydberg (2018, 9) point out possible didactical dilemmas that might arise if teachers aim to balance knowledge transfer, competency generation, and students’ sociopolitical participation. This might also be true for balanced implementation of the three visions of SL.

As a consequence of the reflections of expanding SL to vision III, the vision of knowing-in-action (Aikenhead, 2007, 68), subject teaching, and learning will need to transcend school boundaries and open up students’ lifeworld, acknowledging the importance of transdisciplinary perspectives and fostering active engagement with SSIs (Hodson, 2003, 666; Sjöström and Eilks, 2018, 77; Zeidler et al., 2019, 1) while simultaneously considering possible didactical dilemmas (Sjöström and Rydberg, 2018, 9).

TRANSDISCIPLINARITY IN EDUCATION: LITERATURE REVIEW AND GOOD PRACTICE EXAMPLES

Literature Review and Good Practice Examples of Transdisciplinarity

In this section, the aims, procedures, and further outcomes of transdisciplinary collaborations are discussed. Firstly focusing on transdisciplinarity in science education, Sjöström and Rydberg (2018, 5 and 10) define transdisciplinary Didaktik as partnerships between teachers of different school subjects, who teach about SSI. Further studies on formal school education that discuss transdisciplinarity share a similar definition (e.g., Nordén, 2018, 666–67). In this study, we go beyond this understanding, arguing that transdisciplinarity in school education is rare (Kubisch et al., 2021b, 2); focusing predominantly on higher education [e.g., Clarke and Ashhurst (2018); Beecroft (2019), Pohl et al. (2018), and Clark and Button (2011)], we draw on literature discussing transdisciplinary research and transdisciplinarity in higher education. However, before we clarify how transdisciplinarity and TE are understood in this study, we will explore Lang et al.’s (2012) understanding of transdisciplinary research in the realm of sustainability science and how we share these views.

Transdisciplinary research involves high levels of integration and reflection. Partners from science and societies work together tackling socially relevant scientific issues like CC. Societal partners tend to be those who are affected by a problem and who have different experiences and expertise on the issue. The process of dealing with these challenges is based on scientific research processes and draws on both diverse interdisciplinary methods and mutual exchange of knowledge and experiences, aims, interests, and visions of science and society (Lang et al., 2012, 28–35). All partners are continuously involved in the scientific knowledge production process, co-producing knowledge for sustainable solutions as well as generating societal (e.g., community well-being) and scientific effects (e.g., new scientific insights) (Walter et al., 2007, 326–28). Aligning with transdisciplinary research, an SSI is the starting point of TE, being addressed in a dialogical manner between students and diverse partners from science and outside academia exchanging scientific and everyday life knowledge and experience (Schmohl and Philipp, 2021, 14; Kubisch et al., 2021b, 3–4). This exchange enables mutual learning among all those involved (Clark and Button, 2011, 50; Mitchell et al., 2015, 93). “Learning in this sense is a process that collaboratively generates new rich insights that remain undetectable from a single disciplinary or purpose-less (in Jantsch’s terms) perspective” (Mitchell et al., 2015, 93). In addition to improving students’ research skills (Currie et al., 2005, 405), knowledge production is one of the outcomes of transdisciplinary collaboration. According to the ProClim (1997, 15) report, three kinds of knowledge are required to foster sustainable development, i.e., system knowledge (knowledge of structures and processes and the current *status quo*), target knowledge (visions and goals of society), and transformation knowledge (knowledge of how to achieve targets) (ProClim, 1997, 15). The design of TE study programs [e.g., by Pearce et al. (2018)] aims to enable students to acquire these types of knowledge. Drawing on a conceptual assessment and the experience of the authors of that study, active involvement in scientific processes and collaboration with scientists and societal partners are assumed to promote these kinds of knowledge and generate diverse kinds of competencies (Pearce et al., 2018, 168–171 and 179). Building competencies and environmental awareness are also strengths of TE. Clark and Button (2011, 48) point out the development of critical thinking competency, and Young et al. (2015, 72) name communicative competency and environmental awareness, linking their TE approach science, art, and community. The development of these competencies ascribed to TE is in line with the demands of SDG 4, “Quality Education” for competency generation according to the goals of ESD (UNESCO, 2017, 10). Furthermore, Vilsmaier and Lang (2015, 51) draw attention to the increase of reflective thinking by TE. “Thereby students learn how to change perspectives and create mutual understanding [. . .]. The exploration of the otherness of the other further enhances the understanding of their own perspective, knowledge [. . .] as well as of their social background. This exploration also allows for reflection of the students’ own values, interests, objectives and culturality” (Vilsmaier and Lang, 2015, 51). Consequently, TE creates an environment of deep reflection, which, in turn, facilitates conceptual change of misconceptions and restructures existing mental models (Mitchell et al., 2015, 93; Thomas and Kirby, 2020, 223). According to Mitchell et al. (2015, 93) and Klein (2018, 16 and 20–21), this kind of transformative learning enables reflection and evolution of thought patterns, norms, values, and behaviors, which promote change toward sustainability. This is confirmed by Walter et al. (2007, 333–34) by demonstrating that transdisciplinary collaboration not only fosters the decision-making capacity of partners involved but also supports the generation of transformational knowledge, which is acknowledged to be relevant for action.

Returning to the argument mooted at the beginning of this chapter, namely, that transdisciplinarity in formal school education is rare (Kubisch et al., 2021b, 2), we would finally like to refer to research in the field of place-based SSI approaches. According to Semken and Butler Freeman (2008, 1,043–44), these approaches variously address transdisciplinary knowledge exchange between students and various out-of-school partners (e.g., researchers and community members). Herman et al. (2019, 347–57) demonstrate that students' explanations of an SSI became more discriminating and representative of complex interactions within a system during a place-based intervention, which fostered the exchange of different perspectives with out-of-school partners (Herman et al., 2019, 347–57). Beyond this study, Zeidler et al. (2019, 7) argue that place-based SSI approaches are proven to be effective even if topics to be discussed are detached from student's lifeworld.

Example of SEAS and *k.i.d.Z.21*: A Good Practice Example

The EU funded project *Science Education for Action and Engagement toward Sustainability* (*SEAS*) compares teaching and learning approaches within so-called open schooling networks in different European countries (Austria, Belgium, Estonia, Italy, Norway, and Sweden). Building on a transdisciplinary approach, schools opened to their environment, allowing students and teachers to collaborate with diverse out-of-school partners on finding solutions for real-world sustainability issues within their community. The aim of *SEAS* is to increase students' SL and to trigger transformative engagement in order to contribute to a sustainable present and future (Kubisch et al., 2021b, 9).

The Austrian research education collaboration on CC, *k.i.d.Z.21—competent toward the future*, is an exemplary representation of a successful TE project within the project *SEAS* (see, e.g., Keller et al., 2019; Deisenrieder et al., 2020; Kubisch et al., 2021a). *k.i.d.Z.21* was founded in the year 2012 with the purpose of increasing young people's awareness of CC and its consequences to generate acceptance of necessary socio-ecological transformation and prepare students not just for today's but also future challenges. Over the course of one school year, Austrian and German students aged between 13 and 16 years deal with the topic of CC in different inter-and transdisciplinary modules (Oberrauch et al., 2015, 19–26; Stötter et al., 2016, 214–15). Since the beginning of *k.i.d.Z.21*, more than 3,500 students and 100 scientific partners have worked in collaboration. **Figure 1** shows the modules of *k.i.d.Z.21* during one school year. These are based on didactical approaches of moderate constructivism and inquiry-based learning, and are embedded in an inter- and transdisciplinary setting (red framed modules in **Figure 1**) (Oberrauch et al., 2015, 19–26; Kubisch et al., 2021b, 5–6).

The moderate constructivist understanding of learning originates from the idea that learning is an active, situational, emotional, social, and self-regulated process. Therefore, learning is considered as a constructive process, which builds on available conceptions originating from individual experiences (Riemeier, 2007, 69–70). In order to facilitate individual knowledge construction processes, students need both the space to follow their interests and to tie up with their preconceptions and experiences (Widodo and Reinders, 2004, 237–38), which are implemented with inquiry-based learning modules. Inquiry-based learning enables students to identify problems, build hypotheses, formulate their own research questions, collect data, and construct answers to their individual questions. From a pedagogical point of view, students are guided through this complex scientific process, which is didactically reduced. Research studies in the field of inquiry-based learning demonstrate its potential in comparison to traditional teaching styles of direct instruction (Pedaste et al., 2015, 48). Furtak et al. (2012, 315–16) indicate a positive effect of inquiry-based teaching on students' learning in a meta-analysis, while Pedaste and Sarapuu (2006, 48) show the application and generation of problem-solving competencies during inquiry processes. Furthermore, the European Commission acknowledged inquiry-based learning as an important and effective learning approach to build a scientifically literate society (European Commission, 2007, 2). The expansion of SL and a higher learning effect are also proven by studies in the field of moderate constructivist teaching and learning (Widodo and Reinders, 2004, 233).

The moderate constructivist approach of learning cuts across all *k.i.d.Z.21* modules, while the inquiry-based learning approach is applied in the *individual CC research projects* module and the *Alpine Research Weeks*. The *k.i.d.Z.21* project begins with a logo competition at the start of a school year. Based around the area of arts education, students deal with CC for the first time and capture their association with CC in a logo, which accompanies them through the full-year collaboration. The starting point of the transdisciplinary collaboration is the subsequent *kick-off event*. In this module, students and teachers start a dialog with scientific experts, politicians, and peers to discuss climate change, its consequences, and possible solutions in different fields of everyday life. Besides lectures about CC, students pass through different workshops where, for example, they discuss different keywords such as "youth engagement," "sustainability," and "my city" at the global and local levels in the context of CC with scientific experts, politicians, and peers. Consequently, students' pre-concepts of and experiences with CC are captured and included in the discussions. During the school year, students have *classical school lessons on CC* in different subjects (e.g., in musical education and mathematics education). This module is guided by participating teachers themselves, connecting and expanding the learning objectives of their subject with the topic of CC. Moreover, students generate their own questions about CC and individually develop *CC research projects* that are presented at the end of the school year. Based on the approach of inquiry-based learning and a moderate constructivist understanding of

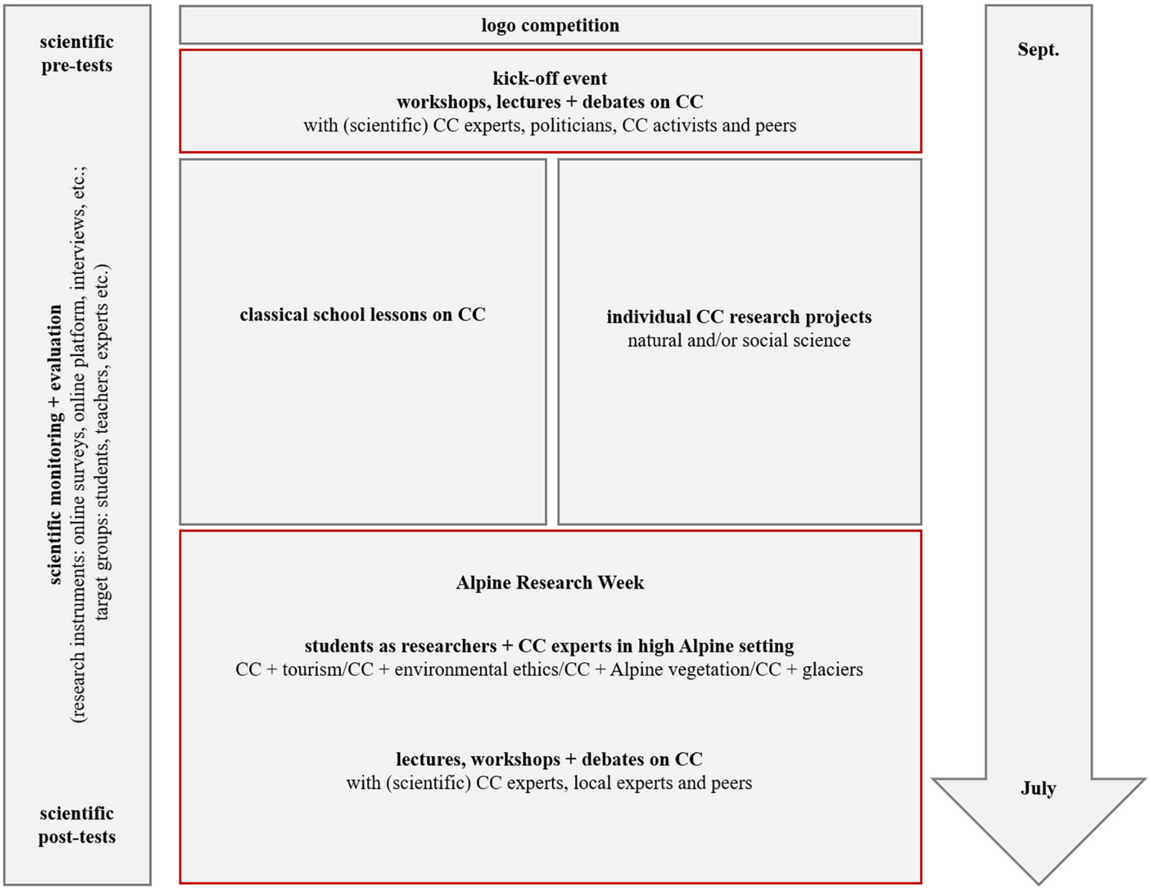

FIGURE 1 | Modules of the Austrian transdisciplinary education (TE) project *k.i.d.Z.21*, with the red-framed modules as transdisciplinary modules [source: modified according to Kubisch et al. (2021b, 6)].

learning, students have total freedom to design their projects. They are able to follow their interests in generating a research question and are free in collecting and analyzing the data as well as in the way they present their findings. They are supported by their teacher, whenever necessary. Students have developed innovative research projects in the past. For example, some students measured the temperature over a period of time in the village in which they lived and compared it to the location of their school within the city. Others analyzed the travel behavior of classmates and teachers and developed an initiative, motivating them to act climate-friendly by going to school by bike. During the inter- and transdisciplinary *Alpine Research Week*, students and scientific experts meet in a high Alpine Mountain area to do research on CC in different fields (e.g., tourism, environmental ethics, glacier, and Alpine vegetation) in a real-world learning setting. According to the moderate constructivist approach to learning, students are only guided by necessary instructions and have the opportunity to develop their own research questions and hypotheses, collect data, and present their findings in groups. Scientific experts and the *k.i.d.Z.21* team take the role of coaches: they support the students whenever necessary in their research process and discuss and interact with them as equal partners (Kubisch et al., 2021b, 5–6). The tourism module, for example, starts with capturing students' pre-concepts about CC and tourism in a concept map. The concept map is continuously expanded during the module. After capturing first associations of CC, students and scientific experts go to an elevation and discuss the change of the city and landscape, comparing a photograph of the past with the reality in front of them. From this discussion, they develop their own research questions in small groups and do research, collecting and analyzing data to finally report their findings in a presentation. Ultimately, the entire group meets again to present and discuss each groups' findings. The module finishes with an expansion of the concept maps. The other modules also offer pre-defined tasks (e.g., an albedo experiment in the glacier module and emotional mapping in the environmental ethic module), and students have the opportunity to conduct research on climate change based on their individual research questions.

The collaboration with participating teachers, who are representatives for their respective schools, starts with a teacher training course, which is offered once a year. During the one-week training, the teachers are introduced to the didactical concept and the modules of *k.i.d.Z.21*, and organizational tasks are discussed. Collaboration with schools is usually through one contact person, namely, one teacher who takes part in the teacher training. This person is responsible for cascading the objectives of the project, in-school modules, and tasks involved to other subject teachers who will be delivering them in their respective lessons, e.g., the module *logo competition* or classical school lessons on CC. In the past, it has been seen that many teachers eventually chose to take part in the teacher training themselves. The transdisciplinary modules are guided by the *k.i.d.Z.21* team and scientific experts who voluntarily support the project.

The didactical approach of *k.i.d.Z.21* appears to be very effective with regard to both learning outcome and potential to increase an environmental-friendly behavior. It also meets the demands of Agenda 2030 and ESD (UN, 2015, 21; UNESCO, 2017, 10). At the same time, it embodies the same claims as transformative science education, being participative, engaging, and allowing the exchange of different expertise (Valladares, 2021, 581). This is reinforced by the findings of accompanying scientific evaluation of *k.i.d.Z.21* so far. Keller et al. (2019) demonstrate that during the module with the highest degree of transdisciplinarity and active involvement in an inquiry-process, the *Alpine Research Week*, students learned the most about CC and its consequences, in second place were the *individual CC research projects* and in third place the *kick-off event.* Classical school lessons obtained the lowest results. Moreover, students felt better prepared to face the challenges of CC after taking part in *k.i.d.Z.21* (Keller et al., 2019, 40–42; Kubisch et al., 2021a, 6–8). The latter may be explained by the simultaneous increase in knowledge of CC, its causes and consequences, and how to act climate-friendly, as unpublished findings in the research education-collaboration demonstrate. Analyzing pre- and post-changes in knowledge, attitudes, personal concern, climate-friendly behavior, and multiplicative action among different types of awareness, Kuthe et al. (2019, 382–83) show that by means of diverse didactical concepts of *k.i.d.Z.21,* weaknesses in students' climate literacy could be addressed. Deisenrieder et al. (2020, 8–11) and Kubisch et al. (2021a, 6–8) indicate that in addition to self-efficacy and future concern, students' climate-friendly behavior in different dimensions (everyday behavior, information seeking, and dissemination as well as engagement) could be significantly raised during the course of one school year. Furthermore, the findings of Kubisch et al. (2021a, 6–8) show that the collaboration during the *Alpine Research Week* resulted in a mutual learning effect among students, teachers, and scientific experts, as opposed to a one-dimensional knowledge transfer. Both teachers and students prefer more frequent collaboration with scientific experts when working on the solution of real-world problems. Additionally, statistical analysis by means of SPSS IBM Statistic 26 of unpublished findings of a standardized questionnaire in the TE project *k.i.d.Z.21* demonstrates an increase in students' understanding of scientific processes, how to argue scientifically, and how to reflect on problems from different perspectives. Students acquired an understanding of why science is important in everyday life and how to apply scientific knowledge in everyday life after collaborating with scientific experts in the *Alpine Research Week* in 2021.

These findings show the enormous potential that the didactical concept of *k.i.d.Z.21* has to contribute to SL and transformative engagement, combining the moderate constructivist approach and inquiry-based learning in inter- and transdisciplinary settings.

STUDY DESIGN AND METHOD

The study was carried out in the project *SEAS* with $N = 162$ secondary school students from Austria and Germany, aged between 13 and 16 years who were part of the research-education cooperation *k.i.d.Z.21*. In total, 27.8% of the students were female, while 31.6% of the students were male; 2.3% were diverse; 38.4% of the students preferred not to answer the question. The students were consulted by means of a standardized online questionnaire before (pre-test) and after (post-test) being part of the TE project. The collaboration started at the beginning of the school year in September 2020 and ended in July 2021. Besides SL (visions I to III), students' climate-friendly behavior, their CC concern, their feeling of responsibility, and their locus of control regarding CC were queried (see **Table 1**). These items were derived and modified in a further *k.i.d.Z.21* standardized questionnaire. The questionnaire has been applied since the beginning of the project in 2012. The items of SL were derived and modified *via* the following assessment instruments (Pugh et al., 2010; Reeve and Tseng, 2011; Heddy and Sinatra, 2017; Patall et al., 2018) and co-developed by SEAS partners. All the questions were closed questions using a five-point assessment Likert scale, in which the dimensions ranged from "I disagree" to "I agree." The standardized questionnaire asked for students' self-assessment, possibly biasing the data, which can be declared as a limitation of this study. The reliability of the questionnaire was tested with Austrian secondary school students independently of the TE project.

The statistical relationship between students' SL and their transformative engagement for climate action was analyzed before and after participating in the TE project *k.i.d.Z.21*. According to the definition in the introduction, transformative engagement for climate action consists of students' awareness of CC and the need to act, their feeling of responsibility, their locus of control, and their climate-friendly behavior (see **Table 1**). Subsequently, the single contribution of the three visions of SL to transformative engagement was assessed in more detail.

The data were analyzed using SPSS IBM Statistics 26. In order to distinguish the three dimensions of SL a factor analysis, more specifically, a principal component analysis with varimax rotation was used (Sedlmeier and Renkewitz, 2013, 684). An analysis of scale reliability (SR) by means of Cronbach's alpha ensures that the constructs analyzed are well represented by the single items. According to Kuckartz et al. (2013, 247), values for SR are interpreted to be acceptable if $SR > 0.7$. In order to assess the predictive quality of the three visions of SL for transformative engagement for climate action, a regression analysis was conducted. Both pre- and post-test data were analyzed by multiple regression analysis in order to detect changes in the predictive power of SL before and after

TABLE 1 | Items and factors used for analysis.

Factors (question)	Items (5 Likert Scale—"I disagree" to "I agree")	Cronbach's Alpha (SR) pre-/post-test
Scientific Literacy (Vision I)	.	0.732/0.814
Which of the following statements describe scientific research?	Scientific research is better, when scientists use a more complicated language. (*with reversed polarity)	
	Scientists cannot be neutral when profit-making companies fund the research. (*with reversed polarity)	
	Researchers can adapt their results and data to give a more favorable impression. (*with reversed polarity)	
	In the development of medicines, it is acceptable to do animal experiments. (*with reversed polarity)	
	A scientist should be driven by his/her personal ideals. (*with reversed polarity)	
Scientific Literacy (Vision II)		0.742/0.892
Which of the following statements describe scientific research?	Observation and experiments are important for scientific exploration.	
	Analyzing data and sharing results is an important principle of scientific method.	
	A scientist contributes to the solutions of societal and/or environmental problems.	
Which of the following examples is a scientific topic for you?	Finding solutions for an environmentally- friendly way of living	
	Measuring your personal electricity consumption as a basis for implementing energy-saving measures	
	Can you add anything to a glass full to the brim with water? Experiment with coins that show the surface tension of water	
	Watch sports news to find out the results of the current football matches. (*with reversed polarity)	
Scientific Literacy (Vision III)		0.927/0.956
To what extent do you agree with the following statements?	I make suggestions about how to improve activities related to science.	
	I talk with my parents about scientific topics that I have learnt.	
	I seek out opportunities to apply my knowledge of science in my everyday life.	
	I worked as hard as I can in topics related to science.	
	I notice scientific facts and events.	
	I participated in discussions related to science.	
	I tried to connect my own experiences with what I previously learned about topics related to science.	
	The scientific topics I am studying are important to me.	
	The scientific topics I am learning can be applied to real life.	
	Scientific topics are practical for me.	
	I felt interested in topics related to science.	
Transformative engagement for climate action		0.887/0.946
To what extent do you agree with the following statements?	It's already too late to act on climate change. (*with reversed polarity)	
	Mankind is primarily responsible for climate change.	
	I feel it is important to take good care of the environment.	
	Every individual must adopt a lifestyle for a future worth living.	
	In our region we are able to contribute to climate protection.	
	I am careful not to waste water.	
	I am careful not to waste food.	
	I separate most of my waste for recycling.	
	I prefer to use public transport or bicycle over car.	
	I try to save energy.	
	With my friends I teach others on the importance to act against climate change.	

taking part in the TE project. Variance inflation factor (VIF) was calculated to prevent multicollinearity of the predictors, and values for VIF < 10 were acknowledged as acceptable (Kuckartz et al., 2013, 271–72). The effect size of the adjusted R^2 was calculated to indicate the practical importance of the results beyond statistical significance ($p < 0.05$). A low effect size is defined for values between $0.1 \leq f < 0.25$, a medium one for $0.25 \leq f < 0.40$, and a high effect size for $f > 0.4$ (Cohen, 1988, 410–14). A test for normal distribution was waived, since the sample size is sufficiently high, preventing major effects on the results of the analysis (Sedlmeier and Renkewitz, 2013, 325).

RESULTS

Preparation of the Data

Before beginning the main evaluation of the data, a principal component analysis was conducted comprising the SL items. The results opt for a three-factorial solution, resolving 61.53% of the total variance. The items, being allocated to the respective factor, substantively fit the definition of the SL visions. Items belonging to SL visions I and II queried students' concepts about science and scientific research; however, vision II was focused more on scientific processes and linked those to student's lives. SL vision III was focused on students' practical and transformative engagement with science inside and outside the classroom (see section "Visions and Limitations of Today's Science Education and Role of Scientific Literacy"). Cronbach's alpha was calculated for the three factors of SL and for transformative engagement for climate action to guarantee the reliability of the factors (for more information, see **Table 1**).

Multiple Regression Analysis Pre- and Post-tests

A multiple regression analysis was performed to analyze the predictive quality of the model. The pre- and post-test comparisons of the multiple regression aimed to show the change in predictive quality of SL on transformative engagement before and after participation in the TE project. The three visions of SL were treated as predictors, while transformative engagement for climate action was treated as criterion variable. In order to adequately determine the contribution of the TE project, change in the predictive quality of the SL model was analyzed. The *status quo* of students' SL visions both at the beginning of the school year (pre-test data) and at the end of the school year (post-test data) were used to predict students' transformative engagement for climate action at the end of the school year (post-test data).

Scientific literacy (SL) visions I to III were able to statistically significantly predict transformative engagement both in the pre-test [$F(3, 73) = 5.777$, $p < 0.01$] and the post-test [$F(3, 168) = 50.86$, $p < 0.01$]. The findings revealed that the predictive quality of the model increased after the project (adjusted $R^2_{pre-test}$ < adjusted $R^2_{post-test}$), explaining more of the variance of transformative engagement. While the pre-test model explained 16.4% of the variance, the post-test model explained 47.1% of the variance of transformative engagement. In the pre-test, considering the standardized *ß* coefficient, only SL vision I had a significant influence on transformative engagement ($ß = 0.413$, $p < 0.01$), whereas in the post-test model all the three visions significantly predicted transformative engagement. The standardized *ß* coefficient of SL vision I, however, decreased in the post-evaluation ($ß = 0.152$, $p < 0.05$), also in comparison to the standardized coefficients of SL vision II ($ß = 0.311$, $p < 0.01$) and III ($ß = 0.34$, $p < 0.01$) in the post-evaluation. Consequently, in the post-evaluation, SL vision III had a higher influence on transformative engagement for climate action than vision I and a slightly higher influence than vision II (see **Table 2**). Referring to Cohen (1988), the effect sizes of both the pre-test model ($f = 0.442$) and the post-test model ($f = 0.944$) were high.

DISCUSSION AND RECOMMENDATIONS: TE FOR TRANSFORMATIVE SCIENCE EDUCATION

The concept of SL is thoroughly discussed by scholars (Norris and Phillips, 2003, 225), being defined as a major goal of science education (Yacoubian, 2018, 308) and as a prerequisite for a scientifically literate and responsible society (OECD, 2017, 39). Current scholarly debates draw on a more comprehensive view and emphasize the need for science education and, thus, SL to address the pressing socio-ecological challenges of our time. Initial definitions were based on a narrower understanding of the term "scientifically literate," focusing on the understanding of scientific knowledge and processes [Showalter (1974) in Laugksch (2000, 74)]. Today's science education is meant to foster change in values, attitudes, and behaviors at individual and societal levels, supporting sustainable development (Laugksch, 2000, 84; OECD, 2017, 39; Sjöström and Eilks, 2018, 78; Valladares, 2021, 581–82). Beyond SL visions I and II, which relate to scientific knowledge and processes for later application and understanding of the usefulness of scientific knowledge in life and society (Sjöström and Eilks, 2018, 65–66), SL vision III is assumed to contribute to transformative engagement by means of engaging teaching methods and knowing-in-action (Aikenhead, 2007, 68; Liu, 2013, 29).

For our research, we collected data by means of a standardized questionnaire from secondary school students in Austria and Germany. The data were evaluated by regression analysis, taking a closer look at the contribution of SL and the single SL visions to student's transformative engagement for climate action, both before and after taking part in the TE project *k.i.d.Z.21* (**Table 2**). The regression analysis of the post-test model reveals that all the three visions of SL statistically significantly predict transformative engagement for climate action, with SL vision III measuring practical and transformative engagement in science and having a slightly higher influence than vision II and greater influence than vision I. Visions I and II, which capture knowledge and concepts of science and scientific processes and practical implications of science, have a (slightly) minor influence on transformative engagement. Despite increasing calls for (science) education to be transformative (Balsiger et al., 2017, 359; Kyle, 2020, 1; Valladares, 2021, 581–82), the results are in contrast to a wide range of school curricula, which are predominantly based on knowledge production and are not connected to students' lifeworld (Balsiger et al., 2017, 359; Kyle, 2020, 1–4). Moreover, the majority of scholarly debates is still focused on knowledge, e.g., improvement of CC knowledge (Monroe et al., 2019, 796–98). Of course, the significance of knowledge should not be underestimated, since the exchange of knowledge and knowledge production is one of the leading aims and outcomes of transdisciplinary collaborations (Lang et al., 2012, 26). We concur with Liu (2013, 31) that all the three visions of SL are important, including knowledge of scientific concepts and processes. Consistent with the emphasis on the importance of (science) education in sustainability discourse (UN, 2015;

TABLE 2 | Pre-post comparison regression analysis—scientific literacy for transformative engagement for climate action.

Variables	$\beta_{pre/post}$	$SE_{pre/post-}$	$t_{pre/post}$	$p_{pre/post}$	$VIF_{pre/post}$
SL vision 1	0.413/0.152	0.123/0.070	3.830/2.181	0.000**/0.031**	1.016/1.552
SL vision 2	0.070/0.311	0.240/0.094	0.538/3.300	0.593/0.001*	1.474/2.812
SL vision 3	0.099/0.340	0.170/0.084	0.767/4.169	0.445/0.000**	1.459/2.110
$R^2_{pre/post}$	**0.198/0.480**	–	–	–	–
adjusted $R^2_{pre/post}$	**0.164/0.471**	–	–	–	–

***Significant results at the level of $p < 0.01$.*
**Significant results at the level of $p < 0.05$.*
β, standardized regression coefficient; SE, standard error; t, t-value; p, statistical significance; VIF, variation inflation factor; pre, pre-test data; post, post-test data; R^2, coefficient of determination; adjusted R^2, adjusted coefficient of determination.

UNESCO, 2017; Kyle, 2020, 1), we propose a more visionary approach to science education considering all the three visions of SL. However, we emphasize the need for didactical concepts, which foster the transformative potential of SL, especially vision III. Hence, returning to the initial question, whether teacher-centered, knowledge-based science education can meet the claims for SL vision III, in accordance with other scholars in the realm of transformative education (Singer-Brodowski, 2016, 15–16; Balsiger et al., 2017, 359; Leichenko and O'Brien, 2020, 1; Valladares, 2021, 581–82) and underscored by missing climate action at a societal level (Maibach et al., 2014, 295–96; Jylhä, 2018, 487), our answer is no.

Since knowledge of climate change and sustainability is, to a large degree, under constant change and context-dependent (Riemeier, 2007, 70–71; Künzli, 2019, 8), knowledge production needs to be a co-production process among students, scientists, and other out-of-school partners who jointly research topics related to students' lifeworld and everyday life (Kubisch et al., 2021b, 1). This is not only consistent with calls for transdisciplinarity (Lang et al., 2012, 25) but also with contemporary approaches to learning, like moderate constructivism (Riemeier, 2007, 69–70), which are frequently discussed in scholarly debates. As shown in the literature review of transdisciplinarity and TE, mutual learning occurs during the collaboration process that fosters knowledge production and provides both new scientific and societal insights (Walter et al., 2007, 326–28; Clark and Button, 2011, 50; Mitchell et al., 2015, 93; Kubisch et al., 2021a). Consequently, the concept of TE captures all the three visions of SL (see **Table 2**). From a didactical point of view, the collaboration needs to be carefully designed, taking into consideration students' interest and allowing them to tie up with their preconceptions and experience, hence fostering an equal exchange (Widodo and Reinders, 2004, 237–38). While jointly researching some real-world issues, students construct knowledge of scientific processes and research skills, and generate competencies like critical, system, and reflective thinking, and communicative and problem-solving competency (Currie et al., 2005, 405; Pedaste and Sarapuu, 2006, 48; Clark and Button, 2011, 48; Furtak et al., 2012, 315–16; Young et al., 2015, 72). This is in line with the didactical approach of inquiry-based learning (Pedaste et al., 2015, 51–54) and claims of ESD (UNESCO, 2017, 10).

In order to demonstrate the success of the TE concept, we conducted a pre-post comparison of the regression analysis of the pre- and post-test data, analyzing change in the predictive quality of SL on transformative engagement for climate action (**Table 2**). The predictive quality of the model is higher after students' have taken part in the TE project, being explained by a higher influence of the SL visions, in particular visions III and II, gained in importance, reflected by a higher standardized *ß* coefficient. The change in predictive quality comparing the pre- and post-test models is 30.7%. Moreover, the pre- and post-test comparison demonstrates that SL visions II and III, which did not significantly predict transformative engagement in the pre-test, did so in the post-test, with SL vision III having a slightly higher influence than vision II and especially vision I. Hence, these findings give reason to assume that the TE concept supports the didactical realization of vision III and that of vision II. The influence of vision I on transformative engagement decreased after the students took part in the TE project. These findings support the assumption that by promoting the three visions of SL *via* the TE concept (see **Figure 2**), connecting knowledge of scientific content and processes (vision I) to a meaningful real-world context (vision II) through students' active engagement in science with scientists (vision III), the significance of pure knowledge decreases. At the same time, the synergy of knowledge, meaningful real-world context, and active engagement in science fosters the significance of vision II and, in particular vision, III for transformative engagement for climate action.

Therefore, the contribution of the TE concept to the didactical realization of SL should be explained in more detail (see also **Figure 2**). The equal exchange of all partners involved, in the form of an inquiry process, fosters deep reflection, allowing for an opportunity to get to know not only different perspectives but also to gain awareness of one's own perspective. This deep reflection is associated with transformative learning, facilitating the restructuring of mental models and enabling conceptual change through change in thought patterns, values, and behaviors (Mitchell et al., 2015, 93; Klein, 2018, 20–21) for transformative engagement (Deisenrieder et al., 2020, 8–11; Kubisch et al., 2021a, 6–8). Moreover, active engagement in a joint inquiry process not only increases scientific skills (Currie et al., 2005, 405), awareness (Young et al., 2015, 72; Kuthe et al., 2019, 382–83), and personal meaningfulness of socio-ecological issues (Monroe et al., 2019, 804–6), but it also draws on all the three kinds of knowledge, system, target, and transformation, which are relevant for action (Walter et al., 2007, 333–34).

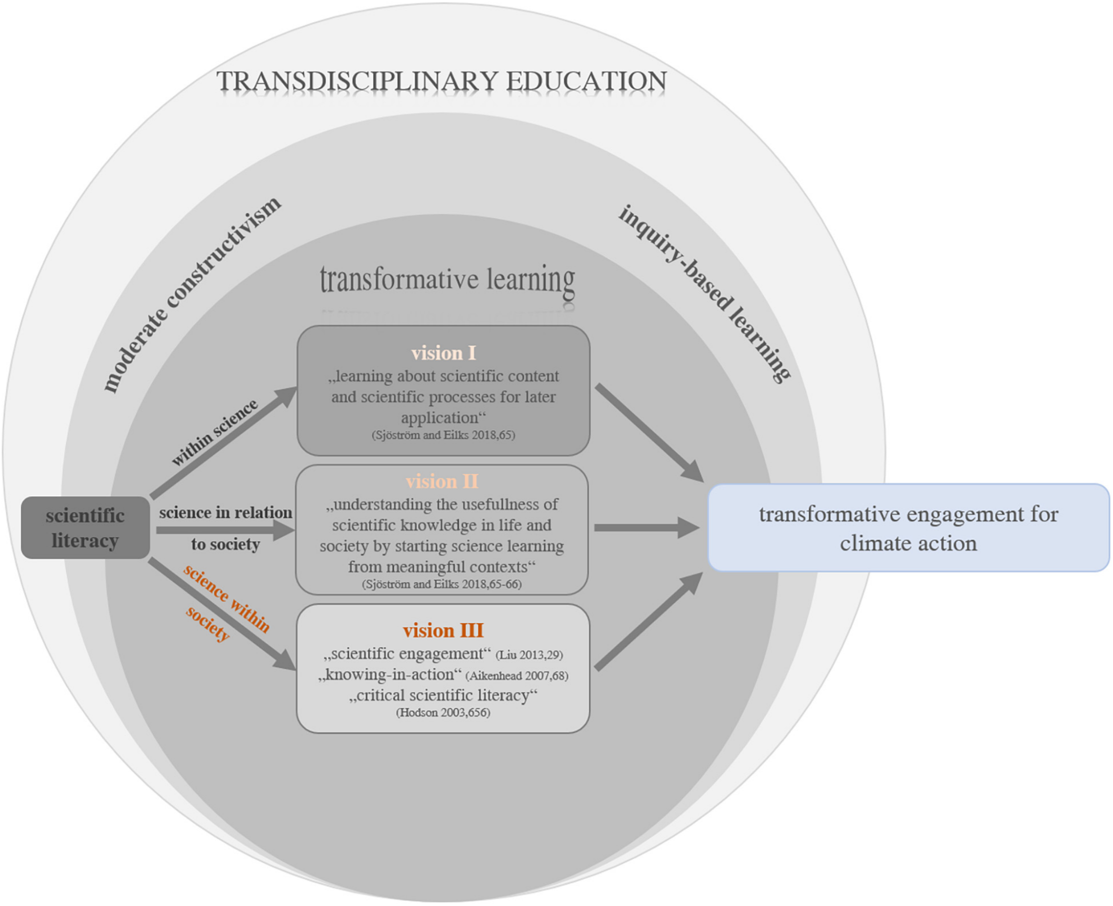

FIGURE 2 | Concept of TE (source: own elaboration).

CONCLUSION AND FUTURE RESEARCH

In order to achieve the 1.5-degree Celsius target, the need for social transformation has been acknowledged in the Paris Agreement (UNFCCC, 2015), requesting changes in values and world-views and, even more importantly, demanding for individual and collective actions (O'Brien et al., 2018, 155–57). SDG4, "Quality Education" plays a key role in this regard and aims to contribute by means of awareness building, and knowledge and competency generation to transformative engagement (WBGU, 2011, 352–58; UNESCO, 2021). In that discourse, science education is understood as making a major contribution to a scientifically literate society, which makes informed and responsible decisions (OECD, 2017, 39).

However, as pointed out in this study and acknowledged by many other scholars discussing the concept of SL, teacher-centered and knowledge-based science education is not the appropriate methodology to reach these goals. TE is a promising didactical concept working toward the claims of SL vision III, which can be described as science for transformation (Sjöström and Eilks, 2018, 78). TE is considered to be a frame, enabling students' active, situational, emotional, social, and self-regulated learning (Riemeier, 2007, 69–70), as well as identification and pursuit of (scientific) issues within students' lifeworld (Pedaste et al., 2015, 55–57). Active engagement in a research process and exchange of different perspectives and forms of knowledge between students and scientific experts are assumed to contribute to transformative learning (Mezirow, 2003, 58), which enables change in habitual thought patterns, norms, values, and, finally, behaviors (Mitchell et al., 2015, 93; Klein, 2018, 20–21). The findings of this study give first indications, demonstrating the influence of SL on transformative engagement for climate action in a TE project.

These promising results need to be replicated and proven by future research also taking into account the limitations of this study. In particular, the SL visions need to be replicated and the constitutive items should be further expanded in terms of their content. SL vision I, in particular, needs to be considered critically. In this study, SL vision I is not specifically focused on "scientific content and scientific processes" (Sjöström and Eilks, 2018, 65) but on a fundamental understanding of the nature of science, capturing students' (mis)conceptions of science. The reason is that operationalizing SL vision I on the basis of disciplinary knowledge does not allow for the replication of the findings and, thus, transfer to other contexts (e.g., different school types, age groups, and countries) because of student's diverse prior knowledge. Consequently, future research needs to rethink the operationalization of SL vision I. Considering the research frame, which was determined in advance in this TE project, we propose to replicate this study allowing students to co-design the whole research process and collaborating with scientists within students' local community.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Review Board and Ethics Committee of the University of Innsbruck. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

SK, HK, LK, VD, MF, KO, NL, SP, and JS: conceptualization. HK and SK: investigation and data evaluation. SK, HK, and LK: writing original draft preparation. LK, VD, MF, KO, NL, SP, and JS: writing review and editing. SK: visualization. LK and JS: supervision, project administration, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

FUNDING

This research received funding from the European Union's Horizon 2020 Research and Innovation Program under grant agreement no. 824522.

ACKNOWLEDGMENTS

We would like to thank Lisa Thompson for the help with style and language.

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Conflict of Interest: HK is employed by alpS GmbH which is part of the project Science Education for Action and Engagement toward Sustainability.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

ORIGINAL RESEARCH
published: 13 April 2022
doi: 10.3389/feduc.2022.838005

The Connection of Finns' Environmental Awareness to Their Anticipatory Competence

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Knowledge of people's abilities must be adapted to a new, sustainable society. Through sustainability competences, the necessary changes in people's behavior in the pursuit of a sustainable society can be intensified. In this study, Finns (n = 2006) express their knowledge of climate change and biodiversity loss and evaluate their own anticipatory competence. The connection between their environmental awareness and the future's orientation toward a society of sustainable actions will be studied by statistical analysis. The study discusses how learning sustainability competences can be promoted in science education and reveals the gap between females and males in their objectives for a sustainable future. Finns with higher education have greater environmental awareness than those with lower education. The connection between Finns' environmental awareness and their structural skills for making a more sustainable future is quite clear.

Keywords: environmental awareness, anticipatory competence, science education, Finns, climate change, biodiversity

OPEN ACCESS

Edited by:
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Alma Mater Studiorum - University of Bologna, Italy

Reviewed by:
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Xi'an Jiaotong-Liverpool University, China
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Specialty section:
This article was submitted to STEM Education, a section of the journal Frontiers in Education

Received: *17 December 2021*
Accepted: *24 February 2022*
Published: *13 April 2022*

Citation:
Ratinen I and Linnanen L (2022) The Connection of Finns' Environmental Awareness to Their Anticipatory Competence. Front. Educ. 7:838005. doi: 10.3389/feduc.2022.838005

INTRODUCTION

To make modern society more sustainable in the future, we need well-educated citizens to take the necessary actions to make changes. This does not merely require enhancing their knowledge; their awareness and commitment to solving these problems must be developed as well. The awareness concept is ultimately a stimulus, and the driving force to acquire knowledge is the need to solve problems. Environmental awareness is one of the prerequisites for an environmental attitude and pro-environmental behavior. Many studies have confirmed that behavioral change may be caused by activities with the objective of raising awareness (Halady and Rao, 2010; Swaim et al., 2014; Ojala and Bengtsson, 2019). Quite a long time ago, Hungerford and Volk (1990) pointed out that environmental education would create awareness and foster the necessary attitudes and behaviors for change. Here, we can assume, based on earlier research (e.g., Kollmuss and Agyeman, 2002; Zsóka et al., 2013; Ratinen and Uusiautti, 2020), that changes in behavior are brought about by increasing scientific knowledge through raising awareness regarding climate change and biodiversity loss and by fostering an appropriate attitude toward the future. Moreover, we propose that individuals review their knowledge and anticipatory competence and then decide whether they have enough knowledge and awareness in the first place.

We need to prepare learners for their future and consider how we can support them in creating a more sustainable future instead of an uncertain future. For this purpose, Wiek et al. (2011) defined key competencies in sustainability and synthesized the substantive contributions in a coherent framework of sustainability research and problem-solving competence: system thinking competence, anticipatory competence, normative competence, strategic competence, and interpersonal competence.

In this study, we focus on anticipatory competence and define that competence as learners' ability to collectively analyze, evaluate, and illustrate the future as it is related to sustainability issues and sustainability problem-solving frameworks. Anticipatory competence includes comparative skills related to estimating the "state of the art," including concepts such as time, uncertainty, and scenarios. It is well known that without appropriate knowledge, learners are not capable of undertaking meaningful and effective environmental actions that increase their hope for the future (Ratinen, 2021). Therefore, we also focus on environmental awareness based on Finns' knowledge of climate change and biodiversity issues.

Science education is one of the keys to helping humankind solve the environmental problems, such as climate change and loss of biodiversity, that we are facing today. Science education focuses primarily on teaching knowledge and skills. Although socio-scientific issues (SSI) (Mogensen and Schnack, 2010) and responsible research (RRI) (Heras and Ruiz-Mallén, 2017) have been developed to foster the learning of environmental issues, it is more common that environmental education stresses the incorporation of values and changing behaviors in education (Wals et al., 2014). Responsible science education needs to support learners' meaning-making coping strategies and thus prevent their environmental anxiety (Ojala and Bengtsson, 2019). In science education, there is a need to consider the means to make science classes more meaningful for learners and bring examples of their everyday lives near—both now and in the future. Science education across the globe holds the responsibility for shaping Students' environmental awareness and changing their attitudes toward the importance of preserving the environment.

Science education has recently focused more on Students' future thinking (Branchetti et al., 2018). Levrini et al. (2021) found that environmentally oriented science education can support learners' future—scaffolding skills. These skills consist of structural skills and dynamical skills. Structural skills refer to learners' abilities to recognize temporal, logical, and causal relationships and build systemic views. Dynamical skills are, in turn, learners' abilities to navigate scenarios, relating local details to global views, past to present and future, and individual to collective actions. Science education helps people to perceive future global multiple scenarios that they can influence and shape in the present while using that knowledge for the future (Rickards et al., 2014). This anticipatory competence leans on interdisciplinary future studies, which typically involves disciplines but also scholars and practitioners from the arts, social sciences, natural sciences, technology, and engineering to orient actions in the present that can influence and create preferable or desirable futures. Levrini et al. (2021) incorporated future thinking skills into school science, including scenario thinking, systems thinking, thinking beyond the realm of possibilities, action competence, and skills to manage uncertainty and complexity, and thus brought future thinking close to the principles of sustainability thinking (Wiek et al., 2011; Sterling, 2021).

ENVIRONMENTAL AWARENESS AND ANTICIPATORY COMPETENCE AMONG FINNS

Learning sustainable development competencies requires a systematic focus on the concepts, methods, and skills of each competence (Brundiers et al., 2021). In addition, competence learning should focus on teaching staff so that awareness and understanding of competencies can be brought into general education for sustainable development. In Finland, sustainability competencies are not well known from the point of view of science education, although environmental crises have been known for a long time. Vuorio et al. (2021) found that university teachers in chemistry evaluated the learning of critical thinking skills as important in teaching. Moreover, promoting the competencies of sustainable development was evaluated as important. Tolppanen and Kärkkäinen (2021a) found that few pre-service teachers seem to examine climate change mitigation through a systems-thinking approach. Pre-service teachers did not internalize that individuals, governments, and businesses all play a role in climate change mitigation.

According to Lehtonen et al. (2020), Finns' average knowledge about climate change is rather good, and they can make a realistic assessment of their own level of knowledge. Most Finnish people believe estimate that climate change is mainly due to increased carbon dioxide in the atmosphere. Finns are also able to link the increased amount of carbon dioxide to the use of fossil fuels. However, there is also misunderstanding of the causes of sustainability issues among Finnish people (Lehtonen et al., 2020). Namely, only about half know that deforestation is not the main cause of climate change and that climate change is not caused by ozone depletion. A closer look at the results of Lehtonen et al. (2020) reveals that 57% of men and 42% of women have good or very good knowledge of climate issues based on knowledge-based questions. The differences between age groups are not large. The knowledge of climate change issues of those under the age of 50 is better than that of older age groups. However, the knowledge of those under 30 is no different from that of others under 50.

Finns' environmental awareness is relatively high, but knowledge moves slowly from words to deeds (Hyry, 2017). More recently, Finns expressed that recycling is the most effective way to reduce one's own emissions, even though its impact is actually quite small (Lehtonen et al., 2020). Therefore, there are shortcomings in Finns' basic information. In Finland, women's attitudes toward the environment are more positive than men's. The general environmental attitudes of young people appear to be more negative than those of older respondents (Hyry, 2017). The general environmental attitudes of respondents who are dissatisfied with their lives or who do not perceive their lives as valuable are clearly more negative than those respondents who say they are happy with their current lives or feel their lives are valuable.

Finns' anticipatory competence related to sustainability issues is not well known. Heikkilä et al. (2017) found that some young people criticize the Western consumption-oriented lifestyle and express a desire for fairness in income and lifestyle in the future. Working together and communality come to the fore as important issues for these individuals. On the technology side, young people being connected in advocating for and promoting environmentally friendly and sustainable energy solutions is expected to become more common. Adults' anticipatory competence is also unknown. Eurobarometer (2021) revealed that climate change and environmental issues are one of the EU's main challenges for the future among European people, but our opinions varied significantly across EU member states.

AIMS

Wiek et al. (2011) and colleagues believe that defining the key competencies required for sustainable development is important to profile and assess the right kind of competence. Although we know about Finns' environmental expertise, we still have gaps in our knowledge of how Finns' knowledge is combined with their anticipatory competence and how that knowledge could be used in the development of science education. This study is based on the following research questions:

- How does Finns' knowledge of climate change and biodiversity loss depict their environmental awareness?
- How is Finns' environmental awareness associated with their anticipatory competence?

The purpose of the present article is to increase our understanding of the relationship between Finns' environmental awareness and their anticipatory competence. Based on the results, novel and more effective ways to respond to sustainability challenges in science education are presented.

MATERIALS AND METHODS

Procedure and Participation

The target group consisted of 2,006 Finnish people living in Finland, Åland excluded. Åland is a Swedish-speaking autonomous region belonging to Finland. The survey was only in Finnish, so Åland was excluded from the survey. The average age was 47.8 years, and the sample was composed of 52.1% females and 47.5% males. Nine respondents (0.4%) did not want to express their gender (**Table 1**). There was no missing data because answering the questionnaire required an expression of opinion on each question. However, two participants did not inform their age and 24 participants their education as well. Nine participants did not identify their gender. All those missing participants were excluded in the analysis because the small number does not allow for comparisons with the rest of the participants. The data collection was carried out as a web survey tool developed by Feedback Group. Web consumer research panels of the CPX (Cint Panel Exchange) network were used for the target group definition. Respondents were selected from several different research panels, thus preventing a possible panel-specific structural skew. Respondents are recruited to various web panels using a registration form that asks the panelist their background information. Based on these backgrounds, respondents can be queried and quota-selected. Upon registration, the panelist also agrees that research invitations may be sent to his or her email. Thus, at the beginning of an individual study, consent to the study is no longer specifically requested, as the panelist has already given his or her consent once. Respondents were determined at the sampling stage based on the demographic structure of Finland. E-mail invitations to the survey were sent to all panelists who participated in the target group selection. During the data collection, additional invitations and reminders were sent to those who did not respond.

TABLE 1 | Respondents' backgrounds.

Gender	Frequency	%
Female	1,045	52.1
Male	952	47.5
No answer	9	0.4
Age		
16–24	156	7.8
25–34	342	17.0
35–44	390	19.4
45–54	311	15.5
55–65	431	21.5
65–	374	18.6
No answer	2	0.1
Education		
Basic school	150	7.5
Vocation school	471	23.5
High school	228	11.4
College	366	18.2
Uni. of applied science	311	15.5
University, bachelor	151	7.5
University, master	305	15.2
No answer	24	1.2

Measures and Statistical Tests

To measure Finns' environmental awareness, the participants were asked to evaluate climate change and biodiversity issues, and 10 possible responses were provided (**Table 2**). Each response could be rated on a five−point Likert scale: strongly disagree = 1, disagree = 2, no disagreement or agreement = 3, agree = 4, or strongly agree = 5. Analysis of variance (ANOVA) was used to look for differences between groups by age and education level and *t*-test for gender. Principal component analysis (PCA) was conducted for the calculation of the principal scores using a regression method. The Kaiser–Meyer–Olkin (KMO) value of 0.861 showed that the sample was suitable for performing PCA, and a varimax rotation method was chosen. The principal component solution accounted for 56.8% of the total variance,

TABLE 2 | Finnish people's environmental awareness (n = 2006).

	Totally disagree	Disagree	Neither disagree nor agree	Agree	Totally agree	Statistics
Climate change is caused by greenhouse gases, such as carbon dioxide methane and nitrous oxide, increasing in the atmosphere.	2.1	3.9	20.0	50.8	23.1	Age: no Gender: $t_{(1,915)} = 3.848$, $p < 0.000$ Edu: $F_{(6,1,975)} = 12.746$, $p < 0.000$
Greenhouse gases decrease the atmosphere (the ozone layer), which causes the Earth to get more heat radiation.	3.8	4.9	20.2	48.9	22.2	Age: no Gender: $t_{(1,811)} = 7.554$, $p < 0.000$ Edu: no
The increase in palm oil consumption has reduced biodiversity.	1.5	5.6	35.7	37.5	19.7	Age: no Gender: $t_{(1,995)} = 2.410$, $p < 0.02$ Edu: $F_{(6,1,975)} = 4.531$, $p < 0.000$
Climate change is natural, as, e.g., volcanoes and water vapor affect current climate change more directly than humans' greenhouse gases.	14.1	34.9	29.0	16.3	5.7	Age: no Gender: $t_{(1,995)} = -5.531$, $p < 0.000$ Edu: $F_{(6,1,975)} = 6.945$, $p < 0.000$
The loss of biodiversity is a result of the current exploitation of nature by humans that occupy the space of nature.	0.9	2.8	16.0	45.1	35.1	Age: no Gender: $t_{(1,995)} = 4.139$, $p < 0.000$ Edu: $F_{(6,1,975)} = 10.515$, $p < 0.000$
Scientists are sure that people are definitely the reason for the current rapid climate change.	2.4	6.4	22.4	42.5	26.3	Age: no Gender: $t_{(1,878)} = 4.116$, $p < 0.000$ Edu: B-F$_{(6,\ 1,569)} = 2.563$ $p < 0.02$
The decrease in the number of species is natural and people are unable to significantly affect the number of species.	20.0	38.9	22.9	14.9	3.2	Age: no Gender: $t(1,954) = -4.710$, $p < 0.000$ Edu: $F_{(6,1975)} = 6.512$, $p < 0.000$
Combustion of fossil fuels releases carbon dioxide into the atmosphere, which binds heat and causes climate change.	1.9	5.0	23.9	49.9	19.3	Age: no Gender: no Edu: [F-B$_{(6,1,611)} = 12.492$, $p < 0.000$]
The main reason for biodiversity loss is that we do not recognize the environmental impact of production chains (manufacturing, distribution, and disposal) adequately.	2.2	11.7	33.6	41.6	10.8	Age: no Gender: $t_{(1,934)} = 4.705$ $p < 0.000$ Edu: F-B$_{(6,\ 1,508)} = 3.864$, $p < 0.001$
Even if we, as individuals, were to significantly reduce material consumption, it would have no effect on biodiversity.	12.0	37.7	26.0	18.6	5.7	Age: $F_{(5,\ 1,956)} = 3.940$, $p < 0.001$ Gender: $t_{(1,940)} = -5.578$, $p < 0.000$ Edu: $F_{(6,1975)} = 5.851$, $p < 0.000$

and the factor loadings were satisfactory (0.50 or greater) (**Table 3**). Finally, two scales were created: understanding (α = 0.79) and misunderstanding (α = 0.76). The principal component scores were calculated using regression methods. These scores were used for the calculation of Pearson correlation coefficients.

In this study, we define competence as a combination of skills, knowledge, and attitudes that enable a particular task to be performed or a problem to be solved (Baartman et al., 2007; Wiek et al., 2011; Voogt and Roblin, 2012). Brundiers et al. (2021) updated Wiek et al. (2011) model. In our questionnaire, the competencies to be added to the original model were an integrated problem-solving competency that included the utilization of combinations of the competencies in the model. Our questionnaire involved identifying and leveraging the necessary problem-solving skills. Another competence to be added was intrapersonal competence. This is described as the ability to be aware of one's own feelings, desires, thoughts, behaviors, and personality, as well as the ability to regulate, motivate, and develop oneself. The third modified competence in our questionnaire was solution competence, which refers to the collective ability to put plans and visions into practice and to understand the long-term and iterative nature of sustainable development projects.

To measure Finns' anticipatory competence, the participants were asked to evaluate their anticipatory competence, and nine possible responses were provided (**Table 4**). Each response could be rated on a five−point Likert scale: strongly disagree = 1, disagree = 2, no disagreement or agreement = 3, agree = 4, or strongly agree = 5. Principal component analysis (PCA) was conducted for the calculation of the principal scores using a regression method. The KMO value was 0.847, and a varimax rotation method was chosen. The total explanation of variance was 61.4%, and the factor loadings were satisfactory (0.50 or greater) (**Table 4**). Finally, two scales were created: structural skills (α = 0.81) and dynamic skills (α = 0.83). The principal component scores were calculated using regression methods. These scores were used for the calculation of Pearson correlation coefficients.

RESULTS

In Finland, citizens' environmental awareness seems to be relatively high (**Table 2**). Both the understanding of the main cause of climate change as greenhouse gases (73.9% agree or totally agree with the statement) and the main roots of biodiversity loss, namely our large-scale exploitation of nature

TABLE 3 | Finnish people's awareness of environmental issues (n = 2006).

	Understanding	Misunderstanding
Burning fossil fuels releases carbon dioxide into the atmosphere, which binds heat and causes climate change	0.714	
The main reason for the decline in biodiversity is that we do not recognize the environmental impact of product production chains (manufacturing-distribution-disposal) well enough	0.671	
Climate change is caused by greenhouse gases such as carbon dioxide, which increase the amount of methane and nitrous oxide in the atmosphere	0.664	
The loss of biodiversity is the result of humanity's current exploitation of nature, which takes over the living space from nature	0.650	
The increase in palm oil consumption has reduced biodiversity	0.635	
Scientists are sure that people are definitely the cause of the current rapid climate change	0.611	
The decline in the number of species is natural and humans are not able to influence the number of species in a significant way		0.806
Climate change is a natural thing, for, e.g., volcanoes and water vapor have a greater impact on current climate change than anthropogenic greenhouse gases		0.799
Even if, as individuals, we significantly reduced material consumption, it would have no impact on biodiversity		0.766
Eigenvalue	3.874	1.232
Exp. of total variance %	43.1	13.7

TABLE 4 | Finnish people's anticipatory competence (n = 2006).

	Structural skills	Dynamic skills
I am ready to vote for decision makers who want to promote solutions that support sustainable living	0.782	
I believe that the climate and sustainability crisis will be resolved in the near future through significant changes in housing, eating, and traveling	0.756	
I believe that material consumption will have to be restricted in the future by legal means	0.761	
I have confidence that the climate and sustainability crisis is largely solvable in the future if we are able to change linear economic thinking (raw material - > waste) to a circular economy	0.543	
I can interpret different climate scenarios, and I know what the most effective climate measures are		0.863
I am able to assess how different climate measures affect the future of the Finnish climate system		0.844
I can assess how current global land use will accelerate the worsening of nature loss in the future		0.748
I can imagine what global food production that sustains biodiversity looks like		0.718
Eigenvalue	3.869	1.654
Exp. of total variance %	43.0	18.4

(80.2%), are scientifically correct. The Finns' ideas that CO_2 emissions are released from burning fossil fuels (70.2%) and that nature loss is caused by the environmental impact of production chains (62.4%) indicate high environmental awareness. Finnish people are also confident that scientists are sure that people are the reason for climate change (68.8%). However, this study, like earlier studies (Ratinen, 2016; Lehtonen et al., 2020), shows that 71.1% of respondents confused climate change with the depletion of the ozone layer. Scientifically, the connection between climate change and ozone depletion is not strong (IPCC, 2007). It is also interesting that many Finns (24.3%) think that even if we, as individuals, were to significantly reduce material consumption, it would have no effect on biodiversity.

According to ANOVA, only one variable— even if we, as individuals, were to significantly reduce material consumption, it would have no effect on biodiversity—differed statistically significantly by age [$F_{(5,\ 1{,}956)} = 3.940$, $p < 0.001$, $\eta^2 = 0.01$]. The effect size for this analysis ($\eta^2 = 0.01$) was found to approach Cohen's (1988) convention for a small effect. A *post-hoc* test (Bonferroni) revealed that the groups from 55 to 65 ($p < 0.003$) and over 65 ($p < 0.05$) years old believed more than 16–24-year-olds that individuals can minimize biodiversity loss by de-creasing consumption.

Gender was a clear distinguishing factor in environmental awareness (**Table 2**). A t-test revealed that females had significantly different ideas about how climate change is caused by greenhouse gases [$t_{(1{,}915)} = 3.848$, $p < 0.000$, $d = 0.18$] and palm oil consumption has reduced biodiversity [$t_{(1{,}995)} = 2.410$, $p < 0.02$, $d = 0.11$], and they also confused climate change and ozone depletion more often [$t_{(1{,}811)} = 7.554$, $p < 0.000$, $d = 0.36$]. Moreover, females more often believe that the loss of biodiversity is a result of the current exploitation of nature [$t_{(1{,}995)} = 4.139$, $p < 0.000$, $d = 0.19$] and believe in scientists' evidence for rapid climate change [$t_{(1{,}878)} = 4.116$, $p < 0.000$, $d = 0.19$]. Males more often believe that climate change is natural [$t_{(1{,}995)} = -5.531$, $p < 0.000$, $d = 0.25$], individuals' consumption reduction does not affect biodiversity [$t_{(1{,}940)} = -5.578$, $p < 0.000$, $d = 0.25$], and people are unable to significantly affect the number of species [$t_{(1{,}954)} = -4.710$, $p < 0.000$, $d = 0.21$]. The effect size for this analysis (Cohen's d) was found to approach Cohen's (1988) convention for a small effect < 0.50.

The level of education affected respondents' environmental awareness, but the effect size for this analysis ($\eta^2 = 0.01$–0.04) was found to approach Cohen's (1988) convention for a small effect: "climate change is caused by greenhouse gases" [$F_{(6,1,975)} = 12.746$, $p < 0.000$, $\eta^2 = 0.04$], "the increase of palm oil consumption" [$F_{(6,1,975)} = 4.531$, $p < 0.000$, $\eta^2 = 0.01$], "climate change is natural" [$F_{(6,1,975)} = 6.945$, $p < 0.000$, $\eta^2 = 0.02$], "the loss of biodiversity" [$F_{(6,1,975)} = 10.515$, $p < 0.000$, $\eta^2 = 0.03$], "scientists are sure that people" [$F_{(6,1,569)} = 2.563$ $p < 0.02$, $\eta^2 = 0.01$], "the decrease in the number of species" [$F_{(6,1,975)} = 6.512$, $p < 0.000$, $\eta^2 = 0.02$], "combustion of fossil fuels releases carbon dioxide" [F-$B_{(6,1,611)} = 12.492$, $p < 0.000$, $\eta^2 = 0.04$]," the main reason for biodiversity loss" [F-$B_{(6, 1,508)} = 3.864$, $p < 0.001$, $\eta^2 = 0.01$], and "even if we as individuals..." [$F_{(6,1,975)} = 5.851$, $p < 0.000$, $\eta^2 = 0.02$].

For more detailed knowledge about how education affects environmental awareness, the PCA was generated (**Table 3**). The principal component of understanding represents higher environmental awareness, i.e., the scientific view of climate change and biodiversity loss, but misunderstanding does not do so. The *post-hoc* test (Bonferroni) indicates that those with bachelor's ($p < 0.008$) and master's degrees who graduated from university ($p < 0.000$) ex-pressed a greater understanding of climate change and biodiversity than people in or who graduated from only basic school education. Similarly, bachelor's ($p < 0.001$) and master's ($p < 0.000$) recipients who graduated from university or college ($p < 0.01$) expressed greater environmental awareness than respondents who graduated from vocational school. Moreover, master's recipients from the university ($p < 0.003$) exemplified greater awareness than bachelor's recipients who graduated from the university of applied sciences. People graduating with a master's at university had less misunderstanding related to climate change and biodiversity loss than people in or who graduated from only basic school education ($p < 0.002$) or vocational school ($p < 0.000$), people who graduated from college ($p < 0.002$), or people who graduated from a university of applied sciences.

The connection between Finns' environmental awareness and their anticipatory competence was studied using Pearson's correlation analysis. Before the analysis, two principal components were generated. Structural skills represent the respondent's confidence that the future will be better if actions are implemented (see Levrini et al., 2021). Dynamic skills describe respondents' personal opinions toward the means or skills to make the better future.

The present study indicates a fairly clear connection between environmental awareness and structural skills for making a more sustainable future. The result of Pearson's correlation explains the connection between Finns' environmental awareness and their anticipatory competence. Finns' scientifically accurate knowledge of the reasons for climate change and nature loss (awareness) correlated rather strongly with their structural skill that climate change and biodiversity loss can be tackled through active measures, such as legislation ($r = 0.446$, $p < 0.000$, $R^2 = 0.20$). Instead, Finns' misunderstanding of environmental issues negatively correlated with their structural skills for solving environmental crises in the future ($r = -0.375$, $p < 0.000$, $R^2 = 0.14$).

However, the result becomes unclear when compared to Finns' personal anticipatory skills in interpreting or assessing climate change and nature loss in the future. Finns' awareness of climate change and biodiversity weakly correlated with their dynamic skills ($r = 0.104$, $p < 0.000$, $R^2 = 0.01$). Surprisingly, Finns' lower environmental awareness also correlates weakly with their dynamic skills ($r = 0.100$, $p < 0.000$, $R^2 = 0.01$). The result suggests that Finns' environmental awareness is not obviously associated with their dynamic skills for building a more sustainable future. However, the R^2-values indicate that only 1% of the variance in dynamic skills is shared with the variations of environmental awareness. The small effect sizes reveal that the correlation is unimportant.

CONCLUSION

According to the present study, environmental awareness among Finns seems to be quite high. Compared to previous studies, climate change awareness is similar (Lehtonen et al., 2020). Finns understand quite well the increase in the concentration of greenhouse gases in the atmosphere caused by climate change. The right information will help mitigate climate change mitigation measures. The most significant misunderstanding is that ozone depletion is causally linked to climate change. This result is very similar to previous studies (Tobler et al., 2012; Ratinen, 2016; Besel et al., 2017; Lehtonen et al., 2020). The understanding of biodiversity is also at a relatively high level. However, the results show that diversity is somewhat more unfamiliar to Finns than climate change, as the percentages of responses in the right direction were slightly lower. The result is similar to that of Lindemann-Matthies and Bose (2008), and they pointed out that limited knowledge of the public about biodiversity might explain why, in surveys, the loss of species is considered only a minor environmental problem.

From the point of view of developing the teaching of science, it is interesting to look at Finns' environmental awareness. Based on the results, it seems obvious that higher education increases environmental awareness. Those who attend primary and vocational school have a lower level of environmental education than those with higher education. However, the effect sizes between the groups remained small. Moreover, Dimante et al. (2016) found that teaching changed some undergraduate Students' household chemical consumption patterns, indicating the ambiguous impact of education on environmental awareness. Based on this study, it can be stated that age and education do not have a very significant effect on Finns' environmental awareness. The environmental awareness of women was somewhat higher than that of men, but for all variables, the effect size remained small.

The results suggest that Finnish primary school teaches students quite well about climate change and biodiversity, or that those who have attended primary school are quite environmentally conscious with information obtained elsewhere. Based on the results, it is worth paying attention to the causes of climate change and emphasizing the human impact on current climate change. In the context of biodiversity, it is worth highlighting the impact of production systems and consumption on biodiversity loss. Because climate change and biodiversity are complex, interrelated issues, it would be worthwhile to look at them simultaneously in teaching. However, as Barelli et al. (2018) indicated, the task is not easy because adults are not very comfortable dealing with scientific and epistemological concepts related to complex systems.

There is a clear link between Finns' environmental awareness and anticipatory structural skills. Conversely, the present research suggests that there is a partly contradictory connection between Finns' more personal dynamic skills and their environmental awareness. It would seem obvious that with an emphasis on future skills in science teaching, attention should be paid to ways to improve individuals' abilities to assess environmental issues from a more sustainable future perspective. As Tolppanen and Kärkkäinen (2021b) pointed out, the task of making education more sustainable is not simple: student teachers seem to have reluctance to make lifestyle changes that could significantly reduce their carbon emissions. This study suggests that Finns think broadly in the same way as Finnish student teachers. Teacher education is needed to foster student teachers' action competence, and thereby their competence to support their Students' and future citizens' action competence (Tolppanen and Kärkkäinen, 2021b). If teachers' own skills and will to make the future more sustainable are uncertain, it is unlikely that they will be able to guide their students toward a sustainable lifestyle.

Based on the results of the present study, it would be worth considering how sustainability education could be extended beyond education to the world of work. Finland is well-known for its education and this study shows the positive impact of Finnish higher education on citizens' environmental awareness. We still need more knowledge how awareness at the work places will lead sustainable environmental measures. The gap between females and males in their objectives for a sustainable future is also revealed, pointing out areas that deserve attention by science education. The better understanding for the results of the present study outside of Finland would be significant if the study was implemented in other countries.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

IR contributed to conception and design of the study, performed the statistical analysis, and wrote the first draft of the manuscript. IR and LL organized the database. Both authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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HYPOTHESIS AND THEORY
published: 12 May 2022
doi: 10.3389/feduc.2022.869156

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ChemoKnowings as Part of 21st Century *Bildung* and Subject Didaktik

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In this article, we elaborate on the construct ChemoKnowings as subject-specific powerful knowings for chemical agency in the Anthropocene era. Related to constructs such as critical chemical literacy, ChemoCapabilities, and eco-reflexive chemical thinking, we unpack the construct as an example of Carlgren's powerful knowings, which relates Young's powerful knowledge to the idea and tradition of *Bildung*. It means powerful knowledge containing embodied and relational (or tacit) dimensions. ChemoKnowings can therefore be described as embodied and relational knowledge in and about chemistry – (critical) chemical knowledge that matters meaningfully to the student, connecting them to themselves and the world, and conferring an ethical compass. By situating the teaching of ChemoKnowings within a vision for chemistry teaching as a part of a world-centered vision for schooling in the Anthropocene, ChemoKnowings are viewed as having the capacity to mobilise an ethico-socio-political action, that is, chemical agency. By focusing on student transformation of content for ChemoKnowings and integrating elements of a theoretical didaktik model for eco-reflexive chemistry education, we develop a vision-oriented didaktik model for ChemoKnowings. More generally, we argue that didaktik models for supporting teachers' consideration of student transformation of content for powerful subject-knowings are an important part of general subject didaktik. We present in the article vignettes that detail personal accounts for each of the three authors describing examples of chemistry-specific knowings that matter meaningfully to each of us, and which articulate our own embodied ethico-socio-political actions as students, teachers, researchers, and consumers. Inspired by Klafki's didaktik analysis, we end the article by proposing four areas of questions that the teacher can use in guiding their preparation and transformation of the content they bring into the classroom for promoting students' ChemoKnowings, and thus *Bildung* in the 21st century.

Keywords: didaktik, Anthropocene, powerful knowings, eco-reflexive *Bildung*, embodied knowledge, chemistry education, critical chemical literacy, agency

Edited by:
Antti Laherto, University of Helsinki, Finland

Reviewed by:
Niklas Gericke, Karlstad University, Sweden
Ron Blonder, Weizmann Institute of Science, Israel

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Specialty section:
This article was submitted to STEM Education, a section of the journal Frontiers in Education

Received: *03 February 2022*
Accepted: *05 April 2022*
Published: *12 May 2022*

Citation:
Yavuzkaya M, Clucas P and Sjöström J (2022) ChemoKnowings as Part of 21st Century Bildung and Subject Didaktik. Front. Educ. 7:869156. doi: 10.3389/feduc.2022.869156

INTRODUCTION

Scientists declared the era of our unsustainable ways of living the Anthropocene (Crutzen and Stoermer, 2000). The school needs to be reoriented toward navigating today's complexity and challenges stemming from the issues of socio-ecojustice and human impacts on the systems of the Earth resulting in, e.g., climate change, biodiversity loss, floods, and health-related issues.

However, at the same time schooling is increasingly impacted by an economic perspective that results in education being viewed as a cause of economic growth through human capital production (e.g., Sundberg and Wahlström, 2012; Gillies, 2014). Guided in part by the Organisation for Economic Co-operation and Development (OECD), this view manifests in the monitoring and measurement of learning outcomes (ibid.). However, in view of the idea that economic growth is also closely linked with increasing consumption and thus unsustainable ways of living (Kopnina, 2012), there is a risk that education for promoting the reorientation needed in the Anthropocene will go unrealised. Indeed, one example illustrating an expression of the risk created by schooling's entanglement with an economic perspective is what Biesta (2009) has called a trend in education toward "learnification," that is, a reduction of education to a discourse built upon a "language of learning" (p. 27) that determines how we describe teachers, students, teaching, and school. Crucially, a focus on education as an environment for the optimal production of learning, in which the teacher is conceived as a facilitator of individual learning outcomes or competencies, marginalises a focus on theories of teaching as well as on didaktik (e.g., Krogh et al., 2021). Thus, teachers' freedom of method in selecting content with the purpose of developing capacities in students that could open toward a critical stance and agency in relation to the Anthropocene are also marginalised. Therefore, when it comes to disciplinary education, specifically in chemistry education in our case, the risk is of school chemistry teaching being reduced to developing student's conceptual understanding of disciplinary chemistry knowledge, in part with a view to preparing future scientists and engineers, and in part to create consumers who place their belief in the products that scientists and engineers produce (see, e.g., Bencze and Carter, 2011 for a general discussion on this). Thus, what is needed is an approach to school chemistry teaching that takes its point of departure in the goals of schooling as a whole in the Anthropocene and that places focus on corresponding relevant content in teaching. We view 21st century *Bildung*, which is in the title of this article, as a part of a theoretically developed understanding of Environmental Citizenship in the 21st century (Hadjichambis et al., 2020). In this, "Knowledge is essential, but fostering knowledge alone in Education for Environmental Citizenship, without links to real life, personal experiences, competencies, and values, is insufficient and pointless for the sake of a sustainable world" (Smederevac-Lalic et al., 2020, p. 71).

Serving as a bridge between natural sciences, life sciences and applied sciences (Mahaffy et al., 2019a), chemistry – a creative science analysing, synthesising, and transforming matter (Sevian and Talanquer, 2014) – contributes to the creation of medicines, materials, and chemicals that are recognised as having high societal value. Talanquer (2016, p. 4) writes: "The signature of chemistry is less its content than the practices that such knowledge enables. Chemistry is [...] a powerful way of thinking about and acting on the material world." Therefore, when knowledge in chemistry is applied, it can contribute to local and global environmental impact, as well as risks (e.g., Sjöström et al., 2016; Eilks et al., 2017), linking the discipline immutably with the idea of a risk society (e.g., Marks and Eilks, 2009; Marks et al., 2014; Sjöström et al., 2016; Eilks et al., 2017), and the Anthropocene (Mahaffy, 2014; Blatti et al., 2019; Mahaffy et al., 2019b; Zowada et al., 2019a,b).

Thus, as a discipline, chemistry should be viewed as being intimately tied to social, economic, political, environmental, and ethical dimensions (e.g., Sjöström et al., 2016). However, even though this is the case, teaching chemistry tends to focus on the explanation of isolated concepts without a purpose (e.g., Sevian and Talanquer, 2014). In an attempt to reconceptualise chemistry education, Talanquer (2019b) writes that chemistry knowledge can play a central role in understanding and solving global challenges. Such knowledge also encompasses engaging in decision-making in relation to sustainable action-taking. In developing a chemical systems thinking model, Talanquer (2019b) brought together a mechanistic-reasoning approach, a context-based approach, and a sustainable-action approach. However, even though there was an emphasis on the relevance of the content or the system under investigation to society, a clear educational goal or guidance for the criteria of content selection was absent. Similar to Talanquer, Mahaffy (2014) has also sought to create a more coherent link between chemistry education and global challenges. Discussing the use of chemistry knowledge in characterising the Anthropocene as a geological phenomenon, and discerning a link between postsecondary chemistry concepts and the chemistry of planetary boundaries (Steffen et al., 2015), Mahaffy et al. (2014, 2019b) have called for a more purposeful focus on the Anthropocene and planetary boundaries in chemistry education. In their view, attention needs to be paid to ideas linking humans and nature to foster action-taking citizens informed by these ideas. With a view to making sense of the current status of our planet and mitigating the human impact on the planetary boundaries, they provide examples of the underlying chemical concepts that are related to planetary boundaries for Anthropocene-aware chemistry education.

Clear in these examples is a linking of chemistry knowledge to the educated subject's agency in relation to sustainable action-taking in the Anthropocene. However, there is also a need for providing chemistry teachers with tools for actively supporting such an agency in chemistry teaching for the Anthropocene in a broad sense. Biesta (2009), argues that we need an ongoing discussion on the aims and goals of education. He writes:

"What is disappearing from the horizon [...] is a recognition that it also matters *what* pupils and students learn and what they learn it *for* – that it matters, for example, what kind of citizens they are supposed to become and what kind of democracy this is supposed to bring about [...]" (Biesta, 2009, p. 39).

Drawing upon contemporary views of *Bildung*, didaktik, and powerful knowings we seek in this article to develop an approach to chemistry teaching in the Anthropocene that re-awakens a discussion on the goals of chemistry education and the choice of content to be taught, providing thus a basis for supporting greater autonomy on the part of both teachers and students (of all ages) in a chemistry teaching in the Anthropocene. Of central importance in relation to achieving these aims will be our further development of the construct *ChemoKnowings* (first introduced in Herranen et al., 2021).

TOWARD ECO-REFLEXIVE *BILDUNG*

In Sweden and the other Scandinavian countries, as well as in Germany, *Bildung* is a central element of the didaktik educational tradition (e.g., Sjöström and Eilks, 2018). The term didaktik is understood differently from how the word "didactics" is understood in English-speaking countries (Sjöström et al., 2017). Didaktik can be seen as the art, philosophy, and science of teaching and learning (Sjöström and Tyson, 2022; see also, e.g., Künzli, 2000; Wickman et al., 2020), which fundamentally concerns questions of *what* content is important to learn, *why* it should be taught, and *how* (e.g., Wickman, 2014). Didaktik "[. . .] concerns the analytical process of transposing (or transforming) human knowledge (the cultural heritage) like domain-specific knowledge into knowledge for schooling that contributes to [. . .] *Bildung*" (Duit et al., 2012, p. 16). German and Nordic didaktik distinguishes itself from the curriculum tradition common to English-speaking countries in some crucial ways (Friesen, 2018). For example, unlike the curriculum tradition, which creates a separation between curriculum (*what* is to be taught and *why*) and pedagogy (*how* something should be taught), didaktik opens for teachers having autonomy not only in choosing how to teach certain content but also in selecting content for teaching (based on their answering of *why* a particular content should be taught) (Gericke et al., 2018). The reason for this is because the curriculum in German and Nordic tradition, or *Lehrplan* (translation from German to English: Learning plan), was traditionally intended as a general guide to teaching, with the selection of content being left to teachers, who were understood to have a unique understanding of the specific needs of students in their local cultures and school context (Hopmann, 2015). Of importance in this regard was (and still is) the need of the teachers to come into a relationship with the *Lerhrplan* as "curriculum theorists" (Deng, 2021) so they might make selections of content for teaching that are both consistent with the goals of schooling and education as expressed through the *Lerhrplan*, and the unique learning needs of their particular students (Hopmann, 2015). In this way, the questions of *why* one should teach a particular content become central to didaktik. An additional aspect that distinguishes didaktik from the curriculum tradition is that didaktik acknowledges a distinction between content that is selected for teaching and the knowledge the student develops in their relationship with that content (Hopmann, 2007). In the curriculum tradition, such a distinction is not recognised (Hopmann, 2015). Teaching thus within didaktik opens for greater teacher autonomy when compared with teaching within the curriculum tradition, which more purposefully embodies content as disciplinary knowledge; this being a consequence of higher education institutions viewing such knowledge as a prerequisite for school students' later entry into higher education (Hopmann, 2015).

Describing the crucial connection between didaktik and *Bildung*, Künzli (2000, p. 46) writes that "*Bildung* serves didaktik as a cypher in its concern to synthesise into a consistently coherent whole everything happening within instruction." As an educational construct, *Bildung* dates back to the late 18th century. Its literal translation into English being "*becoming in the image of*." *Bildung* represents both an ideal image of something for humankind to become (Biesta, 2002; Gustavsson, 2014), and processes of subjectification (Biesta and Leary, 2012; Schneider, 2012) as well as an agency (Sjöström et al., 2017; Taylor, 2017; Eilks et al., 2018), that underlie/are driven by this ideal (see **Figure 1**, which will soon be described more in detail). *Bildung* envisions self-determination, participation, and solidarity (Klafki, 2000b), with the person's self-determination being bound to different ways of relating to themselves and the world (Rucker, 2020).

Significantly, the ideal image that *Bildung* represents is always bound to the culture and society in which the processes of subjectification and agency are a part (Taylor, 2017). Crucially, such processes are "understood as being in responsible relationship with other human beings and, by extension, with the natural world more generally" (Biesta, 2013, p. 739). To specify the meaning of *Bildung* today, we have to base it on the fact that we live in a globalised risk society with many global and ecological challenges (e.g., Straume, 2015). In an essay, Rowson (2019) discusses *Bildung* in relation to future education and sustainability issues. He expresses *Bildung* as being a values-driven applied philosophy of education and connects it to for instance spirituality, transdisciplinarity, and transformative education. He writes: "*Bildung* entails a dynamic world view that values the independence of mind and spirit grounded in ecological and social interdependence" (pp. 3–4).

During the last decade, ideas of less anthropo-centered versions of *Bildung*, where both relations and responsibility are emphasised, have evolved (e.g., Taylor, 2017; Sjöström, 2018). Rucker and Gerónimo (2017) have connected the concept to complexity, and Taylor (2017, 2020) to posthumanism. The latter author writes:

"A posthuman *Bildung* is a lifelong task of realising one's responsibility within an ecology of world relations, [. . . It] is a matter of spirituality and materiality which means that it is not an 'inner process' but an educative practice-oriented to making a material difference in the world. [. . . It is] education as an ethico-onto-epistemological quest for (better ways of) knowing-in-becoming." (Taylor, 2017, pp. 432–433).

Building upon Taylor's (2017) contribution to developing a posthuman understanding of *Bildung*, Clucas et al. (in preparation) has sought to further develop such an understanding of the construct. In their development of a posthuman understanding of *Bildung*, the authors build upon a fundamental view of the construct as standing for both an ideal image of something for humankind to become (Biesta, 2002; Gustavsson, 2014), and processes of subjectification (Biesta and Leary, 2012; Schneider, 2012) and agency (Sjöström et al., 2017; Taylor, 2017; Eilks et al., 2018) that underlie/are driven by this ideal. Presented as a novel posthuman understanding for *Bildung*, these two aspects of the construct are viewed as being intimately related, being defined as (1) a process of subjectification that involves the *Bildung* entity intentionally opening to being renewed through embodied connection with the world, and (2) a process of crafting *Bildung* as an ideal image with a view to the *Bildung* entity guiding itself and others toward relationships for renewal (Clucas et al. in preparation). **Figure 1**

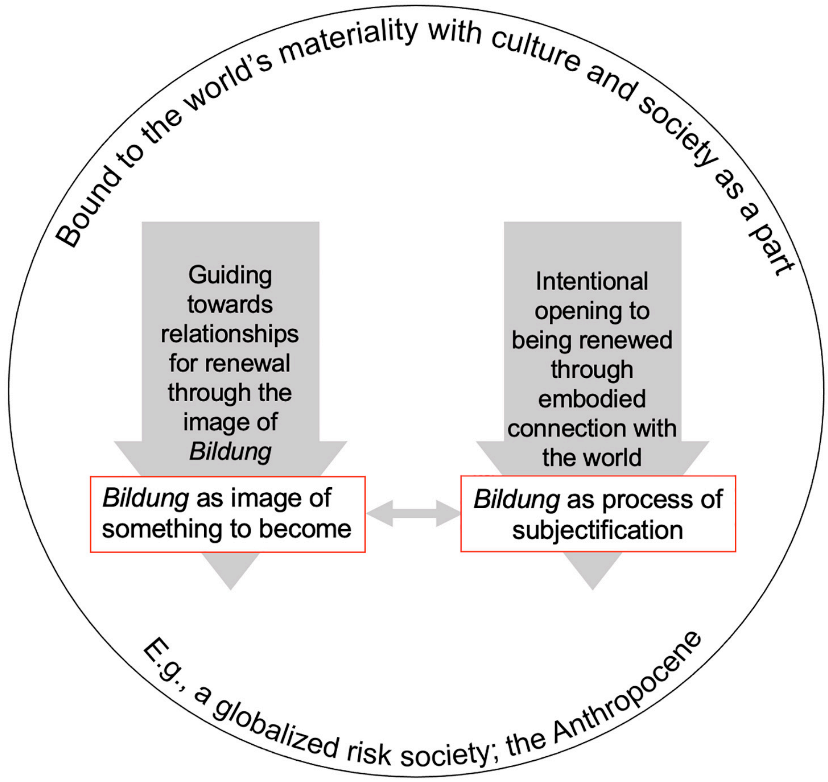

FIGURE 1 | Simplified model of a posthuman understanding of *Bildung* (Clucas et al. in preparation).

shows a simplified representation of the authors' posthuman understanding of *Bildung* that captures these two fundamental aspects. Also shown in the model is the idea that these two aspects of *Bildung* are always situated within, and thus bound to, the world's materiality of which culture and society are a part (Horlacher, 2016), which today would be a globalised risk society and the Anthropocene (Brondizio et al., 2016).

As has perhaps already become clear for the reader, *Bildung*, at least in relation to the nature of learning it specifically entails, can be understood differently depending upon which perspective is used to frame it, and the context *Bildung* is situated within (Horlacher, 2016). We wish therefore to conclude this brief presentation of *Bildung* by distinguishing two (complementary) perspectives that have become valuable to us: *Bildung* seen as a counter-concept, and Sjöström and colleagues' critical- and eco-reflexive *Bildung* construct for chemistry (and science) education.

Bildung as a Counter-Concept

The idea of *Bildung* as a counter-concept finds its origins in the emergence of *Bildung* as a pedagogical construct in the modernising era of 18th century Germany (Alves, 2019). Conceived in the face of developments in the sciences, new technologies, increased division of labour, and knowledge specialisation, the emergence of *Bildung* as a pedagogical construct was a reaction against a perceived fragmentation of knowledge and society (ibid.). *Bildung* became thus a pathway for people to become reconnected to the idea of humanity and be integral or whole "in a world increasingly similar to a vast machine" (ibid., p. 5). As a critical and resistant counter-concept, *Bildung* is seen therefore as an illuminating factor that threatens to reduce or narrow human beings' perception and constitution of reality (Wimmer, 2003). If we compare this description of *Bildung* to the model in **Figure 1**, a view of *Bildung* as a counter-concept reflects an ideal image of something to become, that being the capacity for resisting a narrowing of the entity's perception of reality. Seen in the context of the Anthropocene, the role of *Bildung* as a counter-concept (as an ideal image of something to become) might reasonably be viewed as being critically important in education. This is because it is associated with the idea of education as having a broader value, and not something that can be characterised in instrumental terms only (e.g., Schnack, 2008).

Sjöström and Colleagues' Critical- and Eco-Reflexive Bildung Construct for Chemistry (and Science) Education

Of importance to chemistry (and science) education, Sjöström and colleagues have drawn from the works of Hans-Georg Gadamer (1900–2002), Paul Ricoeur (1913–2005), and the German educational philosopher Wolfgang Klafki (1927–2016) in developing a *Bildung* construct for the

Anthropocene which they term critical- or eco-reflexive *Bildung* (Sjöström et al., 2016, 2017; Sjöström and Eilks, 2018). Posited as a metatheory, critical- or eco-reflexive *Bildung* includes ideas of critical reflexivity, emancipation, critical-democratic awareness, socio-ecojustice, and socio-political action (Sjöström et al., 2016, 2017; Sjöström and Eilks, 2018). As a framework for critically and sustainability-oriented chemistry and science teaching, it suggests a chemistry (and science) teaching that orients student's in "a critical stance toward the modern risk society, an understanding of the complexity of life and society and their interactions, and a responsibility for individual and collective actions toward socio-ecojustice and global sustainability" (Sjöström et al., 2016, p. 336). In developing their framework, Sjöström and his colleagues have closely related critical- and eco-reflexive *Bildung* to a critical view of science education and scientific literacy which they term Vision III (Sjöström et al., 2017; Sjöström and Eilks, 2018). It is a critical scientific literacy relating to urgent socio-political issues and in doing so also emphasises relevant knowledge in and about science and technology in the Anthropocene.

POWERFUL KNOWLEDGE AND KNOWINGS

While criticising the loss of content discourse within educational research, Young and his colleagues have introduced and unpacked the idea of *powerful knowledge*, building on the social realism perspectives of Bernstein and Durkheim (Young, 2013; Young and Muller, 2013). Situated within the curriculum tradition, powerful knowledge is conceived as a curriculum principle, being also strongly aligned with the subject disciplines (Muller and Young, 2019). Significant in this regard, powerful knowledge has two characteristics that differentiate it conceptually from other forms of knowledge: first, it is specialised knowledge within the boundaries of the disciplines, which separates it from general knowledge. Second, it is separate from everyday experiences that the students carry which differentiates it from everyday knowledge (Young, 2013). Significantly, Young and his colleagues draw a distinction between powerful knowledge and what they term "Knowledge of the powerful" (KOTP), where the latter refers to power structures that utilise knowledge to create or uphold domination or "power over" (Muller and Young, 2019). In contrast, powerful knowledge is conceived as the knowledge that gives the holder "power to" act in a manner that generates human value (ibid.). Powerful knowledge is thus "available to all who acquire it [. . . and] infinitely transferable" (Muller and Young, 2019, p. 198). It is a knowledge that allows students "to understand and interpret the world. [. . .] it transcends and liberates [them] from their daily experience" (Young, 2013, pp. 117–118).

Recently, a number of authors have attempted to situate powerful knowledge within the didaktik tradition (Gericke et al., 2018; Carlgren, 2020; Deng, 2021; Hordern, 2022). Of value in this context is that situating powerful knowledge in this way opens to pedagogical questions that are not normally open to examination in the curriculum tradition, namely, questions of *what* content should be selected for teaching and *why*. In this way, the question of what powerful knowledge might be is no longer restricted to subject discipline knowledge, but rather, it becomes an idea for teachers and students to examine and define also (Gericke et al., 2018). Indeed, it becomes an issue for examination and definition in relation to the purpose of schooling as a whole (Hordern, 2022). As a vision for education, and embodied in the curriculum of the didaktik tradition, such a whole is not derived from the separate disciplines, but rather, "through an analysis of the whole life culture" (Künzli, 2000, p. 44). Thus, subject teaching becomes something broader and more integrated than simply teaching subject knowledge (e.g., Gericke et al., 2018), and opens to the possibility of teaching "with an object in view that is complete in itself" (Weniger, 2000, p. 116), e.g., an education that can initiate students in tackling unresolved societal challenges in the Anthropocene (Kvamme, 2021). Significantly, in the didaktik tradition, *Bildung* is commonly viewed as embodying the educational outcome that such a vision for education represents (e.g., Rucker, 2020; Deng, 2021; Kvamme, 2021).

In her situating of powerful knowledge within the didaktik tradition, Carlgren (2020) relates powerful knowledge to *Bildung* by developing the idea of *powerful knowings*. Importantly, when Carlgren is speaking of powerful knowings she is referring to the knowing that the student has come to know through the teachers' teaching of "knowns," that is, the specific knowledge the teacher wants their students to learn. For Carlgren, "knowings" can be distinguished from "knowns" in that they include what she describes as tacit dimensions that are in addition to the "knowns" (Carlgren et al., 2015). However, it is important to point out here that the "knowns" in relation to powerful knowledge may be understood differently according to the teaching tradition a particular teacher is situated within. For example, in the didaktik tradition, "knowns" might be viewed as contents of education for *Bildung* (*Bildungsinhalt*), whereas in the Anglo-Saxon curriculum tradition, "knowns" might be disciplinary knowledge as curriculum content. The factor impacting these differences is the teacher's transformation of curricular content for teaching and the fact that – if taking it to its extreme – in the didaktik tradition the teacher is given freedom in relation to the selection of content that the teacher in the Anglo-Saxon curriculum tradition is not. Crucially, it is through Carlgren's inclusion of tacit dimensions that she is able to relate Young and colleagues' conceptualisation of powerful knowledge to *Bildung* (Carlgren, 2020). Importantly, Carlgren ties tacit knowledge and thus powerful knowings to the idea of knowledge as something "incorporated into our bodies [. . .] which connects us with the world and functions as a tool to widen our interface with it" (p. 326). Therefore, through tacit dimensions of knowing, the idea of powerful knowings can be viewed as containing an embodied and relational view of knowledge, with such a view being also consistent with the idea of *Bildung* (ibid.).

Thus, a core outcome of situating powerful knowledge within the didaktik tradition is of opening powerful knowledge to a discussion on knowledge transformations (Gericke et al., 2018; Carlgren, 2020; Deng, 2021; Hordern, 2022). Critically, such transformations take place both inside and outside of educational settings (Gericke et al., 2018). In this article, we are especially interested in knowledge transformations that take place in relation to chemistry classroom teaching, specifically, students' transformation of content for *ChemoKnowings* and the need for teachers' transformation of content to take such a transformation into consideration. First introduced by Herranen et al. (2021), ChemoKnowings are a specific form of powerful knowings in chemistry education that the student comes to know in the context of the classical didaktik triangle. Of significance in this regard is the crucial role the teacher plays in creating the conditions for students coming into a relationship with a subject matter that can be transformed into powerful knowings as ChemoKnowings. Indeed, this we view as a central task of chemistry didaktik. Situating powerful knowledge within the context of a *Bildung*-centered didaktik, Deng (2021) points to the fact that the teachers' didaktik work is the crucial arena for the transformation of content for *Bildung*. Deng argues thus for teachers' use of Klafki's didaktik analysis in relation to knowledge transformation at the classroom level (ibid.). Developed in 1958, and formulated as five questions, Klafki (2000a) developed his didaktik analysis approach to support teachers' work to transform content for *Bildung*:

I. What general sense, basic phenomena or fundamental principle does this content exemplify and open up to the learner? (Exemplary Significance)
II. What significance does the content in question already possess in the minds of the children in my class? (Contemporary Significance)
III. What constitutes the topic's significance for the children's future? (Future Significance)
IV. How is the content structured (which has been placed in a specific pedagogical perspective by questions 1–3)? (The Structure of the Content)
V. What are the special cases, phenomena, situations, and so forth in terms of which the structure of the content in question can become interesting, stimulating, and approachable for children? (Accessibility) (from Bladh, 2020, p. 210)

In view of the connection between the idea of powerful knowings and *Bildung*, we believe Klafki's questions open to the idea of our discussion on knowledge transformations for powerful knowings (as ChemoKnowings) approaching an outlining of its own question areas for guiding teachers' work in transforming curriculum content. That is, transforming curriculum content to come to understand which "knowns" the teacher wishes to teach for students' intended "knowings." Of central importance in this regard is that any such question areas need to guide teachers in creating the conditions through which students, in their relationship with chemistry teaching content, are enabled in transforming "knowns" toward ChemoKnowings. That is, a knowing in chemistry education (in a broad sense) that includes embodied and relational (or tacit) dimensions in addition to the "knowns" (both in and about the subject, in our case chemistry).

In our view, Klafki's original questions do not sufficiently open for teachers, in their transformation of curriculum content, to take into consideration the volition of students in relation to their own transformations of content for *Bildung*. For Gericke et al. (2018), however, both teachers and students play a role in determining what powerful knowledge is. The student's own role in determining whether or not a particular chemical content knowledge becomes for them a ChemoKnowing must therefore be included. In his recent description of *Bildung*-oriented teaching, Rucker (2020) explored the process of transformation for *Bildung* from the perspective of the student. Rucker describes teaching as an act of summoning the student's self-activity, and the student as developing the ability to self-determination "in the confrontation with a resistant world [. . .] with cultural objects that do not submit to every judgement and action" (p. 56). For Rucker, such a resistant confrontation with content is what opens the possibility of *Bildung*. Recently, Biesta (2022) opened an existential discussion on students and what they might do with taught content. Education needs to encourage students to be in and with the world and it is up to the students how to do so, although guided by the teacher. For students to exist as subjects in and with the world, they need to acknowledge that they navigate within the frame of the world, nature, and the social. Such acknowledgement may call for the kind of confrontation that Rucker is describing. Significantly, and citing Benner (2015), Rucker (2020) writes that "teaching can only be *Bildung*-supportive if it leaves room for the self-relationship of the learner with what is being learned and taught" (p. 59). Thus, placing themselves critically in relation to particular content, the student purposefully examines the content's claim to validity, also making a judgement of what value that content has for the student themselves (ibid.). The student thus has the opportunity to decide for themselves whether or not a particular content is both convincing and of meaningful personal value. Importantly, it is only when both conditions are satisfied that we can speak of a transformation for *Bildung*, which Rucker defines as "the ability to act in light of objective insights and one's own value judgements" (p. 59). Drawing from these ideas, we consider the student's examination of validity claims as well as value judgements in their self-relationship with chemistry teaching content to be crucial to their coming to know as ChemoKnowings. Drawing on different theoretical perspectives, our focus in this article is to begin an exploration of what ChemoKnowings might be in the Anthropocene, and thus to approach outlining some different didaktik models that can support student's transformation of content for ChemoKnowings through the opening to the teacher considering such a transformation in their chemistry didaktik praxis. We will start by briefly exploring three concepts that are related to ChemoKnowings: critical chemical literacy, eco-reflexive chemical thinking, and ChemoCapabilities, respectively.

THREE RELATED CONCEPTS TO ChemoKnowings

In the next section we will elaborate further on the construct *ChemoKnowings* based on ideas of eco-reflexive *Bildung* and powerful knowledge and knowings, and also present a new "vision model," that includes student transformation of content, and which aims to broadly guide teachers in promoting ChemoKnowings and "chemical agency" in their teaching. However, before doing so, we will briefly explore previously discussed ideas and concepts that also have had the ambition to point at relevant chemistry knowledge (in and about) and what to (be able to) do as a citizen with such chemistry-related knowledge. Such related concepts are chemical literacy and chemical thinking. And inspired by the concept GeoCapabilities – suggested in relation to geography education – we will mention the corresponding concept ChemoCapabilities. All these three conceptual ideas are – more or less – related to ChemoKnowings as an idea and construct. However, our focus in this article is on the latter concept, so we will only give short introductions to the three other concepts, as a background to previous research inside the same area of research interest. The three other constructs can also provide theoretical insight into what might be meant (in a broad sense) by ChemoKnowings.

Critical Chemical Literacy

When searching (2022-01-25) on Google Scholar for "chemical literacy" there were 1300 hits. In the top three regarding citations were three articles by Shwartz, Ben-Zvi, and Hofstein published in 2005 and 2006 in IJSE, JCE, and CERP (Shwartz et al., 2005, 2006a,b). The CERP paper (Shwartz et al., 2006b) had about 300 citations in Google Scholar. The authors refer to Bybee (1997) and his definition of multidimensional scientific literacy. In addition to the concepts of scientific disciplines and procedures of scientific investigation, such a view of scientific literacy also includes philosophical, historical, and social dimensions of science and technology.

Shwartz et al. (2006b, p. 206) formulated a definition of chemical literacy consisting of four domains: (1) scientific and chemical content knowledge; (2) chemistry in context; (3) higher-order learning skills; and (4) affective aspects. Domain one is about understanding chemistry as an experimental discipline that tries to explain the structure and dynamics of our material world. Domain two is about the role of chemistry in everyday life. Domain three is about meta-cognitive aspects and domain four is about affective aspects connected with the individuals' view of chemistry and chemical-related issues, e.g., impartiality and interest.

The 15-year-old framework has merits, but also limitations. For example, concentration and transportation aspects as well as technological aspects are not present in the framework. The latter is crucial because chemistry is as much a technology as it is natural science (Sjöström, 2007a; Chamizo, 2013). In addition to understanding and explaining the world, chemistry also aims at making new molecules, materials, product formulations, sustainable industrial processes, etc. (e.g., Sjöström and Talanquer, 2014; Talanquer, 2016; Marcelino et al., 2019). Concentration and transportation aspects are central in relation to environmental issues.

A more general critique of the framework is that there is a need for a socio-critical-political framing. Such humanistic perspectives on chemistry education toward "multifaceted problematisation" are highlighted by Sjöström and Talanquer (2014). It requires problematisation of chemistry content (*in* chemistry) and problematisation of chemistry from humanistic perspectives (*about* chemistry). Such a critical-reflexive approach to chemistry highlights reflecting on the relationship between chemistry, technology, environment, and society within social, historical, and philosophical framings. In addition to understanding, problematising, and reflecting, it also covers decision-making and action taking toward issues framed by chemistry, technology, environment, and society (Sjöström and Talanquer, 2014).

The term "critical chemical literacy," which we believe is pointing in the same direction as ChemoKnowings, has almost not at all been used before, and when so has been done it was used for framing of chemistry by broad societal perspectives and pluralism (Sjöström and Stenborg, 2014). Both "critical chemical literacy" (as used by Sjöström and Stenborg, 2014) and ChemoKnowings are being importantly linked to what can be called eco-reflexive *Bildung*.

Eco-Reflexive Chemical Thinking

When searching (2022-01-25) on Google Scholar for "chemical thinking" there were 1800 hits. In the top six regarding hits and/or citations were articles (co)authored by Vicente Talanquer (Sevian and Talanquer, 2014; Banks et al., 2015; Sjöström and Talanquer, 2018; Talanquer, 2018, 2019a; Freire et al., 2019). The CERP-paper (Sevian and Talanquer, 2014) had more than 200 citations in Google Scholar. In this article, chemical thinking is defined as "the development and application of chemical knowledge and practices with the main intent of analysing, synthesising, and transforming matter for practical purposes" (ibid., pp. 10–11). This idea mainly supports chemistry professionals in a broad sense, but may also be useful as a background in layman decision-making in diverse situations (e.g., Cullipher et al., 2015). Mainly based on ideas of what can be called "sustainability agency" and considerations of the impact of chemical actions – risks and benefits – Sjöström and Talanquer (2018) elaborated on what they called eco-reflexive chemical thinking and action. They related their ideas to eco-reflexive *Bildung* and also discussed implications for education. We believe the term "eco-reflexive chemical thinking" (43 hits in the Google Scholar search, mainly due to references to the article by Sjöström and Talanquer, 2018) is pointing in the same direction as ChemoKnowings, although probably embodied and relational dimensions are even more pronounced in the latter construct, as we will describe more in detail below.

As already mentioned above, Talanquer (2019a) has also discussed the need for chemistry knowledge and chemical thinking in relation to global challenges. Such knowledge encompasses engaging in decision-making in relation to sustainable action-taking. As also mentioned above, Talanquer has developed a chemical systems thinking model, later applied in relation to, for instance, COVID-19 (Talanquer et al., 2020).

ChemoCapabilities

Inspired by the concept GeoCapabilities (e.g., Lambert et al., 2015; Bladh, 2020) – suggested in relation to geography education – we here suggest the new corresponding construct ChemoCapabilities. More generally, what can be called

"SubjectCapabilites" may be viewed as related to subject-specific powerful knowledge. The GeoCapabilities approach seeks to explain human development through education, more specifically through school subject geography. Through its emphasis on engagement in disciplinary knowledge, the GeoCapabilities approach rejects generic 21st-century skills. Through their engagement with disciplinary knowledge, students develop:

[a] A deep descriptive world knowledge. [b] A critical conceptual knowledge that has explanatory power and systematicity, providing a relational understanding of people living on the planet. [c] A propensity to think through alternative social, economic, and environmental futures in specific place and locational contexts (Lambert et al., 2015, p. 732).

The term Capabilities has been developed in relation to *Bildung*-ideas, mainly those by Amartya Sen and Martha Nussbaum. More recently, Bladh (2020) connected it also to the *Bildung*-ideas in Klafki's didaktik analysis. Based on Klafki's more recent thinking there are also connections to concepts such as action, agency, and curriculum content, in the Anthropocene. Furthermore, connections can be found between GeoCapabilities and Klafki's *Bildung* as self-determination, co-determination, and solidarity. Capabilities connect educational aims to school subject teaching, and crucially they can be understood as subject-specific powerful knowings as they understand knowledge in a relational sense based on Carlgren (2015). We believe, therefore, ChemoCapabilities to be a construct close to ChemoKnowings, although the first mentioned construct not necessarily include embodied dimensions.

POWERFUL CHEMICAL KNOWLEDGE FOR SCHOOLING: ChemoKnowings AND "CHEMICAL AGENCY"

In order to embed chemistry education into environmental and sustainability education (ESE), Herranen et al. (2021) developed a new theoretical "didaktik model" (**Figure 2**) based on a previous model. Generally speaking, didaktik models are reflection tools (or frameworks) supporting teachers when deciding on one or several didaktik questions in relation to local "curriculum-making" and/or instruction design (e.g., Ingerman and Wickman, 2015; Sjöström et al., 2020; Wickman et al., 2020). Such models facilitate teacher didaktik decisions as they provide new perspectives in relation to why, what, and how questions. Furthermore, didaktik models provide a professional language for teachers for communication and documentation. They can be useful for teachers when having certain situations, questions, and student groups in mind. However, as local curriculum-making, didaktik analysis, didaktik decisions, and instruction design are complex processes, it can be argued that a specific didaktik model only facilitates certain aspects of this complexity (e.g., Wickman et al., 2020).

In their article Herranen et al. (2021) first proposed the term ChemoKnowings, which can be seen as an example of powerful subject-knowings. The term was coined within the fields of ESE and Curriculum Theory. It was also related to already mentioned systems thinking in chemical education (Mahaffy et al., 2018) and eco-reflexive *Bildung* (Sjöström et al., 2016). Herranen et al. (2021) described ChemoKnowings as including "[. . .] relevant theoretical and practical knowledge in and about chemistry as well as about the nature and culture of chemistry" (p. 17). The term encompasses action taking with socio-eco-critical awareness. Herranen et al. (2021) also argued that chemistry, as an example of one important knowledge area in relation to the challenges of the Anthropocene, shouldn't be understood in a fragmented way. In the didaktik model in **Figure 2** (from Herranen et al., 2021), ChemoKnowings are presented as encompassing four elements: critical views on chemistry's distinctiveness and methodological character; powerful chemical knowledge; critical views on chemistry in society; and eco-reflexivity through environmental and sustainability education.

However, we feel that student transformation of (and relation to) content for ChemoKnowings is not sufficiently explicit in the model of Herranen et al. (2021). Indeed, the model includes powerful chemical content knowledge in relation to so-called wicked problems, but it does not clearly take into consideration Carlgren's (2020) important powerful knowings-construct, including embodied and relational (or tacit) dimensions, in addition to the "knowns."

In an attempt to re-think a science curriculum oriented toward sociopolitical action, Hodson (2003, p. 658) formulated four elements of a science curriculum:

- *Learning science and technology* in relation to "conceptual and theoretical knowledge."
- *Doing science and technology* in relation to "scientific inquiry and problem-solving."
- *Learning about science and technology* in relation to learning the nature and the methods of science and technology together with their interaction. This element can be understood as including Science, Technology, Society, and Environment.
- *Engaging in sociopolitical action* in relation to responsible action.

Instead of the latter element, Aikenhead (2007) emphasised "knowing-in-action" and he was the first who suggested connecting it to a Vision III of scientific literacy. This idea, already mentioned in section "Towards Eco-Reflexive *Bildung*," has been broadened and developed further by Sjöström and Eilks (2018).

Based on Hodson's (2003) subdivision as well as on our own discussion above, we want to suggest that student's transformation of content for ChemoKnowings is related to the following four dimensions:

1. Learning chemistry (e.g., conceptual understanding)
2. Doing chemistry (e.g., chemical inquiry)
3. Learning *about* chemistry (philosophical, historical, socio-political, etc., perspectives)
4. Engaging in socio-political action (in a broad sense) related to chemistry (in a broad sense) (here called "chemical agency")

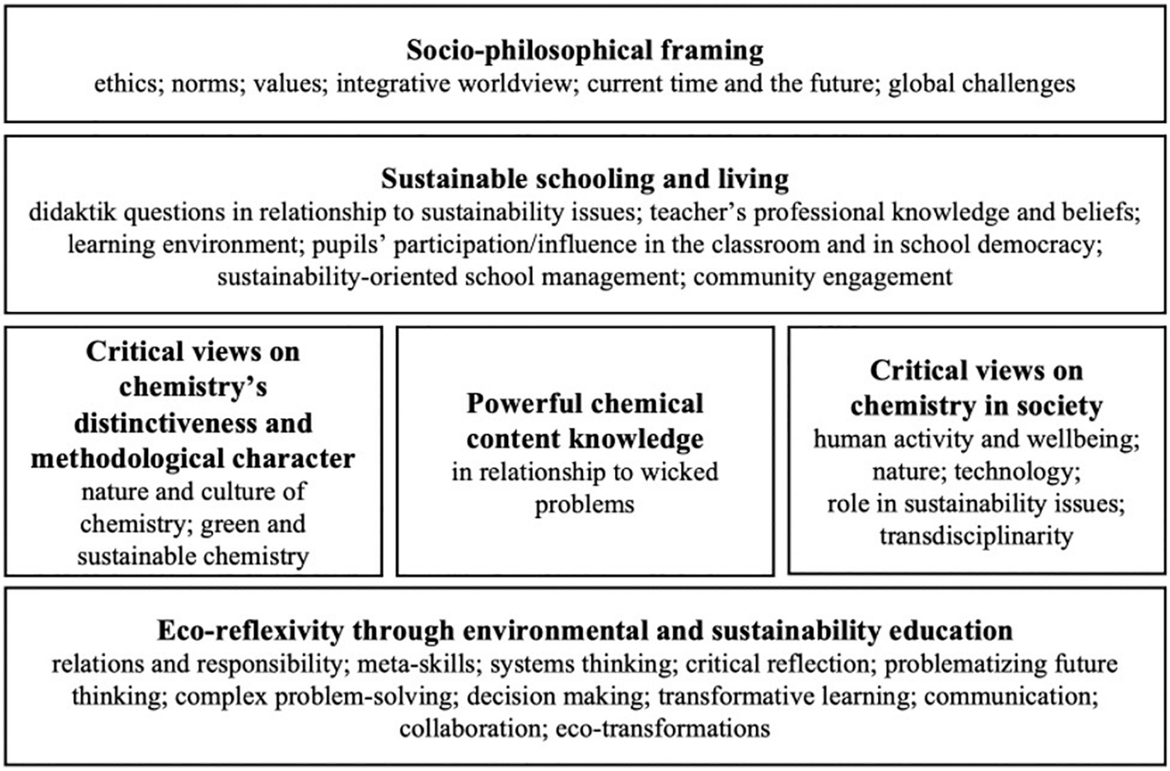

FIGURE 2 | Didaktik model for eco-reflexive chemistry education (Herranen et al., 2021, p. 5).

We believe that these four dimensions can be related to the four ChemoKnowings elements in **Figure 2**, opening to a linking of these elements to student's transformation of content (see **Figure 3**; the figures/numbers refer to the four dimensions just tabled).

From a *Bildung* perspective, three kinds of chemistry knowledge can be viewed as essential: (a) ontological knowledge meaning knowledge about chemical concepts and processes, (b) epistemological knowledge which is knowledge about chemistry, including the community of scientists ("nature of chemistry practice"), and (c) social or ethical knowledge, which takes chemistry into consideration together with society (Krageskov Eriksen, 2002; Sjöström, 2007a, 2013). These three kinds of chemistry knowledge can to some extent be related to the first three dimensions mentioned above (i.e., learning chemistry, doing chemistry, and meta-perspective on chemistry, especially in relation to society). As a corresponding kind of chemistry knowledge to the fourth dimension, one could add: (d) *embodied and relational chemistry knowledge*. Such knowledge is important for engaging in socio-political action (in a broad sense), although also the other kinds of chemistry knowledge (ontological; epistemological; social/ethical) are important for this (see the further discussion on this below). In this article, we use the term "chemical agency" for the capability and practice of socio-political action related to chemistry in a broad sense. This is a new way of using this term; in policy contexts, the term refers to an agency/bureaucracy governing chemicals used in society.

However, despite the pronounced link with *Bildung*, the embodied and relational (or tacit) dimensions that are crucial to Carlgren's distinction between powerful knowledge and powerful knowings and thus a fundamental link between ChemoKnowings and *Bildung*, remain predominantly unarticulated in **Figure 3**. Drawing from Rucker's description of *Bildung*-oriented teaching, and of the student's purposeful examination of a content's claim to validity, as well as the judgement of what value that content has for the student themselves, we suggest that a crucial embodied and relational dimension of ChemoKnowings is that they are experienced as meaningfully valuable. That is, they are knowings that matter meaningfully to the student and connect the student to themselves and the world (von Humboldt, 2000).

Interestingly, Biesta (2022) seems to touch on the embodiment of knowledge and its relationality in his recent description of a world-centered education, stating that it is about "[. . .] equipping and encouraging next generations [students] to exist 'in' and 'with' the world and do so in their own right" (p. 3). Significantly, a fundamental dimension that Rucker (2020) places on knowings that confer *Bildung* is that they lie always "under the claim of morality" (p. 51). Indeed, Klafki (2000b) also viewed the "ethical compass" as an essential dimension of *Bildung*. The ethical compass we suggest therefore is a fundamental tacit dimension of ChemoKnowings and a contemporaneous outcome of knowings mattering meaningfully to the student. Importantly, in their conferring of ethical compass, any actions ChemoKnowings may mobilise in the student ought themselves be ethically oriented.

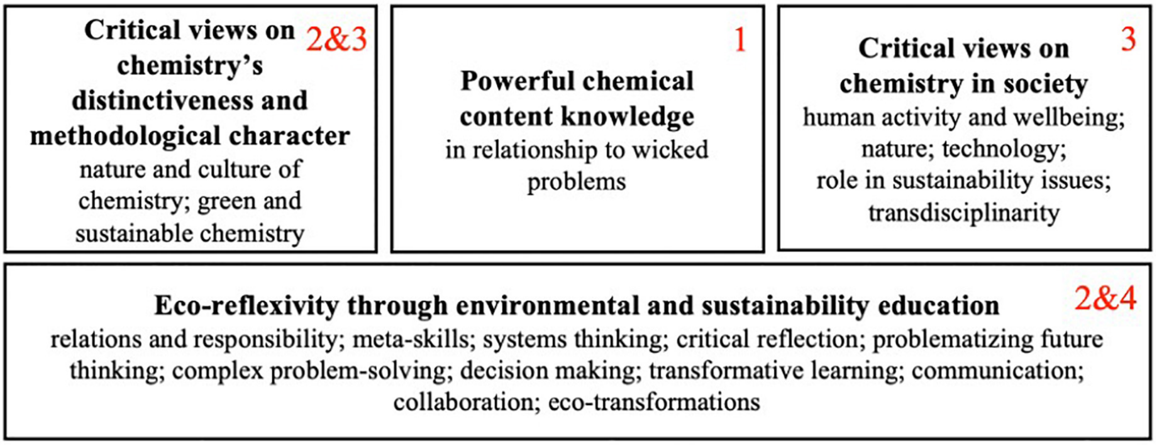

FIGURE 3 | Model linking student transformation of content for ChemoKnowings to four elements of Herranen et al.'s (2021) model viewed as important for ChemoKnowings. The context is ESE-framed chemistry education.

This is also consistent with ideas of *Bildung* (e.g., Klafki, 2000b; Rucker, 2020).

As was mentioned before, students' need to acknowledge nature, the world and social limits in the context of guiding their action "in their own right" means that they cannot do whatever they want with the world. According to Biesta (2022), it is a matter of democracy and ecology, which we believe, points toward ethically motivated action. In the context of ChemoKnowings, we believe the direction of such action can be informed by the teacher making salient a vision for chemistry teaching as a part of schooling as a whole, with the vision of schooling as a whole being a world-centered vision for schooling in the Anthropocene. In such a context ChemoKnowings would be viewed as having the power to mobilise ethically oriented socio-political actions as world-centered actions in the Anthropocene.

However, crucially and in line with what van Poeck and Östman (2020) have described as a "double responsibility of the teacher," we believe content brought into the classroom needs, explicitly by the teacher, to be "put on the table." To emphasise world-related problems in the classroom, the teacher takes responsibility for answering questions "*what* to put on the table and *how* to make it free" (van Poeck and Östman, 2020, p. 1010) and makes didaktik choices accordingly. By putting it on the table and "making it free," the teacher opens up possibilities for students to engage and study what is put on the table and make it meaningful for them. In other words, students' engagement in content that has been "put on the table" engenders open-ended inquiries which facilitate critical and plural points of view on the issue at hand (Öhman and Sund, 2021). Such an idea we believe is consistent with what Rucker (2020) means by teaching being only *Bildung*-supportive when it leaves the room "for the self-relationship of the learner with what is being learned and taught" (p. 59).

Figure 4 presents the four ChemoKnowings elements of Herranen et al.'s (2021) model (shown in **Figure 3**) situated within (1) an ethically oriented vision for chemistry teaching as a part of an ethically oriented world-centered vision for schooling in the Anthropocene, and (2) the student's ChemoKnowings as embodied and relational knowings that matter meaningfully to the student, conferring ethical compass, and having the power to mobilise ethico-socio-political action. Knowings that come to matter meaningfully for the student, conferring ethical compass and engendering a power that can mobilise ethico-socio-political action, can be viewed as ChemoKnowings (for the individual student or world citizen). Therefore, we view each of the selected elements of Herranen et al.'s (2021) model as potentially giving rise to students engaging in socio-political action related to chemistry in a broad sense, that is, what we here call the chemical agency. When the selected elements (**Figure 3**) are put in the context of an ethically oriented world-centered vision for schooling in the Anthropocene, embodiment, relationality, and chemical agency are visible in every element of the model. That is why the 4th dimension of students' transformation of content for ChemoKnowings (marked with "4") is shown in all four boxes in **Figure 4**. Significantly, we also include in the model in **Figure 4** van Poeck and Östman's (2020) idea of putting content "on the table" and "make it free."

By *chemical agency* we mean engaging in socio-political action related to chemistry in relation to the different elements/boxes within the circle in **Figure 4**, that is, "critical views on chemistry's distinctiveness and methodological character," "powerful chemical content knowledge," "critical views on chemistry in society," and "eco-reflexibility through sustainability and environmental education."

AUTHORS' REFLECTIONS ON PERSONAL EXAMPLES OF ChemoKnowings

This article seeks to explore what ChemoKnowings might mean for us, the students or world citizens in the Anthropocene and, based on that, to outline didaktik models for promoting

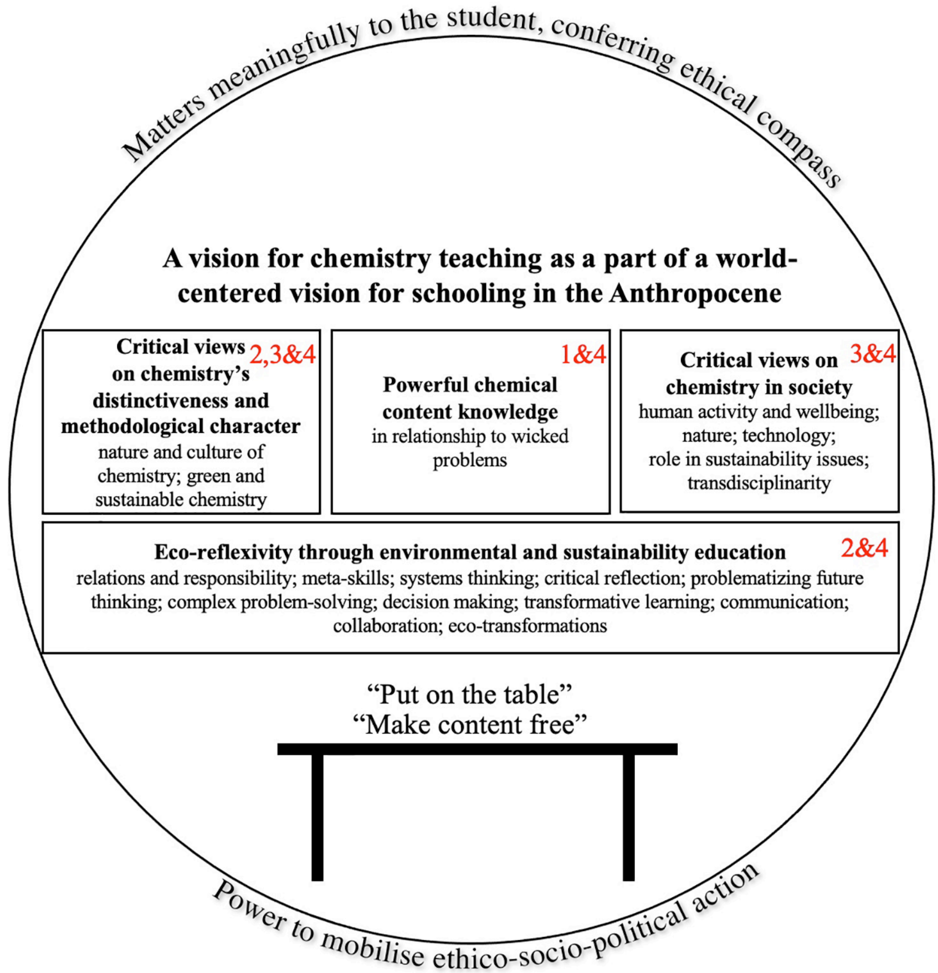

FIGURE 4 | A vision-oriented didaktik model for promoting ChemoKnowings and "chemical agency" in chemistry teaching. It includes the teacher's consideration of student transformation of content. Note that the numbers in red indicate connection to Hodson's (2003) four elements of the science curriculum: (1) learning relevant chemistry concepts; (2) doing chemistry (in a broad sense); (3) critical contextualisation of chemistry; and (4) chemical agency, including relational and embodied elements.

ChemoKnowings that include teachers' consideration of student transformation of content for ChemoKnowings and chemical agency. Although we believe the vision-oriented didaktik model presented in **Figure 4** can be valuable in itself in helping teachers orient themselves to the goal of promoting ChemoKnowings in chemistry teaching in the Anthropocene, we feel our aim can be further strengthened by reflecting (guided by for instance the model in **Figure 4**) over what ChemoKnowings have been for us individually in our own schooling, careers and everyday lives, as well as in relation to our didaktik thinking and choices as teachers. In the reflections, we give different examples on how chemistry knowing has mattered to each of us individually in a meaningful way (driven by an ethical compass), including being a basis for chemical agency.

P. Clucas. As an undergraduate and graduate student in organic chemistry, I was always fascinated by reactions and reaction mechanisms. It created a sense of awe in me to draw these mechanisms, to experience the movement of electrons both within and across different structures. Engaging myself in this elegant art opened my imagination to another world, "the molecular world": An engaging world of molecular interactions and creative human invention. As a Ph.D. student in polymer technology during the 1990s, I spent many hours connected with this world, fueling my wonder and exploration of mechanisms that might be with the results of my experimental work. As a teacher, later, I wanted to share this world with my students. I wanted them to experience the art and wonder of "the molecular world" by our becoming a part of it. I will always remember the very first "performance": Climbing out through the classroom window onto a flat inner roof, together we stepped into this world and became connected as we acted and danced Kekulé's electrons chasing each other in a benzene ring.

The elegance, wonder and creativity of "the molecular world" stands in stark contrast, however, to the messiness, difficulty, and moral ambiguity of human utilisation of chemistry knowing in the real world. Indeed, coming to know this ambiguity, as well as the multiplicity of motives that drive our utilisation of chemistry knowing, is for me a crucial knowledge outcome in our education of future scientists, teachers, and citizens. Inspired by Sjöström and Eilks (2018) critical-reflexive *Bildung*, I have sought to generate a dialogue amongst chemistry students that situates them in a critical examination of the ethics of our use of chemistry knowledge, of how it improves and even saves lives, but also creates risk and leverages potentially catastrophic costs. To achieve this goal, I have provided students with a detailed summary of the industrial production, use, and environmental impact of two common chemical products; namely, acetylsalicylic acid and polyvinyl acetate. I have also presented green chemistry's 12 principles (Anastas and Warner, 1998) and a model for ethical leadership that draws from Starratt (2004). Putting the information "on the table," I have asked students, in groups, to make an analysis and come to their own conclusions regarding the ethics of our using chemistry knowledge, as a society and in our everyday lives. In this course, which I have given in high school chemistry as well as in science teacher training settings, I have witnessed and participated in dialogues that have awoken in students an awareness for complexity in relation to the question in hand. Also, I have experienced the dialogues connect us to a shared sense of moral purpose in connection with human use of chemistry knowledge in our world.

Both examples describe ChemoKnowings for me because they matter to me in a meaningful way that connects me to something greater than myself. In the case of "the molecular world," I am connected through awe, an appreciation of beauty, and creativity. By opening the door to this world for my students we become connected as we experience it together. In the case of critically examining the morality of human use of chemistry knowing, I am again connected with the students, but this time it is within the context of a dialogue that is much greater than any of us, a dialogue that is purposeful and which connects all of us to the complexity of the issue at hand, and to our world whose health is benefited and threatened at the same time.

J. Sjöström – life as a chemist 25 years ago. Just like Clucas, I was very fascinated by "the molecular world." Therefore, I chose chemistry as my major at university level and in 1998 I started as a doctoral student in surface and colloid chemistry. However, early on, I became skeptical of the lack of a good working environment at the large chemistry research center at Lund University, Sweden (approximately 600 researchers, including doctoral students, around year 2000) (Sjöström, 2007b). During my first 2 months as a doctoral student, a number of events occurred that was an alarm clock for me personally. One example was a mercury thermometer that evaporated in the lab in which I worked. Through such events, I realised that risk awareness was actually not that great at the Chemistry Center (CC). As an embodied reaction, I wrote an e-mail to the professors in my research department. I thought it felt like they were prioritising research results ahead of safety and a good working environment (ibid., p. 224). During the following years, my frustration grew over CC's lack of good physical working environment, and I considered quitting as a doctoral student. However, the incidents also became seeds to my increasing interest in the philosophy and culture of chemistry (Sjöström, 2007a), with important implications for my thinking about chemistry education (e.g., Sjöström, 2013).

During my years at CC, I observed a number of serious errors in the handling of chemicals. It was common for toxic chemicals and solvents to be handled outside fume cupboards. The worst example was a distinct odor of mercaptoethanol in the laboratory where I worked. The guest researcher who handled the toxic chemical blamed bad fume cupboards and wondered what he could do about it. Refraining from experiments, while waiting for better fume cupboards, never seemed to be relevant for him, which shows the risk tendency of some chemists in the pursuit of new results and careers (Sjöström, 2007b, p. 225). Also, during my undergraduate education, I had experienced a lot of remarkable things from a safety point of view. One example is how one of my teachers handled residues of a very toxic and carcinogenic chemical (divinyl sulfone) without protective gloves – outside the fume cupboard – and how I imitated his behaviour, although my body said that this is wrong (ibid., p. 224). In addition to intellectual (the head) and practical (the hand) knowledge in chemistry, ChemoKnowings also include embodied chemical knowledge (the body, including the heart).

When it comes to the working environment at CC, I was frustrated by the often poor air quality and the strange smells in corridors and in the lab. It was very common with a nauseating and pungent smell in corridors and labs. I very often felt irritation in the airways when I was staying at CC. Almost daily, there were various chemical odors in stairwells and corridors. Such chemical fumes irritated my eyes and caused me a headache. I addressed these major shortcomings in the physical work environment at CC in a sharply worded letter to CC's board in December 1999. As a doctoral student member of the board, I demanded that the handling of volatile and reactive chemicals at CC be stopped while waiting for rebuilt premises. However, one male board member and chemistry professor was very clear that he believed that as a chemistry researcher you must be prepared to sacrifice yourself for the research! (ibid., p. 226). My opinion is that the local culture at CC at least until 25 years ago was characterised by a "macho culture" that denied the severity of chemical risks, both for the practitioners' own health and the environment. I now move in time to the present.

J. Sjöström – everyday life. That it is very difficult to be a conscious consumer, I realised (again) at the time of working with this article. I decided – based on my ChemoKnowings – more than 10 years ago that I don't want to buy and eat food with artificial sweeteners. Nevertheless, I by mistake bought and drank a sweetened Fanta Orange during the New Year's Eve 2021. The bottle wasn't marked in an informative way, at least not from my point of view. Its label said, "New fantastic taste" (translated from Swedish), but otherwise it looked like "normal" orange Fanta without artificial sweeteners. However, I didn't think it tasted the way it should, so I looked at the ingredient list and then saw that it contained three artificial sweeteners, in addition to everyday sugar (sucrose): acesulfame K, aspartame, and sucralose. For most artificial sweeteners there are concerns about their safety. Some critics say, for instance, that they may be carcinogenic, but food safety authorities claim that they make overall assessment mainly focusing on consumption patterns and health aspects. All the three artificial sweeteners in the above-mentioned Fanta Orange are approved by the Swedish Food Agency, so legally there is no problem at all. However, based on a precautionary principle I am skeptical to eating/drinking food containing sucralose, which is chlorinated sucrose. Thus, sucralose belongs to the chemicals group chlorocarbons. Examples of other more well-known chlorocarbons are DDT, PCB:s, and dioxins. Common for many chemicals of this kind is that there were early warnings, most often before mass production and large-scale use. For example chloracne from PCB:s were identified among workers already 30 years before commercial use (Koppe and Keys, 2001).

Especially when heated, sucralose may dechlorinate and decompose into compounds like carcinogenic chloropropanols and polychlorinated dibenzodioxins. Another probably bigger problem with artificial sweeteners are uncertainties about their impact on the environment. Some artificial sweeteners are not easily decomposed in the environment. For instance, the environmental fate and effects of acesulfame K (another sweetener in the above-mentioned Fanta) have recently been reviewed by Belton et al. (2020). Also sucralose is problematic in a similar way. The Swedish Environmental Research Institute have shown that wastewater treatment has little effect on sucralose. Because sucralose is only slowly degraded in nature, there is a risk of continuously increasing levels in rivers and lakes.

For the case of sucralose there has been some reporting in Swedish mass media, for instance a news article in *Svenska Dagbladet*, January 30, 2008, with the heading "Sweeteners threat against environment" (translated from Swedish), but it is mainly other sweeteners – for instance aspartame (also in the above-mentioned Fanta) – that a decade ago was highlighted in the public debate, mainly connected to their potential health effects. A more general public discussion on food additives in Sweden started with the publication of the book "The Secret Cook" (translated from Swedish), criticising the use of food additives (Nilsson, 2007).

Around 2006 a sucralose-sweetened version of the much consumed Swedish tomato ketchup, Felix Tomato Ketchup, was introduced on the Swedish market. Driven by "chemical agency," I sent a mail to the producer. They answered and motivated with "that the approval of sucralose is based on EU's scientific committee's review of all scientific reports on sucralose and food safety. [...] It is Europe's leading scientists who review research studies and based on these have approved sucralose" (translated from Swedish). Three years later, after a boost in the debate about food additives, the producers' rhetoric had changed a lot. The sucralose-sweetened version of Felix Tomato Ketchup had by then been taken away from the market again. The producer now wrote: "Swedish authorities have approved sucralose and there is no decision to ban sucralose, but there is uncertainty about the impact of sucralose on the environment. Several studies are ongoing around this. We have received many consumer reactions due to our use of sucralose" (translated from Swedish). It is now more than a decade ago since there was a focus on food additives and among them artificial sweeteners in the public Swedish debate, and apparently sucralose (and other artificial sweeteners) are now back in some food products. However, it is now much more hidden than before! It can therefore be regarded as a contemporary example of "chemicalisation" of our society, our bodies and nature (Hodges, 2015). One could, as suggested by Belova et al. (2017, pp. 298–299), even talk about a "chemical oppression," where people are exposed to different risk-related chemicals, such as additives and contaminants, generally without being aware of the fact. Therefore, teachers should put examples of chemical oppression on the table for their students, as a potential basis for the students' development of ChemoKnowings and chemical agency.

M. Yavuzkaya. As a young student teacher (in the field of chemistry), I was trying to make sense of and contextualise the chemistry knowledge I had built so far. Therefore in 2013 and 2014, I enrolled in two senior undergraduate courses in the chemistry department, "Environmental Chemistry" and "Chemistry in Everyday Life," which changed my perspective on chemistry, teacher education, and research in chemistry education. The Environmental Chemistry course I took was taught by a professor who had gotten sick due to chemical exposure in his early years as a researcher and who later dedicated his teaching time to Environmental Chemistry. The course, taken in 2013, opened with the statement: "According to OECD, more than 500 million tons of man-made chemicals are manufactured per year and there are approximately 100,000 synthetic chemicals in everyday use." Later, so as to introduce what having 100,000 synthetic chemicals in one's everyday life means, the course moved on with the documentary "Underkastelsen" (title in Swedish; English translation: "the Submission"), that engaged me by presenting a blood analysis to determine which chemicals are present in human blood. It made me think what kind of man-made chemicals there are in my own blood and what the "cocktail effect" might potentially lead to. I realised, then, the molecules in my textbooks and notepads are indeed in my blood and are doing "something," which was a frightening thought. However, when I took the course "Chemistry in Everyday Life," I started to find this reality intriguing too. This is because my professor encouraged us "enjoy creating [on paper] the molecules" and experimentally thinking about their interactions. What I did in this course was to be creative with chemistry ideas, such as thinking about the following example: Liquid soaps include water and many organic substances which creates a nutrient media for bacteria. Therefore, commercial liquid soaps already have to include anti-bacterial agents to prevent bacterial growth. So, the difference between regular liquid soaps and the soaps that are labelled "anti-bacterial" is the addition of extra anti-bacterial substances. Is it necessary to purchase them? What are the consequences for health? Overall, my gains from these courses connected with my chemical knowledge like puzzle pieces and created a "way of thinking." I have been, as a consumer, problematising the foodstuffs I buy, as well as the ingredients of the products of everyday use (such as medicines, toothpaste, cosmetics, and clothing). It was not something that I forced myself into; it was my new way of thinking about the world, after taking the mentioned courses. Almost 10 years later, as an academic and doctoral student, I realised the courses indeed had put "something" on the table (van Poeck and Östman, 2020) that helped me realise that chemistry is not only about how we act on the material world, but also what the material world does to us, living and non-living. What my professors put on the table, be it with facts, dilemmas, or a documentary, got me (re)thinking, as I was learning about photochemical smog or phthalates in plastics, what chemistry means, for example, in our bodies, in our environment, in the bodies of other beings.

Such chemistry education has a potential to address powerful chemical knowledge in relation to wicked problems, such as ozone hole, ozone depletion, hazardous waste (plastics, toxic heavy metals, toxic organic waste, etc.), and hormonal pollution. Both courses I mentioned above addressed critical views on chemistry's distinctiveness and methodological character, by including green chemistry, regulations, and organisations to control chemical hazards and pollution, and how for example chemical industry works in the particular context. This also is related to critical views on chemistry in society. A transdisciplinary perspective was integrated in especially the Environmental Chemistry course, by mentioning major industrial chemical accidents that also includes the thalidomide scandal with a historical and futures perspective, which also is related to eco-reflexivity through environmental and sustainability education. I, back then, was feeling both amazed and frustrated because these courses helped me to make sense of the chemistry knowledge I had learned, but at the same time enabled me to problematise my own chemistry education and why we did not have the chance to problematise and contextualise chemistry in the mainstream courses. This – almost – existential questioning gave me insight into what chemistry is about for me and what it means in relation to health and environment. This, in turn, helped me develop my agency at several levels, such as my everyday choices and my consuming habits. Also as a consequence, I changed my interest of research from conceptual understanding to problematising the vision of chemistry with the help of an article by Sjöström and Talanquer (2014). As a result, my ChemoKnowings shape what kind of consumer, citizen, teacher, and researcher I am and allow me to keep an inner discussion alive: How do we relate to the world; what is our place in the world; and our responsibility?

TEACHING CONTRIBUTING TO STUDENTS' ChemoKnowings

We start this section by listing some of the major aspects of ChemoKnowings highlighted in the personal reflections in the previous section, although the list is not at all absolute in the sense that it is including all possible ChemoKnowings. The list gives some major examples of ChemoKnowings, but other ChemoKnowings and variants of ours are of course also possible.

Crucially, we are chemistry teachers (in addition to being researchers), and as such we are mindful of the fact that we view our own ChemoKnowings as being knowings that can have important value for our chemistry students. However, we are equally mindful that in our own chemistry didaktik praxis we need to consider the volition of our students in transforming the content we bring into the classroom (put on the table) for ChemoKnowings. That is, what ChemoKnowings are for us as teachers might not necessarily become ChemoKnowings for our students in their transformation of content, and if it does their ChemoKnowings probably differ from the teacher's ChemoKnowings, at least to some extent. It is important that the teacher is aware of this fact. Keeping this in mind, we want now to list some of the major aspects of ChemoKnowings highlighted in our personal reflections, and thereafter present some ideas and models that we believe can also be of value to teachers in their didaktik work in selecting content important for ChemoKnowings, and thus what they view as important for the student to learn for *Bildung*, and how to work with it in practice.

- ChemoKnowings often include *embodied chemical knowledge* (the body, including the heart), *intellectual chemical knowledge* (the head), and *practical chemical knowledge* (the hand).
- *Benefit-risk-perspectives and corresponding moral aspects* in relation to usefulness and risks of "the chemical life" (Hodges, 2015), especially related to environmental and health issues – awareness of "chemical oppression" (Belova et al., 2017), cocktail effect in the body by mixing of many synthetic chemicals, artificial sweeteners and other food additives, phthalates in plastics, etc.
- *Traditional culture of chemistry* – previously a "macho culture" at chemical research departments. Embodied chemical knowledge and risks – irritated eyes, precautionary principles, chemicals in human blood, etc.
- *Chemical agency framed by ethico-socio-political action* – alarming, protesting, highlighting, avoiding, etc.
- *Meaningful connection with the molecular world* and the possibility of "analysing, synthesising, and transforming matter for practical purposes" (Sevian and Talanquer, 2014, p. 11). "Molecular dancing" in teaching – e.g., the electrons in a benzene ring.
- *Eco-reflexivity through* understanding the role of chemistry in environmental systems thinking.

A chemistry teaching aiming at contributing to students' development of ChemoKnowings (with an ethical–political compass) needs to be varied. Generally, one can say that different types of *(post)humanisation* are needed in the choice of questions/content (Sjöström and Talanquer, 2014) – or what is put on the table – as well as in the choice of teaching methods (in a broad sense). In addition to intellectual reasoning, there is also a need for the experience of the fascinating molecular world (e.g., through playing and virtual reality simulations) as well as different types of chemical praxis (in a broad sense), as a way of understanding and developing embodied and practical chemical knowledge. Another related idea is to meet different kinds of chemists (in academia, industry, etc.), preferably in their own working environments, as a way to get a more multifaceted idea of the culture and nature of chemistry. However, such meetings need to be followed up by critical discourse analysis.

Also important is to better understand the role of chemistry in society, especially in relation to environmental systems and the planetary boundaries. Here well-selected current and historical cases can be put on the table and elaborated on from complex systems thinking perspectives (e.g., Mahaffy et al., 2019a,b; Talanquer et al., 2020), as a way for the students to develop benefit-risk-reasoning (including moral aspects) as well as eco-reflexivity.

The interdisciplinary area of Environmental Citizenship in the 21st Century Education (Hadjichambis et al., 2020) has ideas and models that can be used and transformed into chemistry teaching. Some examples are ideas regarding youth activism (Reis, 2020) and different approaches and teaching models in "the pedagogical landscape of Education for Environmental Citizenship" (Hadjichambis et al., 2020). One of these is socio-scientific inquiry-based learning (SSIBL) (Levinson and PARRISE Consortium, 2017; Ariza et al., 2021). Generally, it is important to work with what can be called controversial socio-chemical issues (type of socio-scientific issues, SSI) (for references about SSI in a broad sense see, e.g., Sadler, 2009; Hand and Levinson, 2012; Bencze et al., 2020) in chemistry teaching. This is a way of contributing to students' development of ChemoKnowings. This is connected to the development of reflective judgment (Zeidler et al., 2009) and a risk understanding (e.g., Christensen, 2009; Schenk et al., 2019) based on critical realism as an ethico-onto-epistemology (e.g., Zembylas, 2006; Levinson, 2018). It can also be connected to a critical and *Bildung*-oriented vision (Vision III) of scientific/chemical literacy (e.g., Sjöström and Eilks, 2018), emphasising "engagement with social participation and emancipation" (Valladares, 2021, p. 557). In relation to chemistry, it is about being aware of the already mentioned "chemical life" surrounding us (Hodges, 2015) as well as about chemical risks, society, and discourses (Sjöström and Stenborg, 2014) as a basis for *Bildung*-oriented action competence (e.g., Sass et al., 2020), i.e., chemical agency. Some examples of socio-chemical issues in relation to teaching are nanotechnology (Jones et al., 2013), use of different types of pesticides (Zowada et al., 2020), phosphate use and recovery (Zowada et al., 2019a,b), hydraulic fracturing ("fracking") (Dunlop et al., 2021), and fuels choice (Banks et al., 2015). Cullipher et al. (2015) have discussed different levels of sophistication of reasoning about the benefits, costs, and risks of chemical substances. This would have been interesting to relate to individual ChemoKnowings, which is, however, beyond the scope of this article.

In their *Bildung*-oriented didaktik model for sociocritical and problem-oriented chemistry teaching, Marks and Eilks (2009) emphasised a mixture of teaching methods/approaches, such as authentic media, learner-centered instruction, and controversial issues debating, and chemistry lab work. Their suggested chemistry teaching is clearly *(post)humanised* but at the same time close to chemistry content and practice. Dudas et al. (2022) have developed and mangled another didaktik model with the purpose of supporting chemistry teachers when designing activities aiming to support students' exploratory considerations of complex issues. They recommend "real-life issues to invite the unpredictability needed for experiencing complexity and the exploratory nature of chemistry" (p. 1 a.o.p.). Such issues enable students to increase their understanding of the nature of chemistry by experiencing aspects of tentativeness in chemistry.

FINALISING WITH FOUR POWERFUL KNOWINGS-ORIENTED DIDAKTIK QUESTION AREAS

In this article, we have sought to develop ChemoKnowings as a subject-specific form of powerful knowledge for (becoming) world citizens. Chemistry education (in a broad sense) has a central role in catalysing the individual learning processes which include knowledge transformation for *Bildung*. In this context, we have come to view ChemoKnowings as including embodied and relational dimensions as tacit dimensions (Carlgren, 2020). Crucially, we have come to view the teacher's consideration of students' volition in transforming content for ChemoKnowings as an important dimension of chemistry didaktik, something which is achieved in part through the teacher's own knowledge transformations. More generally, we would claim that teachers' consideration of student transformation of content for powerful subject-knowings is an important part of 21st century general subject didaktik (Vollmer, 2021).

In order to begin understanding what ChemoKnowings might be for the student in the Anthropocene, we have suggested and argued that critical chemical literacy, eco-reflexive chemical thinking, and ChemoCapabilities are related constructs. We have thus also begun to consider several potentially important dimensions, for example, "the role of chemistry in everyday life," "meta-cognitive dimensions," "affective dimensions," "concentration and transportation aspects in relation to environmental issues," "technological aspects related to chemistry" and "humanistic perspectives toward multifaceted problematisation." In addition to considering these relations, we further developed our ChemoKnowings construct by linking student transformation of content for ChemoKnowings to selected elements of a theoretical didaktik model proposed by Herranen et al. (2021) describing ChemoKnowings as consisting of: "critical views on chemistry's distinctiveness and methodological character," "powerful chemical knowledge," "critical views on chemistry in society," and "eco-reflexivity through environmental and sustainability education."

In our view, however, neither relating of ChemoKnowings to the other three constructs nor linking student transformation of content for ChemoKnowings to elements of Herranen et al.'s (2021) theoretical didaktik model, has enabled us to sufficiently articulate the constructs' embodied and relational dimensions. Drawing from Rucker (2020), as well as the classical writings of Klafki (2000b) and von Humboldt (2000), we have here suggested that ChemoKnowings are such knowings that matter meaningfully to the student and connect the student to themselves and to the world, and as a consequence confer ethical compass and promote an ethics-oriented agency. We have also suggested that when a vision for chemistry teaching (all educational levels) as a part of a world-centered vision for schooling in the Anthropocene is made salient in the classroom, such agency will become a chemical agency, that is, eco-reflexive and embodied ethico-socio-political action competence. Further, and in view of these ideas, we have suggested that each of the four selected ChemoKnowings elements of Herranen et al.'s (2021) model potentially give rise to world citizens' chemical agency. This is something which we believe should be cultivated by the teacher by bringing content into the classroom (put on the table) that has the potential to become ChemoKnowings through student transformation (make content free).

By including the above mentioned aspects, we have opened to accounting for the embodied and relational dimensions of the ChemoKnowings construct. A crucial consequence of this, we believe, is that these aspects have shifted the construct to embody ideas of personalness and plurality. Indeed, this is something powerfully brought out through our personal reflections with examples of what ChemoKnowings are for each of us. Clear in each account are chemistry-related knowings that matter meaningfully to us, and which have mobilised in each of us an embodied ethico-socio-political action. Significantly, in all the accounts, the idea of content brought into the classroom being "put on the table" and "made free" has been seen as crucially important.

We believe that the ChemoKnowing construct we have elaborated on in this article, embodying ideas of personalness and plurality, opens toward a more extensive empirical exploration of what ChemoKnowings might be for students (and teachers) in the Anthropocene. Based on such an exploration, it would be possible to construct an empirically based didaktik model (e.g., Sjöström et al., 2020; Wickman et al., 2020) on ChemoKnowings. It can guide the teacher when designing teaching that can promote ChemoKnowings and chemical agency. However, such a model is never fully ready-made in the meaning that it has to be tested in different settings, mangled, specified, and revised in an iterating process.

In this mainly theoretical article, we have, for instance, presented a visionary didaktik model (**Figure 4**), aiming to broadly orient teachers toward the idea of promoting ChemoKnowings and chemical agency in their teaching and broadening their chemistry didaktik praxis by taking into consideration student's transformation of the content the teacher brings into the classroom. We wish to conclude the article by presenting also another complementary "didaktik model" that more specifically can promote teachers' own critical reflection on, as well as preparation and transformation of, content for the classroom with a view to promoting students' ChemoKnowings. Crucial we believe in this regard, is the idea that for the teacher to come into a position of being able to consider the volition of students in transforming content for ChemoKnowings, they must first connect to their own personal transformations of content for ChemoKnowings. That is, they must consider their own experiences as learners. Inspired by Klafki's didaktik analysis questions (section "Powerful Knowledge and Knowings"), and drawing from the visionary model in **Figure 4**, as well as insights gained when writing about what ChemoKnowings are for us personally, we propose the following four areas of questions for subject teachers to consider (when concerning another subject area than chemistry, one should of course exchange "chemistry" or "chemical" with the other subject area and ChemoKnowings with another [subject]Knowings):

Discovering One's Own View of ChemoKnowings

Can you think of specific knowledge (or knowing) that has enabled you to come into a relationship with chemistry and therefore has mobilised for ethico-socio-political action? (For example, protecting and/or nurturing your own health, or the health of others, including other species, a particular ecological environment, or a non-living thing.) Can you imagine what ChemoKnowings could be for you also in a broader sense?

Getting Awareness of One's Own Worldview and Educational Vision

What is your own worldview and how does it affect your view on *Bildung* and education in the Anthropocene era? How might your reflections in relation to this question as well as the ChemoKnowings that are salient for you (e.g., your own ChemoKnowings) guide you in conceiving a vision for chemistry teaching as a part of a world-centered vision for schooling in the Anthropocene?

Discovering the Content

What is your view on content for teaching – powerful knowledge in and about chemistry – that is potentially relevant to your students and potentially contributes to their ChemoKnowings, eco-reflexive *Bildung*, and chemical agency?

Putting the Content on the Table and Make It Free

In what ways can you put this content on the table so that you engender open-ended inquiries which facilitate critical and plural points of view on the issues at hand? Try to think in terms of complex challenges and creative practical–theoretical–aesthetical representations.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

MY, PC, and JS have together developed the conceptualisation and the models and have written the manuscript. All authors have read and approved the submitted manuscript.

FUNDING

Open Access funding was provided by Malmö University. The research was funded by Malmö University (MY and JS) and the Swedish National School in Science and Technology Education Research (FontD) (Swedish Research Council Grant No. 2019-03852) (PC).

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
published: 22 June 2022
doi: 10.3389/feduc.2022.910128

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Policymakers' Views of Future-Oriented Skills in Science Education

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The rapid changes in science and society during the last decade have demonstrated the need for readiness to address the uncertain future through the development of future-oriented skills. Despite previous attempts, there is still no consensus regarding what is meant by "future-oriented skills" and how these could be integrated into science curricula. Stakeholders' views about what future-oriented skills are and how they should be taught would provide a clearer understanding of their needs and their perceived characteristics of effective new teaching approaches. Thus, given the pivotal role that policymakers play in education policies, this study investigated the views of 35 policymakers based in the United Kingdom, Italy, Finland, and Lithuania. Participants completed an online survey that elicited their views on future-oriented skills, as well as ways of integrating them into national science curricula. The data analysis included descriptive statistics and qualitative analysis based on the principles of thematic analysis. The qualitative analysis followed a combination of inductive and deductive coding approaches. The findings of this study highlight that among other skills, participants stressed the need for introducing problem-solving and critical thinking in science classrooms in order to better address the uncertainty of future challenges, such as environmental issues. Therefore, policymakers seem to agree that there is a need for moving away from traditional teacher-centred approaches when teaching future-oriented skills. These results provide valuable insights into policymakers' needs and expectations. In doing so, this study can serve as a starting point for a systematic approach toward integrating future-oriented skills into science curricula.

Keywords: future challenges, futures education, future-oriented skills, science curriculum, policymakers' views

OPEN ACCESS

Edited by:
Muhammet Usak,
Kazan Federal University, Russia

Reviewed by:
Nicolas Herve,
Université de Toulouse, France
Vincentas Lamanauskas,
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Specialty section:
This article was submitted to STEM Education, a section of the journal Frontiers in Education

Received: *31 March 2022*
Accepted: *16 May 2022*
Published: *22 June 2022*

Citation:
Ioannidou O and Erduran S (2022) Policymakers' Views of Future-Oriented Skills in Science Education. Front. Educ. 7:910128. doi: 10.3389/feduc.2022.910128

INTRODUCTION

Future-oriented skills are part of what are often called the "twenty-first century skills." Politicians, employers, and educators alike have advocated students' acquisition of twenty-first century skills in order to deal with some pressing issues (Wagner, 2015) such as climate change and environmental pollution. The ability to foresee future scenarios, anticipate potential problems and critically engage with problem-solving strategies are skills that students need to develop in order to function effectively in their everyday lives. Given its conceptual, as well as methodological qualities, future-oriented skills in education can be regarded as part of educational innovation.

Although there may be numerous issues related to the implementation of educational innovation, such as future-oriented thinking, the conceptualisation and generation of educational policies are prerequisite for educational systems in setting new and innovative objectives for educational practice. Policymakers play a central role in how new approaches to curriculum, instruction and assessment are framed in a particular national context (Sebba, 2007). Debates in educational policymaking have been framed from the point of view of interactions between research, policy and practice (Locke, 2009), and how research evidence can inform policymaking (Vanderlinde and van Braak, 2010; Cherney et al., 2012). The significance of mediation for bridging and linking between educational research and policy has been highlighted (Saunders, 2007). Yet, despite such wealth of research at the nexus of educational policy, research and practice, research about policymakers' own views of educational innovation has been understudied in the context of science education (Fensham, 2009). Future-oriented skills are no exception to this observation where empirical investigations into policymakers' own views about the matter have been rare.

The study explores how a sample of policy makers from Italy, Finland, Lithuania, and the United Kingdom view future-oriented skills in the context of science education to illustrate what is envisaged to be significant skills of the future, as well as possible ways of incorporating these skills into science education curricula. By doing so, the empirical study takes an inclusive and participatory approach to investigating relevant stakeholders' views of contemporary reforms in education.

Educational Innovation and Future-Oriented Skills

Recent trends in science education have included an emphasis on "twenty-first century skills." Politicians, employers and educators alike have advocated students' acquisition of twenty-first century skills in order to deal with some pressing issues (Wagner, 2015) such as climate change and environmental pollution. Since the assumed future is a rapidly changing world of fierce global competition, education should focus on knowledge-intensive sectors, highlighting that "each citizen will need a wide range of key competences to adapt flexibly to a rapidly changing and highly interconnected world" (p. 13). In the same vein, scholars within the field of Education for Sustainable Development (ESD) have discussed the need for including a problem-driven and solution- oriented approaches to teaching about global "wicked" issues such as climate change, poverty and pandemics (e.g., Wiek et al., 2011).

Although the term "twenty-first century skills" is commonly used in educational contexts as a desirable student outcome, there is no clear definition on what is precisely meant by this concept (Kereluik et al., 2013). OECD has indicated that "developments in society and economy require that educational systems equip young people with new skills and competences, which allow them to benefit from emerging new forms of socialisation and to contribute actively to economic development under a system where the main asset is knowledge" (OECD, 2019, p. 5). In order to prepare students for this future, the OECD had proposed three "dimensions" in twenty-first century skills and competences: (a) information, (b) communication, (c) ethics and social impact (p. 8). All three dimensions encompass numerous skills. The OECD paper explicitly names the following 15 twenty-first century skills and competences: "creativity/innovation, critical thinking, problem solving, decision making, communication, collaboration, information literacy, research and inquiry, media literacy, digital citizenship, ICT operations and concepts, flexibility and adaptability, initiative and self-direction, productivity, leadership and responsibility" (p. 21). Likewise, the European Union (EU) formulated a framework for "Lifelong Learning as a key measure in Europe's response to globalisation and the shift to knowledge-based economies" (European Union, 2006, p. 10).

These conceptualisations contribute to the definition of future-oriented skills, as they refer to skills that are necessary to navigate the imagined futures. However, it can be argued that there is a distinct preceding set of skills that one should demonstrate in order to imagine the possible futures. These are often termed "future-scaffolding skills" and they refer to "the capacity of organising knowledge in the present imagining futures and moving dynamically and consciously, back and forth, globally–locally, between different "space" and "time dimensions" (Tasquier et al., 2019). The ability to think forward through time is considered advantageous and at times even essential for survival (Suddendorf and Corballis, 2007). Given that students are often regarded as future "problem solvers" (Wiek et al., 2011) this ability to foresee future scenarios in order to anticipate potential problems and to critically engage with problem-solving strategies effectively in their everyday lives is of great importance.

Recent accounts of OECD Future of Education and Skills 2030, such as the OECD Learning Compass (OECD, 2018), highlight the interplay between knowledge, values and skills through the lens of anticipation, action and reflection. Although conceptually, these skills are part of a broader definition of twenty-first century skills and future-oriented skills, they emphasise foresight, anticipation, risk assessment, and imagination (Levrini et al., 2019).

Arguments for the inclusion of future-oriented as well as future scaffolding skills in education have been raised given increasing concerns that the schooling systems, are not able to prepare today's learners for the fast-changing world in which they will live and work. For instance, ESD teaching approaches is "envisioning a better future," because it aims to establish a link between long term goals and immediate actions, as well as to motivate people to take action (Rieckmann, 2012). Similarly, teaching and the learning about socio-scientific issues (SSI), such as climate change, promotes the idea of science education for global citizenship (Lee et al., 2012), as it highlights the breath of values, knowledge and perspectives, as well as the various stakeholders that contribute to SSIs at a global level.

Although there may be numerous issues related to the implementation of educational innovation, such as future-oriented thinking, the conceptualisation and generation of educational policies are prerequisite for educational systems in setting new and innovative objectives for educational practice. Policymakers play a central role in how new approaches to curriculum, instruction and assessment are framed in a particular national context (Sebba, 2007). Debates in educational policymaking have been framed from the point of view of interactions between research, policy and practice (Locke, 2009), and how research evidence can inform policymaking (Vanderlinde and van Braak, 2010; Cherney et al., 2012). The significance of mediation for bridging and linking between educational research and policy has been highlighted (Saunders, 2007). Yet, despite such wealth of research at the nexus of educational policy, research and practice, research about policymakers' own views of educational innovation has been understudied in the context of science education (Fensham, 2009). Future-oriented skills are no exception to this observation, as empirical investigations into policymakers' own views about the matter have been rare. The few studies that have addressed the issue of future-oriented skills in education aimed to explore the extent to which these skills are present in policy documents, such as curricula and textbooks (e.g., Matthewman and Morgan, 2014; Pauw and Béneker, 2015).

This study aims to address this gap by exploring policymakers' views about future-oriented skills in the context of four European countries with a range of educational systems. These countries are Italy, Finland, Lithuania, and the United Kingdom and they represent different regional and cultural traditions from the Baltic to the Mediterranean. As such, they have vastly different educational systems and varying traditions in educational reform, although in the case of Italy, Finland and Lithuania there is also some common educational approaches given these countries are part of the European Union.

Research on the Inclusion of Stakeholders in Educational Innovation

Although there is an increasing emphasis on future-oriented skills in terms of their relevance for effective participation of regular citizens in contemporary issues and problems faced by society (e.g., Levrini et al., 2019), the question remains as to how the content of future-oriented skills can be shaped in order to impact teaching and learning. Considering the vast range of stakeholders in educational research, policy and practice, it becomes imperative to investigate how different cohorts that have a stake in education may define as priorities for student learning. In other words, it is important to incorporate the different stakeholders in the conceptualisation and implementation of educational innovation such as the embedding of future-oriented skills in science education. Understanding different stakeholders' views are particularly important because research has shown that there are gaps between different stakeholders' expectations. For instance, there is research that demonstrates gaps between what students might like to pursue in their education and how school science has been taught, as well as gaps between

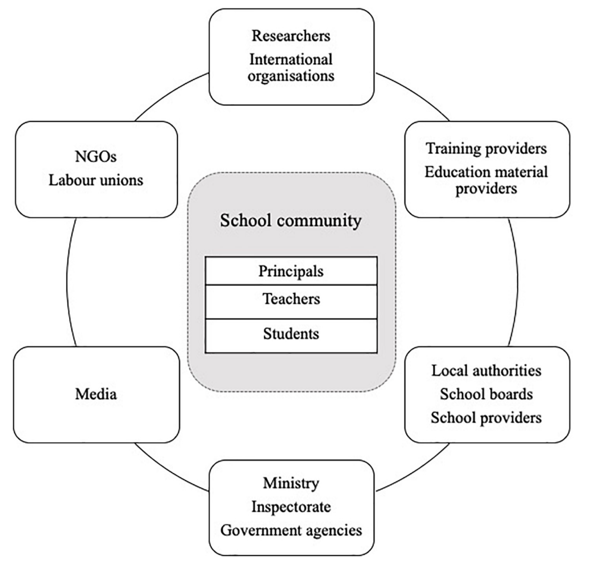

FIGURE 1 | Stakeholders in education. Adapted from Burns and Köster (2016).

employees' opinions and school science education goals (Choi et al., 2011). Likewise, there may be issues related to teachers' role in supporting students to engage in lessons that would enhance their future-oriented skills. Many teachers would not have received any training to teach components of future-oriented skills such as critical thinking and, as a consequence, they may not feel confident about teaching such skills (Post et al., 2011). In the case of school science, apart from students and teachers, there are various other stakeholders such as members of school boards, parents and teacher training providers (see **Figure 1**).

Policymaking in education may follow different routes depending on the various national and socio-cultural contexts. Therefore, the term "policymaker" is significantly dependent on the various traditions and degrees of stakeholders' involvement in the policymaking process. However, despite this heterogeneity, the stakeholder groups that shape nation-wide policymaking can be generally regarded as policymakers. These are policy actors previously who serve as the "architects of policy," including politicians, civil servants and advisers (Bangs et al., 2010). In order to design, generate and implement educational policies, policymakers participate in a multifaceted process that includes multiple cycles of agenda setting, formulation, legitimation, implementation, evaluation and maintenance, succession or termination of education policies (Jann and Wegrich, 2007). **Figure 2** illustrates the policy cycle theory that has been used in numerous frameworks and adapted by many policymakers and implementers (e.g., DeLeon, 1986).

Thus, it can be argued that the design and implementation of innovations, such as future-oriented science education need to be explored from the view of such stakeholders. According to a report by OECD, there have been at least 450 education reforms between 2008 and 2014 in OECD countries (OECD, 2015). Yet,

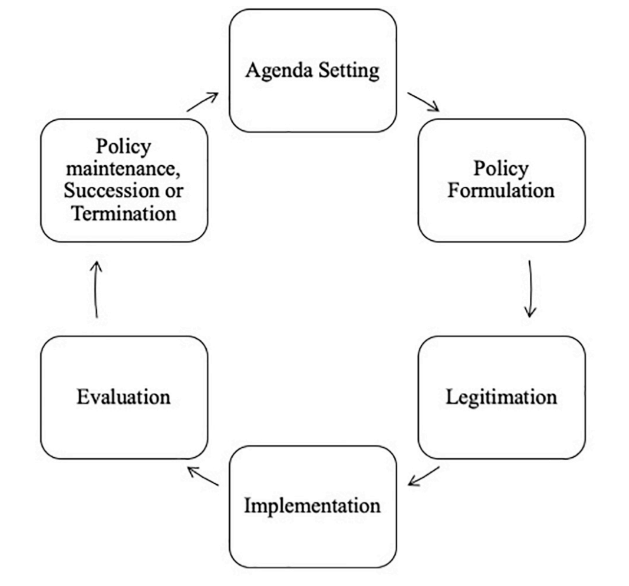

FIGURE 2 | Theories of the policy cycle. Adapted from Jann and Wegrich (2007).

evidence for the effectiveness of these policies is fairly scarce. Researchers have highlighted that even when reforms do have an impact, stakeholders can be dissatisfied with the outcomes of the implementation of the policy, and they tend to hold policy makers accountable for them. Some recent European Union-funded projects have nevertheless tapped into providing some evidence on how various stakeholders might perceive what innovation can look like in science education. For example, the PROFILES project (Bolte et al., 2012) involved stakeholders from science and the science education community in a Delphi study to explore what content needs to be identified for science curricula. Other studies such as Gören Niron (2013) researched views of policy makers, academics, and practitioners about governance of early years education in Turkey. As a result, a framework was developed aligning with policies of international organisations and existing systems of the European Union countries, by taking into consideration current policy frameworks. The research illustrated the divergences in different stakeholders' views on endorsement of educational models in general and possible implementation in the Turkish context in particular.

The cultural context of policy making may also influence how educational policies are interpreted, particularly when they involve themes that may deem to be sensitive in particular social traditions. For example, in a research study conducted with policy makers, health-care providers, teachers, and religious scholars in Saudi Arabia (Horanieh et al., 2020), stakeholders differentiated between who should be in charge of designing the programmes and who should deliver them. For instance, researchers observed tension on the role of religious scholars within these two phases of implementation, as some of their beliefs were not aligned with the teaching content. Furthermore, particular topics of innovation may demand that researchers generate specific methodological approaches. In investigating various stakeholders' views in environmental education, Eisenhauer and Nicholson (2005) recognised that different stakeholder groups have different understandings of wetlands and associate diverse meanings with these landscapes, and that these types of differences are factors in many attempts to design communications about controversial environmental issues. The researchers used focus group and social research survey methods to gather information about the diverse perspectives held by stakeholder groups.

Taking into account (a) the relevance of future-oriented learning as contributing to twenty-first century skills and the need to include such skills in science education curricula, as well as (b) the central role that policymakers play in shaping national curricula and teaching practices, this study focused on policymakers as major stakeholders in education. In this study, the term "policymakers" refers to those stakeholders who engage in the design of curricula, assessments, and teacher training frameworks for implementation at a national level. Nevertheless, other stakeholders, such as educational researchers, teachers, and examiners would equally be important to investigate in further studies. The study, thus, aimed to provide some insights into policymakers' views and set the ground for further investigations following a systematic participatory approach to educational innovation.

Context of Science Curriculum Policy

This study explores policymakers' views about future-oriented skills in Italy, Finland, Lithuania, and the United Kingdom. These countries were included to demonstrate the relevant heterogeneity within European countries with regard to their educational system, as well as the degree of stakeholder engagement in educational policy.

Out of the four countries, Italy has the most centralised educational system, as the Ministry of Education, University and Research (Ministero dell'Istruzione, dell' Università e della Ricerca, MIUR), is responsible for setting the minimum standards and education principles. However, some decisions can be made at a regional level and schools demonstrate relative autonomy with regard to curriculum and assessment (Figueroa et al., 2017). As a result, school reforms are proposed, managed, and regulated centrally. Parliamentary initiatives for educational reforms often arise from downstream consultation with political parties or parliamentary groups. Formal consultations for parliamentary proposals take place as a result of conversations with spontaneously formed expert groups, that may consist of academics, teacher associations, student associations, and private institutions.

Educational policies in the United Kingdom are designed and implemented at a nation level. Unlike Scotland, Wales and Northern Ireland, England does not have its own devolved government (National Education Systems, 2022). Thus, education in England is overseen by the Department for Education. Although there are various types of schools in England (e.g., state-funded and independent schools), all are subject to assessment and inspection by Ofsted (the Office for Standards in Education, Children's Services, and Skills). The state-funded education system is divided into Key Stages based upon age groups (Government Digital Service, 2014). The National Curriculum provides pupils with an introduction to the essential knowledge they require to be educated citizens. It covers what subjects are taught and the standards children should reach in each subject. There are several examination boards (also known as awarding bodies) set award qualifications in state schools and colleges across England. Exam boards follow strict guidelines from Ofqual (Office of Qualifications and Examinations Regulation) to regulate standards and ensure parity. However, the content and format of examination varies from board to board (Cullinane et al., 2019). In summary, although the curriculum is national and centralised, there can be variations in how policies get interpreted and implemented at the level of schooling given the specifications of particular examination boards.

Lithuania's education system is more decentralised than centralised. National institutions, municipalities and educational institutions all share responsibility for the quality of the education provided. The parliament (Seimas) forms education policy at the national level. It adopts laws and declarations and initiates educational reforms and policy changes. The government and the Ministry of Education, Science, and Sport (and other related ministries) also formulate and implement education policy and adopt and implement legal acts other than laws and declarations. The parliament adopts the main laws and legal acts regulating the system of education and science, which are applicable at a national level. The Ministry of Education, Science, and Sport or the government adopts other legal acts applicable at the national level such as the description of the primary, lower secondary, and upper secondary curriculum. The municipalities set and implement their own strategic education plans that are in accordance with the national documents.

Finally, Finland has a decentralised education system, as local authorities have considerable autonomy. However, this autonomy is situated in a complex context: the strategic government programme sets key goals, the parliament is responsible for related legislation, the Ministry of Education and Culture oversees policy implementation, while the Finnish National Agency for Education is responsible for developing curricula and related requirements as well as expenditures and supporting teachers. Furthermore, the Finnish Education Evaluation Centre acts as an external evaluator of educational institutions, while the Regional State Administrative Agencies evaluate issues related to regional equality. The OECD Policy Outlook (OECD, 2021) lists key stakeholders: The Association of Finnish Local and Regional Authorities, the Confederation of Finnish Industries, the Confederation of Unions for Professional and Managerial Staff, student and parent associations, and organisations representing educational professionals. National core curriculum reforms take place approximately once per decade. This process takes place at three levels: state, municipal, and school, as the national core curriculum is adapted to use. However, this takes place over a cyclical process during which stakeholders and institutions collaborate closely; curricula are drafted, commented on and improved over many iterations. Furthermore, after the core curriculum is finalised, municipalities develop a detailed local curriculum that corresponds to the extensive goals and criteria set by the core curriculum. In this process, schools are often given considerable autonomy.

While similar rhetoric about the significance of educational reforms may be present, particularly in relation to twenty-first century skills, the precise ways in which such policies would be conceptualised and implemented in each country are expected to differ given the structural changes in the education systems. For example, in a country such as Finland where the education system is decentralised and teachers have much say in the development of policies, one would expect that teachers' views about future-oriented skills will be represented to a greater extent than in a system such as Italy which has a fairly centralised system where ministry level professionals drive educational reforms. However, such details are a matter of empirical questions and as such, they provided the motivation for the study reported in the rest of the paper.

Research Questions

The empirical study was guided by the following three research questions:

1. What future challenges do policymakers in Italy, Finland, Lithuania, and the United Kingdom anticipate and how can future-oriented skills in science education address them?
2. What factors do policymakers perceive as barriers for curriculum change to integrate future-oriented skills in science education?
3. What are policymakers' views for including future-oriented skills in science curricula?

MATERIALS AND METHODS

Context of Research

The research was conducted in the context of a funded 3-year project that included partners from Italy, Finland, Lithuania and the United Kingdom. The primary objective of the project was to enhance future-oriented thinking in science education through engagement with a range of stakeholders such as policymakers, teachers and students.

Sample

Since the target population of this study was policymakers in science education, judgemental sampling was used to generate lists of potential participants, based on their professional experience and their role within education policymaking in their country. To obtain relative heterogeneity between experts (Bolger and Wright, 2011), it was decided to include participants with experience and demonstrable impact on: (a) science education assessment, (b) curriculum, (c) teacher training, or (d) general education (e.g., Ministry of Education). This would allow comparisons between the participating countries, as well as areas of expertise. A questionnaire was distributed via individual email invitations to experts from each national context.

The sample consisted of 35 education policymakers based in Italy, Finland, Lithuania, and the United Kingdom. **Figure 3**

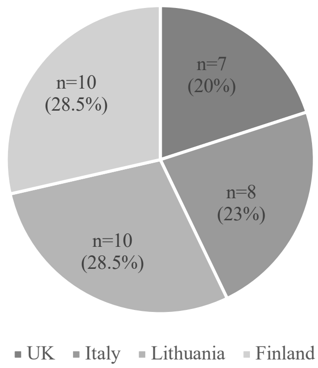

FIGURE 3 | Sample distribution per country (*N* = 35).

shows the sample distribution per country. Out of 35 participants, 21 were female and 13 were male; their age was $M = 51.82$ years ($SD = 7.7$). The majority of the participants held a Ph.D. (60%) or a Master's (29%) diploma and their academic background included STEM (63%), Social Sciences (29%) and Arts and Humanities (17%). Almost all the participants (94%) had teaching experience [$M = 18.7$ years ($SD = 10.3$)] in secondary (63%) and/or higher (57%) education. Their roles covered a range of areas in education policy from teacher education (e.g., university professors) to centralised education policy (e.g., adviser to president), while the average length of service in their current position was $M = 9.56$ years ($SD = 8.8$).

Selected Sub-Group

In order to increase the homogeneity of the sample, a matching method was performed based on participants areas of expertise; four representatives from each country (overall $n = 16$) were selected based on their expertise in: (a) science education assessment, (b) curriculum, (c) teacher training, or (d) general education. This selection would allow comparisons between experts from the same areas of expertise. It would also enable us to detect trends and patterns in policymakers needs and views that could be later compared and contrasted against the views of the rest of the sample.

Instrument

A questionnaire was designed to capture experts' views of future-oriented skills in science education from a range of policy levels (e.g., curriculum developers, assessment boards, teacher trainers). The questionnaire was conceptually developed based on previously published studies and reports. However, since the questionnaire was adapted for the needs of this study, its content validity was examined by a panel of 10 experts in future-oriented skills. The questionnaire was revised based on the panel's feedback until consensus was reached.

With regard to the designed questions, Part 1 of the questionnaire included questions regarding the participants' demographic information. In addition to demographic questions commonly used in educational research (e.g., age), this section included questions that are relevant to policymakers' academic and professional background. As part of their professional background, a set of questions regarding their teaching experience was included, as this could be a potential contributing factor to the shaping of their views regarding future-oriented competencies in science education.

Questions included in Part 2 address policymakers' views. Questions 12–16 (**Appendix**) aimed to elicit policymakers' definitions on future challenges and key future-oriented and future-scaffolding skills, as well as their views on how these can be integrated into science education. These questions were produced based on open-ended questions developed by Rieckmann (2012). Question 18 includes a set of recommendations previously published by the European Commission regarding science education for responsible citizenship (European Commission, 2015). This question aimed to explore policymakers' views on how relevant and plausible they find the stated recommendations. The questions included in Part 3 referred to policymakers' recommendations. The items that are included in this part are adapted items by Jones and Walsh (2008) and aim to identify common obstacles, as well as recommendations for the uptake of research evidence from science education and policymaking.

Data Collection and Analysis

The questionnaire included both closed and open-ended questions. With regard to the closed-ended questions, descriptive statistics were performed in order to examine participants' demographic information, as well as their agreement with the presented statements (e.g., Likert scale items). The open-ended questions of the questionnaire were analysed through a qualitative analysis based on the principles of thematic analysis. The qualitative analysis followed a combination of inductive and deductive coding approaches. In the first coding phase, deductive coding was performed based on the themes-topics derived by the questionnaire questions. During this phase, the participants' answers were clustered according to the topics presented in the question items (e.g., future challenges). In the second coding phase, open coding was performed to identify the initial codes based on the participants' answers. In the third coding phase, the open codes were clustered into larger categories and all the codes and sub-codes were organised hierarchically to reflect the initial themes-topics. Some of the qualitative data were quantified in order to illustrate emerging trends in participants views.

In order to explore potential trends in policymakers' views and recommendations by country, a more fine-grained analysis was conducted on experts in a selected sub-sample ($n = 16$). The aim of this analysis was to discuss any country-specific obstacles, challenges and needs. For this reason, we examined the extent to which policymakers from the same national context would refer to the same themes and codes that were presented in the previous section. In doing so, we included only the codes that appeared in more than two documents within the same group. Thus, only the themes and codes in which policymakers from the same national context showed agreement will be presented. The aim of this analysis was to reveal potential country-specific needs and nuances that may be influenced by the educational context of the four countries included in the study.

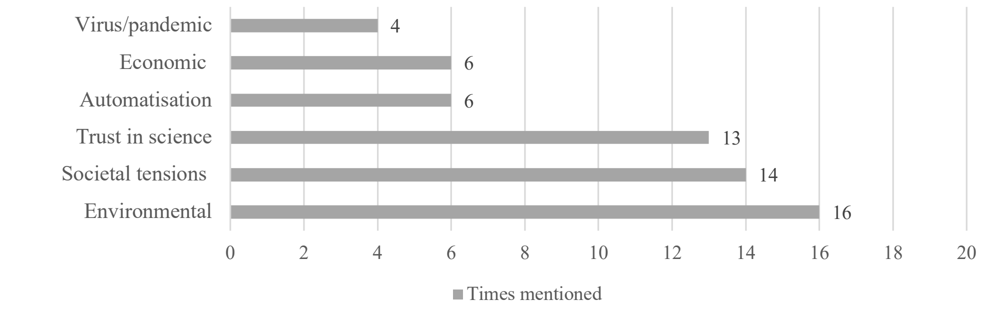

FIGURE 4 | Future challenges.

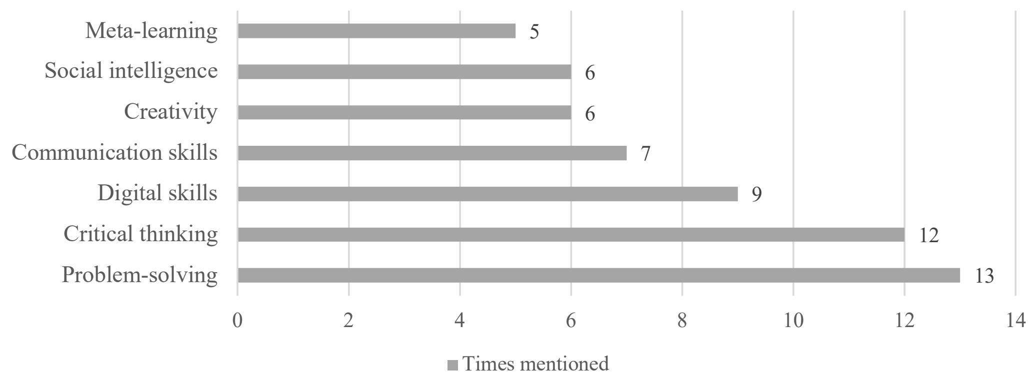

FIGURE 5 | Key competencies for addressing future challenges.

RESULTS

Future Challenges

As can be seen in **Figure 4**, environmental issues, such as climate change and sustainability were the most frequently mentioned challenges. Societal issues, such migration and civil rights were mentioned by almost half of the participants. In addition, a number of participants identified the lack of trust in science and scientific thinking as potential future challenges.

Key Future Competencies

In the following question, policymakers were asked to identify some key competencies that would be necessary in order to face future challenges in science and society. As presented in **Figure 5**, the majority of the policymakers referred to problem solving competencies, as well as critical thinking and digital skills. In addition to the competencies presented in **Figure 5**, some policymakers referred to national or international frameworks describing core student competencies for science education. For example, one policymaker referred to "PISA 2025 Strategic Direction and Vision for Science framework" and "OECD's Learning Compass 3030."

With regard to students' personal future, policymakers expressed the need for a "growth mindset" or "lifelong learning" (9/33), as "students should feel empowered to improve themselves." This was linked to the concept of personal agency that was present (e.g., "they can and need to actively shape their future"). Some policymakers also mentioned students' professional future as "*[students should think] what skills will they need to thrive in their careers and personal lives.*" With regard to the global future, 17/33 policymakers mentioned that students should feel a sense of agency, for example "They should feel to be active agent for projecting and taking care of global future." In addition, some policymakers (7/33) referred to the environmental issues (e.g., "Sustainability and Climate change") as issues that students may have to address utilising future-oriented skills. When asked about the role of technology in students' future lives, most of the participants held neutral views (15/33) (e.g., "we can't even imagine what technology may bring . . . we need to have an open mind"), while some of them (6/33) stressed the positive impact of technology on individuals' daily lives (e.g., "it is used for solving future problems or challenges").

Proposed Curriculum Approaches

With regard to the ways in which these competencies could be integrated into science education curricula, most of the participants mentioned the need for more interdisciplinary approaches in teaching science. For example, one policymaker suggested the introduction of "courses with two teachers (history and science, art and science.). We should mix subjects more." Another participant stated that "*Institutions have to permit students to make flexible choices. Students must be able to complete* *their studies with soft skills (problem solving and decision making, creativity and innovation, complexity, etc.) and core competencies (philosophy, statistics, etc.).*" In addition, participants suggested that the integration of multiple stakeholders into the policy decision-making processes would be beneficial (e.g., "close collaboration with universities, schools and other working life is a key for success").

Another suggestion was the integration of more student-centred approaches, such as project-based learning, as according to a policymaker "*A learning process has to be based on an authentic and situated learning task and hands-on work.*" Participants suggested that within this student-centred learning environments, there will be more opportunities to promote creativity and imagination, as well as problem-solving. In order to achieve this goal, it was suggested that there should be a shift from the content-oriented curriculum to teaching and learning approaches that would facilitate collaboration and the discussion of open-ended issues (e.g., socio-scientific issues). The frequencies of the participants' answers as can be seen on **Figure 6**.

Teacher training and professional development was regarded as the most relevant recommendation by the majority of the policymakers, even though less than half of them regarded it as plausible (**Figure 7**). The same trend was observed for the rest of the stated recommendations; although more than half of the participants found all of the recommendations relevant, significantly fewer found them plausible (i.e., easily applied within the curriculum).

Barriers for Curriculum Change

With regard to which obstacles that policymakers identify for curriculum change, participants indicated that teachers' perceptions and skills often influence the adaption of new teaching approaches. For instance, one policymaker stated that "*Traditional teaching still prevails; even new teachers often find themselves in an unfavourable environment for change.*" In addition, participants mentioned that the rigid organisation of the curricula in their national context is a factor that hinders educational reforms ("*I think that there are issues due to the need for a national curriculum and national assessments*"). The frequencies of the themes identified in this category are presented in **Figure 8**.

Regarding potential obstacles for the uptake of research findings by policymaking in education, participants mostly agreed that the low scientific understanding of policymakers, as well as the limited openness by politicians, are potential hindering factors. The frequencies of policymakers' agreement with the presented statements are presented in the figure below (**Figure 9**).

In addition to the statements presented in **Figure 9**, the questionnaire included an open-ended item that prompted additional comments on potential obstacles for the uptake of research findings by policymaking in education. Almost all the participants stated that the traditional decision-making processes do not leave room for new evidence that would lead to policy changes. Participants mentioned among other factors, the lack of political will and incentives, the lack of communication channels, as well as the low participation of multiple stakeholders in the decision-making. Some representative examples of coded segments are presented in **Table 1**.

In addition, participants referred to time restrictions (e.g., "*Politicians do not understand how much time and effort is needed to get quality learning outcomes*"), as well as policymakers' low understanding of research findings (e.g., "*The biggest problem is the lack of literacy of a significant number of politicians*").

Policymakers' Recommendations

In the last part of the questionnaire, participants were prompted to provide some key components of effective policies to enable future-oriented skills. Their answers were clustered into four themes: collaboration between stakeholders, opportunities for teacher training, consistent goals and resources, and addressing fundamental needs. The themes, as well some example segments are presented in **Table 2**.

Country-Specific Views

The fine-grained analysis showed that policymakers from Finland and United Kingdom tended to show the most homogeneity, followed by Lithuania and, lastly, Italy. Despite the various patterns in which policymakers responded to the questionnaire, the qualitative analysis revealed that *teacher training*, *competencies*, as well as their *willingness* to collaborate, are considered obstacles for effective curriculum and policymaking changes. This view was shared among policymakers in all the participating countries, as well as areas of expertise.

United Kingdom

With regard to future challenges, two English policymakers referred to "*fake news,*" "*conspiracy theories and alternative facts*" (ENG3) and students' need to "*think critically about evidence that is presented by e.g., the media*" (ENG4). As key future competencies, English policymakers identified "problem solving" (ENG3; ENG4) and "*critical thinking,*" ["*e.g. being able to think critically about evidence that is presented by e.g., the media, challenges related to the internet and global society*" (ENG4)]. Three out of four English policymakers emphasised the importance of scientific reasoning and understanding of "how science works," while they considered the content-heavy curriculum currently taught in the ENG as an impeding factor for curriculum change. To integrate these competencies into current science curriculum they suggested the introduction of "the big picture" with regard to scientific concepts. One of the English policymakers stated: "*the science curriculum therefore needs to be designed so that pupils build knowledge of important scientific concepts over time and that they learn how these concepts are connected into general scientific principles/ideas*" (ENG2). Moreover, a gradual introduction of open-ended issues, such as socio-scientific issues (e.g., "*COVID,*" "*socio-environmental*" issues) was suggested as a way of integrating future-oriented competencies into science curriculum. With regard to effective policymaking, participants called for evidence-based decision-making (ENG3; ENG4) arguing that the latter "*should be based on sound systemic research findings, not popularity*" (ENG3).

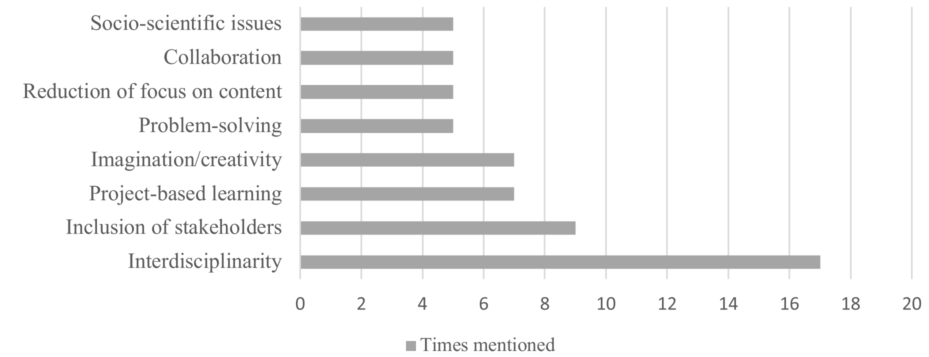

FIGURE 6 | Ways of introducing future-oriented competencies in science curriculum.

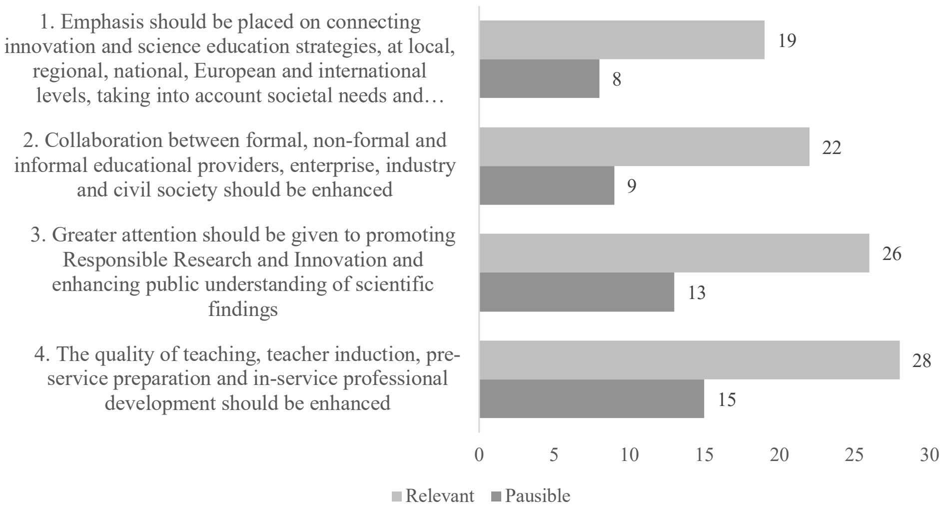

FIGURE 7 | Policymakers' views on European Commission's recommendations. Adapted from European Commission (2015).

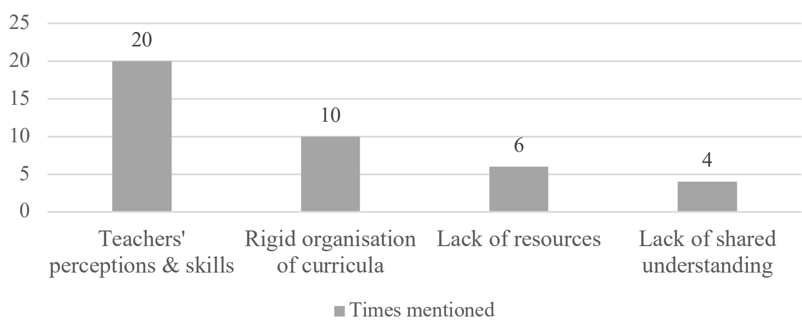

FIGURE 8 | Obstacles for curriculum change.

Finland

Policymakers in Finland indicated that environmental issues [e.g., "*climate change*" (FIN3)] and automatisation ["*digitalisation*" (FIN1)] will be some of the main future challenges. They argued that students will need a "interdisciplinary" attitude to address future challenges [e.g., *learning from history, data mining* (FIN3)], as well as "*creativity*" (FIN1; FIN4). Participants mentioned future-oriented skills, such as the "*readiness for life-long, continuous learning*" (FIN2) and "*the importance of learning to learn competence*" (FIN1). One participant referred to a specific approach with which the Finnish curriculum addressed these challenges: "*In order to support the*

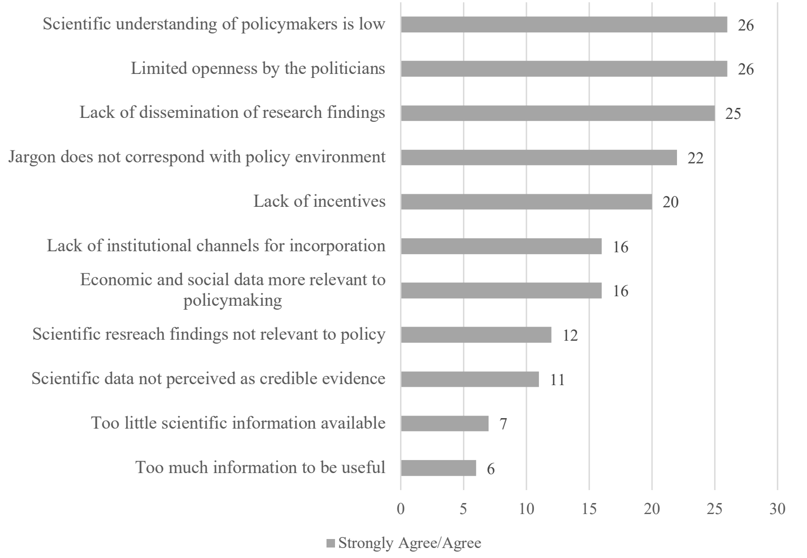

FIGURE 9 | Obstacles to the uptake of research information in the development of policymaking.

TABLE 1 | Example segments with policymakers' views on traditional decision-making processes in education policy.

Example segment	Country
"*Policymakers tend to seek 'scientific arguments' for the decisions already made*"	Lithuania
"*Universities, primary schools, secondary schools and industries need to talk together more than [they do] now.*"	Italy
"*Political will–popularity and party politics being favoured over sound research-based approaches*"	United Kingdom
"*. . .the politicisation of educational policymaking might make it harder and harder for scientific experts to get heard*"	Finland

TABLE 2 | Absolute frequencies of themes and example segments regarding key components of effective policies.

Theme	Frequency	Example segment
Collaboration between stakeholders	12/35	*"Policymakers need to be more open, listening to the words and recommendations of scientists. Unfortunately, some politicians think they are the wisest and just don't hear the expert insights of scientists."*
Opportunities for teacher training	7/35	*"Organise research-oriented pilot projects that support the professional learning of science teachers and at the same time the dissemination of the policy or strategy and pilot project outcomes."*
Consistent goals and resources	7/35	*"Agreed and accepted by all the stakeholders' vision of the system."*
Addressing fundamental needs	5/35	*". . .exploring world developments and communicating tendencies for "here and now." Future is built here and now; thus, science can be better related to nowadays."*

learning of transversal competences in science classrooms, year 2014 framework curriculum emphasises collaborative classroom practices and engagement of students in multidisciplinary, phenomenon- and project-based studies" (FIN1). Regarding the obstacles for effective policymaking, policymakers in Finland noted that researchers are often disinterested in engaging with policymakers (FIN1; FIN2): "*Science education researchers themselves do not take seriously research policy partnership and research practice partnership.*" (FIN1). The lack of dialogue and communication channels between researchers and policymakers was also mentioned when describing the tradition decision-making processes in education policy.

Lithuania

Apart from environmental issues, policymakers in Lithuania considered "*societal tensions*" (LTH1; LTH2) as future challenges. *"Creativity"* was mentioned as a desirable future-oriented competency (LTH2; LTH4), as well as "*digital skills*" (LTH1; LTH3). In order to integrate these skills into the curriculum, participants suggested the adoption of "interdisciplinary" and "transversal skills" (LTH2; LTH3). They also expressed the need for increased consistency between goals and resources in education policy (LTH2), as well as the collaboration between different stakeholders: "*Close science, business, and education system collaboration starting from kindergarten to higher education.*" (LTH1).

Italy

Policymakers based in Italy expressed a range of views and needs. They agreed that there is an increased need for students to trust science: "*Science has to (re)build a relationship of trust with society, according to new media*" (IT2) and "*to overcome the widespread negative attitude toward scientific rationality*"(IT1). Problem-solving was considered one of the key future competencies for science education (IT1; IT2).

Overall, although the policymakers in each country did refer to some specific themes, there was significant consistency across them in how they viewed future-oriented skills and the content of the science curriculum and pedagogical approaches required for teaching innovative skills.

DISCUSSION

As contemporary societies are faced with rapid changes in technology, science, and society, the ability to anticipate future scenarios is increasingly becoming a crucial skill for survival (Suddendorf and Corballis, 2007). Given the importance of these skills, this study aimed to investigate policymakers' views on future-oriented skills in science education and the ways in which they can be introduced through current national curricula. Despite our intention to provide a comparative account of policymakers' views in four European countries, a significant finding of the study is that even though the participants were situated in vastly different national educational policy contexts, they expressed fairly similar views of future-oriented skills and their pedagogical affordances. One possible explanation is that in the context of the empirical study, policymakers focussed on some global outcomes for education rather than nation-specific outcomes. This approach is extensively described by Global Education Policy scholars through the "World Society" theory suggesting that policymakers and governments often receive pressure to demonstrate that they are building a "modern state" according to international standards and the values of the West (Meyer et al., 1997; Verger, 2014).

With regard to possible challenges of the future, policymakers emphasised environmental challenges, such as climate change, while fewer participants referred to future viruses or pandemics. This finding illustrates that despite the overwhelming attention that COVID has received in the past years, policymakers agree that pressing global issues, such as climate change, should be a lasting priority for school curricula (Casas et al., 2021). With regard to the conceptualisation of future-oriented skills, among other skills, policymakers stressed the need for introducing *problem-solving* and *critical thinking* in science classroom, as they believed that these skills would equip students to better address the uncertainty of future challenges (e.g., environmental issues). This finding is in line with current global education policies that have emphasised the importance of such skills, such as the global competency (OECD, 2016) and global citizenship education (UNESCO, 2014). In addition, student competencies for environmental sustainability have been highlighted in the recently published European sustainability competence framework, which encompasses future literacy and adaptability as core competencies for envisioning sustainable futures (Bianchi et al., 2022).

While discussing the importance of these skills, policymakers suggested the inclusion of more interdisciplinary approaches to teaching science (e.g., the combination of school subjects) in combination with project-based and student-centred approaches. In addition, they suggested the introduction of socio-scientific issues (SSI) as a vehicle to introduce global challenges and future-oriented skills. SSI have been introduced in science education as "open-ended" scientific issues with societal impact (Zeidler et al., 2005), as a way of introducing authentic problems from an interdisciplinary perspective (e.g., scientific, social, political). However, in this study, policymakers have demonstrated the opportunity to use such issues to teach about risk and decision-making with regard to the short-term as well as long-term future (Branchetti et al., 2018; Levrini et al., 2019). Therefore, policymakers seem to agree that there is a need for moving away from traditional teacher-centred approaches when teaching future-oriented skills. In addition, they perceived the rigid organisation of knowledge within current curricula as a barrier to the adoption of more innovative approaches to teaching about science and society. For instance, in the case of the United Kingdom, taught curricula are highly influenced by high-stakes assessments, which gives teachers little freedom to follow innovative teaching methods (e.g., Childs and Baird, 2020).

Since educational policies influence how teaching and learning are framed in practice, policymakers recognised the need for engaging a range of stakeholders (e.g., teachers, researchers) in the design and implementation of the science curriculum. There was an almost unanimous expression of the need for inclusion of teachers in decision-making processes, as well as their support throughout the implementation of new future-oriented teaching strategies. This observation shows that policymakers were aware that change in educational practice is often difficult and complex (Guskey, 2002) given that when new policies on curriculum, instruction, and assessment are introduced, teachers play a key role in transforming such policies for implementation in their classrooms (van der Heijden et al., 2018). There is substantial amount of research on how teachers engage with educational policy, ranging from rejection to assimilation of new policies (Cotton, 2006) depending on their educational philosophy, the context of their schools and their professional goals (Ryder et al., 2018). Policymakers in this study emphasised the need for teacher education and training programmes, that would allow teachers to engage in more student-oriented interdisciplinary approaches to teaching future-oriented skills. However, although they identified a need to enhance the quality of teaching though teacher training and professional development, they recognised the difficulties in addressing this issue. Previous literature refers to these difficulties that often include technical, cultural as well as political dimensions of teacher education (e.g., Johnson, 2006).

Although the study provides insights into policymakers' views about future-oriented skills in science education, it is also constrained by a set of limitations. There is an assumption in our study that the policymakers' statements are authentic. In other words, we assumed that their statements correspond to actual conceptualisations and decision-making that policymakers engage in when formulating policies. However, policymakers may not always be willing to disclose the full account of how educational policies may be shaped, nor share their personal opinions when they represent their governmental vision for the policies that are put in place. Furthermore, there may be discrepancies between beliefs and actions where policymakers' beliefs may not necessarily correspond to how they ultimately shape educational policies due to various reasons including political pressures. In addition, this study aimed to elicit policymakers' ideas regarding the possibility of introducing future-oriented skills in national curricula. In that sense, the study captured policymakers' views in the agenda setting phase of the policy cycle (Jann and Wegrich, 2007). Taking into account the multiple steps that the policymaking process includes, future studies can investigate further views of the stakeholders in light of policy design, evaluation and revision.

CONCLUSION AND IMPLICATIONS

The overall findings of this study can serve as baseline information for a systematic approach toward integrating future-oriented skills into science curriculum. Given the role of policymakers in the process of developing and implementing national curricula, the findings of this study illustrate that policymakers support the inclusion of future-oriented skills in science classrooms. Although they provide ways in which they can be integrated into science curricula future studies should examine whether such skills are clearly presented in learning outcomes and textbooks.

With regard to teacher training, this study suggests the inclusion of future-oriented skills in teacher education programmes. By being exposed to global challenges (such as SSI) and ways of teaching about them, teachers will gain the knowledge and strategies for introducing such topics in their classrooms. However, teachers are likely to be reluctant to adopt innovative teaching approaches, unless these are approved by official policies, outlined by curricula and textbooks. Thus, further research can explore the degree to which future-oriented skills are included in current science curricula, as well as existing opportunities for teachers to engage with relevant teaching resources.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

OI contributed to the development of the survey and to the data collection and analysis and wrote the first draft of the manuscript. SE contributed to the conception of the study, wrote parts of the manuscript, and revised and edited the final version. Both authors contributed to the article and approved the submitted version.

FUNDING

This study was conducted as part of project FEDORA – Future-oriented Science Education to enhance Responsibility and engagement in the society of Acceleration and uncertainty (www.fedora-project.eu). This project received funding from the European Union's Horizon 2020 Research and Innovation Program under Grant Agreement no. 872841.

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APPENDIX

Policymakers' Views Questionnaire

TABLE A1 | Open-ended items used in policymakers' views questionnaire.

1. Country
2. Gender
3. Age
4. Highest degree or level of education
5. Professional background
6. Area of expertise
7. Length of service in your current position (in years)
8. Do you have any teaching experience?
9. How many years of teaching experience do you have?
10. Have you taught science subjects (Biology, Physics, Chemistry)?
11. In which educational level have you taught?
12. What are, in your opinion, the central challenges for science and society of the future?
13. What key competencies will be needed for students to address the future challenges in science and society?
14. What competencies do students need for envisioning the future?
15. How can the competencies for addressing and imagining the future can be integrated into science education? For example, what can be included in the science curriculum?
16. What do you think is important for secondary school students to think about in relation to (a) their future (b) the global future (c) the role of technology in sharing their future?
17. What are some obstacles to the uptake of scientific information in the development of policy making?

TABLE A2 | Closed-ended items used in policymakers' views questionnaire (raking).

18. Please rank the following items.
a) The quality of teaching, teacher induction, pre-service preparation and in-service professional development should be enhanced to improve the depth and quality of learning outcomes
b) Collaboration between formal, non-formal and informal educational providers, enterprise, industry and civil society should be enhanced to ensure relevant and meaningful engagement of all societal actors with science and increase uptake of science studies and science-based careers and employability and competitiveness
c) Greater attention should be given to promoting Responsible Research and Innovation and enhancing public understanding of scientific findings and the capabilities to discuss their benefits and consequences
d) Emphasis should be placed on connecting innovation and science education strategies, at local, regional, national, European and international levels, taking into account societal needs and global developments

TABLE A3 | Closed-ended items used in policymakers' views questionnaire (scale).

19.To what extent do you think that the following can be obstacles to the uptake of scientific information in the development of policy-making?					
	1	**2**	**3**	**4**	**5**
	Very much				**Not at all**
a) Too much scientific information to be useful					
b) Too little scientific information available					
c) Jargon does not correspond with policy environment					
d) Scientific data not perceived as credible evidence					
e) Scientific research findings not relevant to policy					
f) Economic and social data more relevant to policy-making					
g) Lack of institutional channels for incorporation					
h) Lack of incentives					
i) Lack of dissemination of research findings					
j) Limited openness by politicians					
k) Scientific understanding by policy-makers is low					

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ORIGINAL RESEARCH
published: 07 July 2022
doi: 10.3389/feduc.2022.897582

Imagining the School of the Future Through Computational Simulations: Scenarios' Sustainability and Agency as Keywords

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Computational simulations are fundamental tools not only for scientific research but also for education. They are frequently used as virtual laboratories to foster students' understanding of the theoretical concepts that lie at the basis of the simulated systems. Recent research works in STEM education have started to explore the potential of simulations as future-oriented objects, to support students in the development of future scenarios for real-world situations. In this paper, we present a teaching-learning module targeted to upper high-school students on simulations of complex systems. The peculiarity of this course is that, guiding the students through the conceptual and epistemological analysis of some computational agent-based models, we were able to ground on these disciplinary bases the introduction of key concepts of the futures studies, like that of scenario. More specifically, in this paper we address an original future-oriented activity in which the students were required to choose an urgent problem of their interest, imagine possible and desirable scenarios based on a simulation and identify the sequence of actions to be undertaken to reach the preferable future. In presenting the results of the module's implementation we focus on two groups of students who spontaneously decided to address a problem related to the current educational system. In particular, we discuss how the future-oriented activity based on simulations led the students (i) to imagine sustainable scenarios for the school of the future, in which a dynamical equilibrium between opposite tensions is achieved, without any of them being eliminated and (ii) to recognize themselves as agents of transformation in a public, professional, and personal dimension.

Keywords: simulations, future scenarios, agency, equilibrium, future-oriented science education, school

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Specialty section:
This article was submitted to
STEM Education,
a section of the journal
Frontiers in Education

Received: *16 March 2022*
Accepted: *03 June 2022*
Published: *07 July 2022*

Citation:
Barelli E (2022) Imagining the School of the Future Through Computational Simulations: Scenarios' Sustainability and Agency as Keywords. Front. Educ. 7:897582. doi: 10.3389/feduc.2022.897582

INTRODUCTION

It was almost seventy years ago that computational simulations entered the realm of scientific methods. In these frightening times, it is impressive to recall that these techniques were first developed for military purposes, in the research context that led to the nuclear bomb in Los Alamos (Galison, 1996). Following World War II, the range of disciplinary fields in which simulations started being used has been expanding until nowadays, when it is almost impossible to name any discipline that has not used or developed computational tools and simulations to advance its research (Borrelli and Wellmann, 2019). In all these disciplines, simulations are used for different scopes among those one very common is that of prediction i.e., the elaboration of possible future scenarios for a target system based on the behavior of the simulated one (Grüne-Yanoff and Weirich, 2010).

Computational simulations are not only fundamental pillars of scientific research: they have become important instruments also for education, as they are frequently used as virtual laboratories to foster students' understanding of the theoretical concepts that lie at the basis of the simulated systems. Even if simulations have been used for teaching-learning purposes for decades at many levels, educational research has rarely focused on the use of simulations to obtain future scenarios, but rather has investigated their role in formulating explanations or the difficulties encountered by novices in interpreting these types of models of complex systems (Jacobson and Wilensky, 2006; Hmelo-Silver et al., 2014).

Supported by the recent body of literature in future-oriented science education, our hypothesis is that computational simulations, if adequately exploited in STEM teaching, can become laboratories to imagine possible scenarios for real complex systems, with the potential to stimulate students' reflections on the future. Moreover, we believe that by using in teaching activities a specific category of simulations, named *agent-based simulations*, students can be guided not only to envision a plurality of scenarios but also to find spaces of action in the present to contribute themselves to the realization of their desirable futures. Indeed, agent-based simulations show that the evolution of a system strongly depends on the rules that regulate the interactions among the individual components of the model, and the introduction of different local rules can lead to a range of global behaviors. In our approach, the simulations are not meant to predict the future perfectly or produce realistic pictures of it. Guiding the students to recognize conceptual and epistemological details of computational simulations, the aim is rather to construct disciplinary lenses to prepare the students to look at the future in a new way. Indeed, students are led to explore the mechanisms to build a plurality of different scenarios using these tools, hence enhancing their imagination of their personal future and the future of cities, countries, and society, and become responsible agents and citizens able to navigate the complexity of time (Barelli, 2022).

In the paper, we will present the design and implementation of an innovative teaching-learning activity of scenario construction based on simulations, within an 18-h module targeted to upper-high school students on the topic of computational simulations of complex systems. The article is structured as follows.

In the framework, after introducing the educational potential of agent-based simulations through an overview on the literature in STEM education, we introduce concepts of the discipline of future studies with a specific focus on the concept of scenario and present examples of previous future-oriented activities that framed these concepts within an educational perspective, as well as research results about the participants' reactions to this kind of activities. The next part of the framework is centered on the specific role of simulations to construct future scenarios and on the possible connections that can be established between agent-based simulations and the concept of agency. The elements introduced in the framework will lead to the statement of six design principles at the basis of our original future-oriented activity which is the object of the following section. The paper continues with the description of the module and of the future-oriented activity, providing details on the implementation, the participants, and the data collection tools. In the following section, we describe the methodology of thematic data analysis conducted to answer two research questions. The same two-pronged structure will be followed to present the findings and discuss them.

FRAMEWORK: FROM THEORETICAL FRAMEWORK AND RESEARCH BACKGROUND TO DESIGN PRINCIPLES

The Educational Potential of Agent-Based Simulations: Overview on the Literature in STEM Education

Within the wide set of simulation tools that nowadays are used as a pillar of the scientific method, two main categories can be distinguished (Grüne-Yanoff and Weirich, 2010): the equation-based and agent-based ones. In the former case, the evolution of a target system is described by differential equations; once they are numerically solved, they allow to determine the future state of the system starting from the present state. On the opposite, in agent-based simulations, the dynamics of the target system is generated making the individual agents evolve according to behavioural rules. Because of that, equation-based models and simulations are often claimed to have a *top-down* character while the agent-based ones are *bottom-up*. In science education, equation-based and agent-based simulations are mainly introduced when complex systems are addressed. In particular, they are used when the science complex system is emphasized as the discipline that studies how behaviour of phenomena at different scales is related to the interdependent components at lower scales (Bar-Yam, 2016). This should already recall the distinction between equation- and agent-based modelling addressed above in terms of their top-down vs bottom-up nature.

Equation-based and agent-based models and simulations have also become a way within educational research to address in teaching different forms of reasoning about dynamic systems, with special regard to the formulation of explanations (Jacobson and Wilensky, 2006). The first form of reasoning is positioned on a "macro" level: the focus is on the system conceived as a population (sometimes as composed of different groups) with its own macroscopic properties that evolve over time according to rates of change, for example of transitions between groups. On the contrary, the second form of reasoning acts at a "micro" level: the attention is on the minimum elements of the system, the agents, which interact according to local rules.

Traditional mathematical and science education mainly encourage aggregate reasoning, also through the introduction of differential equations as descriptive tools of dynamic systems. More recently, since the 90s, importance of agent-based reasoning has been emphasized within education to foster understanding on the systems and to enter the mechanistic dimension of local interactions (Wilensky and Reisman, 2006) that has been found to be a relevant component of students' sensemaking about phenomena (Kapon, 2016). Nowadays, the two forms of reasoning are considered both essential to reach a profound understanding of complex systems and to comprehend the emergence of global patterns and behaviours from the local interactions among agents. This concept has been expressed as the "embedded complementarity" of aggregate and agent-based reasoning (Stroup and Wilensky, 2014). Even if they have their own very different features, they are not incompatible, nor necessarily working against one other. On the opposite, they are complementary for reaching a mature reasoning about emergent phenomena in complex systems. Moreover, this complementarity is "embedded" because it requires not to consider the two forms of reasoning as juxtaposed, but to move from one to the other, in a dynamic mutual relationship where elements of connection can be pointed out. Several strategies can be found to connect aggregate and agent-based reasoning: Levy and Wilensky (2008) have identified relevant at this account the construction of mid-level groups, that are in-between the level of the agents and that of the emergent property. Barth-Cohen (2018) has instead focused on the role of transitional explanations between microscopic and macroscopic levels of the system.

Another significant body of research literature is focused on the effectiveness of programming environments to learn about the simulated systems and to develop abilities of computational thinking (Sengupta et al., 2013; Wilensky et al., 2014). For what concerns agent-based simulations, the most used platform for the use and development of simulations is NetLogo (Wilensky, 1999). It is not only a platform where simulations, from a wide range of diverse domains, are available to learners, but it is a "low threshold and no ceiling" programmable environment, in which the users can create their own models using a high-level language. In the module that is object of this paper, three simulations of the NetLogo Models Library were introduced to the students and built the basis for the future-oriented activity that they carried out.

The Concept of Scenarios From the Futures Studies to Future-Oriented Science Education

How has the field of future-oriented science education inherited many concepts coming from the fields of futures studies has been widely discussed in previous research works (Levrini et al., 2019). The very same distinction between certain predictions and a range of possible projections—graphically represented in the futures' cone (Hancock and Bezold, 1994; Voros, 2003)—is at the basis of conceiving the future as a plurality of probable, plausible, possible, and preferable scenarios. For the purposes of this paper, the concept of scenario deserves to be discussed in more detail.

Scenarios are the methods of choice in the discipline of futures studies and can be defined as descriptions of possible future situations including the paths of development which may lead to these situations (Kosow and Gaßner, 2008). Far from aiming at achieving a comprehensive image of the future, the development of a scenario relies on the selection of key factors that are considered important for the future time horizon imagined. To obtain future scenarios, several techniques can be used separately or in combination (Börjeson et al., 2006). Kosow and Gaßner (2008) identify three main families of methods:

- Trend extrapolation: the scenario is constructed based on trends that already exist in the present or have existed in the past. These trends are "projected" into the future by quantitative analyses or qualitative methods. A typical scenario that can be obtained by trend extrapolation is the so- called "business as usual" which is the most probable future in case nothing changes with respect to the current situation; it is often used as a reference scenario against which other scenarios are compared.
- Systematic-formalized techniques: to this family belong all the scenario methods grounded on the definition and mutual combination of key factors for the system's evolution. These methods are named "systemic-formalized" in contrast with more "intuitive" techniques (Heinecke, 2006, p. 187). Examples are the impact analysis, the consistency analysis, and the cross-impact analysis that, in different ways, analyze quantitively the effect of a certain key factor on others, and the conditional probabilities for the events hypothesized.
- Creative-narrative techniques: as the name suggests, in this case, the focus is on the power of creativity and narrative development to construct visions of the future. Because of their emphasis on the elaboration of scenarios as communication and participatory process, they are often used in explorative phases of scenarios construction and in the development of the desirable futures.

If these three families of techniques are clearly disjointed, in practical contexts constructing scenarios is a hybrid process that integrates methods belonging to different families. It is the case of the modeling and simulation methods that will be discussed in the next paragraph.

From this overview on the concept of scenario from the futures studies' literature, we can sketch the first design principles at the basis of the design of the original future-oriented activity that we will present in the next section:

(DP1) Provide the opportunity for students to conceive the future as a plurality of scenarios rather than as the unique result of deterministic predictions.
(DP2) Present different types of futures, especially the possible and the desirable ones, and suggest the related methods for developing these scenarios.
(DP3) Introduce complementary ways for constructing scenarios, alternating the use of systematic-formalized and creative-narrative techniques.

As for futures studies, also future-oriented science education recognizes the centrality of the concept of scenario to foster students' engagement in imagining personal and societal futures. In particular, in experiences related to the

ISEE (https://www.iseeproject.eu/) and FEDORA (www.fedora-project.eu) projects, a bunch of activities have been designed to guide the students to construct possible or desirable scenarios for the future (Barelli, 2017; Barelli et al., 2018; Levrini et al., 2019, 2021; Barelli and Levrini, 2021). In some cases, they were required to individually write an essay to describe their ideal day twentyish years later; in others, they had to work in groups to identify a problem of the present and imagine a future in which this issue had been solved, highlighting possible actions to be undertaken to reach the preferable scenario. The reactions of the participants to this kind of activity have been studied. On one side the high potential of scenario-based reasoning has been emerging as a way to structure future thinking and develop so-called future-scaffolding skills (Levrini et al., 2021). However, criticalities have been arising too. If dystopian and pessimistic views are very common when students imagine the future—for a recent review of the literature we refer to the work by Rasa et al. (2022)—when they are asked to imagine a desirable scenario the result is often a picture of static, idealized stillness (Barelli, 2017). The request of dreaming about a preferable future triggered attitudes of detachment from reality that resulted in fictional, idealized scenarios that avoid any possible tension or conflict between interests or people. This made the scenarios totally unrealistic for the students (Levrini et al., 2021), violating in this way one of the main criteria that ensures the quality of a scenario: its *plausibility*, i.e., the belief in the fact that the possibilities of the developments presented in the scenarios *are* possible developments (Greeuw et al., 2000; Kosow and Gaßner, 2008). Therefore, the following phase of the activities in which the students had to identify possible actions became impoverished: being the future unrealistic and explicitly unsustainable, it is unfeasible, undoable, and unactionable.

The Role of Simulations to Construct Future Scenarios

The genesis of the idea of constructing scenarios to gain an understanding of the future dates to the 1950s when, after World War II, "the U.S. Air Force tried to imagine what its opponents might do and to prepare alternative strategies" (Mietzner and Reger, 2004, p. 48). Going beyond the military planning, it was in the early 1970s that the scenarios reached the general public with the publication of the highly contentious "The Limits to Growth" (Meadows et al., 1972). In this report, the members of the so-called Club of Rome drafted several future scenarios based on "World 3", a system dynamic simulation that accounted for the interactions between population, industrial growth, food production, and limits in the terrestrial ecosystem.

The role of simulations to develop scenarios is not only restricted to a historical circumstance but extends up to the present. Both equation- and agent-based models allow obtaining pictures of the future depending on initial conditions. In the case of equation-based models, differential equations are numerically integrated, while with agent-based approaches, the evolution of the system is generated by the actions and interactions among simulated individuals that follow specific behavioral rules (Grüne-Yanoff and Weirich, 2010). However, even if simulations are undoubtedly important tools in the process of scenario construction, the need for effective communication of their results has led to flank formal modeling activities with narrative techniques. For example, in the "Story-and-Simulation" approach, formalized by Alcamo (2001), a "storyline describes in story form how relevant events unfold in the future, while the model calculations complement the storyline by presenting numerical estimates of future environmental indicators and helping to maintain the consistency of the storyline" (p. 6). More than that, in such hybrid approaches, the benefit of combining simulations and narratives is mutual: the storyline usually helps identify the elements to be simulated, and the computational model allows refining, complementing, and giving validity to the narrative (Kosow and Gaßner, 2008, p. 84).

On these theoretical bases, other two design principles can be outlined, regarding the specific role of simulations to develop scenarios:

(DP4) Value simulations (particularly agent-based ones) as tools to model a future-oriented issue and as virtual laboratories to obtain possible evolutions of the system.
(DP5) Complement the imagination of the future scenario with the sketch of the related storyline including possible paths of development.

The Role of Simulations to Trigger Student Agency

Even if there is no global consensus on the definition of "student agency", a recent OECD report (OECD, 2019) puts this concept at the center of the 2030 Learning Compass framework. Here, the student agency is conceptualized as a rather general sense of responsibility that the students perceive as members of society who can influence other people, events, and circumstances for the better. The importance of developing students' awareness of their role as agents for their own future and for that of society is widely recognized, but the discussion on how science education can contribute to this objective remains open (Barton and Tan, 2010; Arnold and Clarke, 2013; Stroupe, 2014; Sjöström and Eilks, 2018). In the following we will focus on the potential of computational simulations, specifically of agent-based ones, to foster students' reflection on their agency and transformational role.

As we anticipated in the previous paragraph, agent-based simulations are a type of model in which the components of the modeled system interact with each other according to some behavioral rules. The so-called *agents* have some features, receive instructions from the programmers, and, following them, generate the evolution of the system. For example, it happens that agents that can be orange or blue, randomly arranged on a bi-dimensional grid, following rules like "if more than 70% of your neighbors are of a different color, randomly move to an empty cell", create a situation in which blocks of agents of the same color are separated (Schelling, 1971). This approach to modeling strongly differs from more "traditional" methods based on the resolution of equations. While with equation-based models the system is modeled as an undifferentiated whole and its behavior is estimated only at the macroscopic level, for agent-based simulations the discrete minimum components are emphasized, and their local interactions lead to emergent phenomena observed by the macroscopic behaviors at the aggregate level. Moreover, while equation-based simulations are deterministic, the agent-based counterparts generate different temporal evolutions every time they are executed because of the stochastic character of the behavioral rules (Barelli, 2022). These differences between the two approaches make agent-based simulations particularly well-positioned to trigger reflections on student agency. Firstly, they show how the role of the individual is essential to produce a global behavior. At the back of an evolving system and a scenario reached, there is a multitude of individuals that have carried out specific actions. Secondly, agent-based models allow us to highlight that the actions taken by the agents are in fact *inter*actions between agents and their neighbors. Finally, the stochastic feature of the model resembles the unpredictability of the effects of given causes in complex systems.

The last design principle aims to exploit in the future-oriented activity the role of student agency:

> (DP6) Give to the students the possibility to make students think at themselves as protagonists of the paths of development toward the desirable scenario.

CONTEXT AND SAMPLE

The Future-Oriented Module on Computational Simulations

The context in which we conducted the study object of this paper is a teaching-learning module on simulations of complex systems that was implemented in January-February 2021 as part of the program of the Department of Physics and Astronomy of the University of Bologna, Italy for university orientation of high school students. It was implemented in six lessons of 3 h and was articulated in five activities whose main goals are summarized in **Table 1**. For a detailed description of the module, we refer to its extended analysis in Barelli (2022).

Since in this paper we will focus on the results of students engaging with the future-oriented activity, we provide some more details about the last part of the module. The students were divided into groups and were asked to address different tasks. The first task consisted of the identification of a real-world problem of students' interest, followed by the request to explore possible future scenarios based on a NetLogo agent-based simulation that they considered suitable to address the topic. Then, they were asked to imagine a desirable scenario and to engage in a back-casting procedure, identifying the actions, decisions, policies, and contingencies which have made it possible to realize the ideal future in 2040. To exploit the role of individual agency in the imagination of the future, in this phase the students were required to make explicit which role they had in the path of changes from the present to the future they foresaw, as professionals, members of society, and as individuals in general. To summarize their work, the students had to prepare a presentation about their story of success. The structure of the activity was borrowed from similar ones previously implemented within the I SEE project and described by Levrini and colleagues (2021). The novelty of this one consists in the fact that to imagine the possible future scenarios, the students were asked to rely on a NetLogo simulation of their choice.

The Participants

More than 50 students voluntarily applied and 35 of them (25 males and 10 females) were selected for participation in the course. The criteria of selection were established by the overall organization of the orientation initiative and aimed at avoiding the presence of more than 5 students from the same class and guaranteeing the gender balance as more as possible. All students attended the third or fourth year of a dozen of secondary schools in Emilia-Romagna (Italy). The majority (30 out of 35) attended a "scientific lyceum", a type of high school centered on scientific subjects; three students came from a "classical lyceum," which is focused on teaching-learning humanities and ancient languages; two students attended a technical-aeronautic institute. The students took part at most of the activities of the course; only one participant abandoned the course after one lesson. For the group activities, the instructors arranged in advance seven teams of five students each to avoid as much as possible the presence of more students of the same class in the same group and guarantee the presence of at least one female student in each group.

Tools of Data Collection

Several data were collected during the module's implementation using individual questionnaires, shared digital boards, sheets and presentations produced by group works, collective discussions, video-recordings of lectures, group works, and interviews. For the analysis this paper is focused on we considered the video recordings of (i) the final presentations of the seven groups of students at the end of the future-oriented activity described above and of (ii) the collective discussion that followed the groups' presentations. Before being analyzed the data were transcribed and anonymized. The names of the students were replaced by pseudonyms to keep the reference only to the students' gender.

RESEARCH QUESTIONS AND METHODOLOGY

In this paper we address the following research questions.

1) How do the students construct their desirable futures using agent-based simulations?
2) What kind of issues are touched by the students when they describe the current problems of school, their ideal future, and the priorities for its transformation? What is the role of students and teachers' agency in the process of transformation envisioned?

To address RQ1, the first step consisted in analyzing the video recordings of the seven groups' presentations. In particular, we were interested in finding common features of the desirable scenarios imagined by the students, across the huge variety

TABLE 1 | Articulation of the module on simulations of complex systems and the main goals of each activity.

Title of the activity	Main goals
Lectio magistralis: "Computational physics in the era of big data"	- To situate the simulations in the wider panorama of the computational physics as the third pillar of contemporary scientific research
Roundtable with early career researchers: "Simulations as research tools"	- To show different research contexts in which simulations are used or developed by physicists - To enrich students' imagination about the frontiers of physics research and orient them to the university choice
Interactive analysis of agent-based simulations of complex systems	- To show the differences between equation- and agent-based models - To make students experience first-hand NetLogo agent-based simulations that embed different interaction's dynamics i.e., the predator-prey mechanism, the opinion dynamics, and the cooperative behaviours
Activity of analogies' development: "From models of systems to real problems"	- To guide the students to extend the three agent-based models learnt during the previous activity to other real-world problems
Future-oriented group activity of scenarios' construction based on simulations	- To exploit the role of agent-based simulations to construct possible, probable, and desirable scenarios for real-world problems

of the issues chosen. Comparing the presentations of the seven groups, we found that a recurrent theme in many desirable scenarios was the concept of equilibrium. After having identified this main feature, we focused on analyzing how the different groups embedded an aspect of balance in their desirable scenarios, and how the work on the agent-based simulations allowed them to make it explicit. In the second phase, we analyzed the video recording of the final collective discussion, when students were guided by the instructors to reason about the types of scenarios identified. In this way, we checked whether the students were aware of the peculiarity of the scenarios of equilibrium to produce reliable future scenarios.

Differently than RQ1, RQ2 is a question related to a specific issue imagined by the students i.e., the school, so we could not consider all the groups' presentations as a dataset: we had to focus just on the presentations of the two groups that, in the future-oriented activity, decided to address a problem related to school (Group 4 and 7). To identify the main features of the students' ideal school in the future, we chose thematic analysis (Braun and Clarke, 2006) as the qualitative method "for exploring and interpreting patterned meaning" in our dataset (Braun and Clarke, 2022). We proceeded following the process of the so-called reflexive approach to thematic analysis that envisions a recursive engagement with the data to produce a robust analysis, despite the non-theoretical orientation of the method (Braun and Clarke, 2006). The main phases that Braun and Clarke (2022) delineate for reflexive data analysis are: (1) familiarization with the dataset, (2) coding, (3) generation of initial themes, (4) development and review of themes, (5) refinement, definition, and naming of themes, (6) writing and contextualization within the literature. In the following paragraphs, we describe how we operationally addressed these phases.

According to the methodological prescriptions, after having listened the presentations and read the transcripts multiple times (*familiarization with the dataset*), we arranged a preliminary organization of the dataset into an Excel grid in which each row corresponded to a sentence of the transcript (i.e., a text's excerpts ending with a period).

The second phase, that Braun and Clarke name the *coding* phase, consisted in adding columns to the Excel grid in order to write the bottom-up tags that corresponded to each excerpt. In this bottom-up process, the words or expressions used as codes were strictly connected to students' words. For example, a sentence like:

> *A source of stress, as we know, for all students is the final result of that path, that is the final exam and we currently know how the exam tests greatly influence the final evaluation and therefore we decided to favor more the path that is carried out in all school years compared to evaluating only the final exam. (Group 7)*

was coded with "cause of stress," "final exam" (in Italian: "maturità"), and "enhancement of the whole study path."

The bottom-up coding of the transcripts of the two groups' presentations was followed by the third methodological phase in which the codes were organized in categories, namely the themes (*generation of initial themes*). Operationally, the codes written were listed and grouped in 10 themes, as reported in **Figure 1** (bottom right). For example codes referring to students' way to deal with time for study, hobbies, and relax ("management of time," "time for themselves"), to the hours dedicated to school and study ("school in the afternoon," "less autonomous study"), or to the time needed for understanding ("same amount of information but more diluted") were all colored in light blue and grouped in a theme concerning the relationship between routine and time management ("school determines routine and time management"). It can be noticed that for the first two themes, two colors have been used. Indeed, the students talked about technological innovations and marks-provoked anxiety in two different ways. Regarding technology, they wish for the use of more technological devices (darker yellow) but at the same time recognize the need to keep something on paper (lighter yellow). The same concerns anxiety: on one side they feel enormous stress caused by marks and evaluation processes (darker green) but on the other, they recognize the importance of forms of evaluation to keep students motivated. We remark that the passage from the codes to the themes was for us a delicate methodological step since it required passing from something that was anchored to the specific set of raw data to more general categories that found

FIGURE 1 | Grouping of the bottom-up codes in themes.

confirmation also in the sociological or educational literature or in the findings from previous studies.

The fourth and fifth Braun and Clark's phases regard the *review, refinement, and naming of themes*. The main criteria we chose were: (i) grouping "similar themes" to avoid redundancies, (ii) formulating the macro-themes in a way to address the RQ, and (iii) keeping firmly distinguished from the other themes the issues concerning students and teachers' agency. If the first and second criteria are rather transversal to the thematic analysis as a methodological process, the second is more specific for our study, since it allows to address the second part of RQ2 (*What is the role of students and teachers' agency in the process of transformation envisioned?*). The output of this stage of themes review was the list of the seven macro-themes in **Figure 2** that we will illustrate in depth in the analysis section. Here, we briefly comment, with some examples, on the adherence of the process to obtain macro-themes with respect to the aforementioned criteria. First of all, we noticed that, for the role they had in the story we wanted to tell with our analysis, some themes overlapped. It was the case of "application of knowledge for the future career" and "trade knowledge" that we grouped in only one macro-theme referring to the need of rethinking knowledge's organization at school. The same happened for the macro-theme related to agency that summarizes three themes ("agency in a public dimension," "agency in a private dimension," and "school as an institution"). To comply with the third criterion, this macro-theme was kept separated with the others, especially to that of pandemic with which some superpositions were observed (e.g., the role of students' demonstrations during the pandemic can be interpreted as a manifestation of agency too). Finally, according to the second criterion, all the macro-themes were named in order to outline the problems of the present, needs, dreams for the future, and priorities of transformation; indeed, we have "the problem of...," "the role of...," "the dream of...," "the hope for...," "the priority of...".

Once the macro-themes were identified, preparing to the last phase of *narrating the results*, we looked again at the transcripts and improved the division in paragraphs according to two criteria. First of all, different phases of the activity (introduction, statement of the problem, introduction of the simulation, explications of the scenarios obtained with the simulation, presentation of the ideal future, and back-casting) could not be mixed in the same cell. Secondly, in each excerpt, only one macro-theme should have appeared. At this point, we counted the number of words in each text excerpt to have a measure of its length and adjusted the height of the row accordingly. In this way, we were able to obtain a visualization of how the two groups' presentations were articulated in macro-themes and what was the relative frequency of each macro-theme with respect to the total coded part of the transcripts.

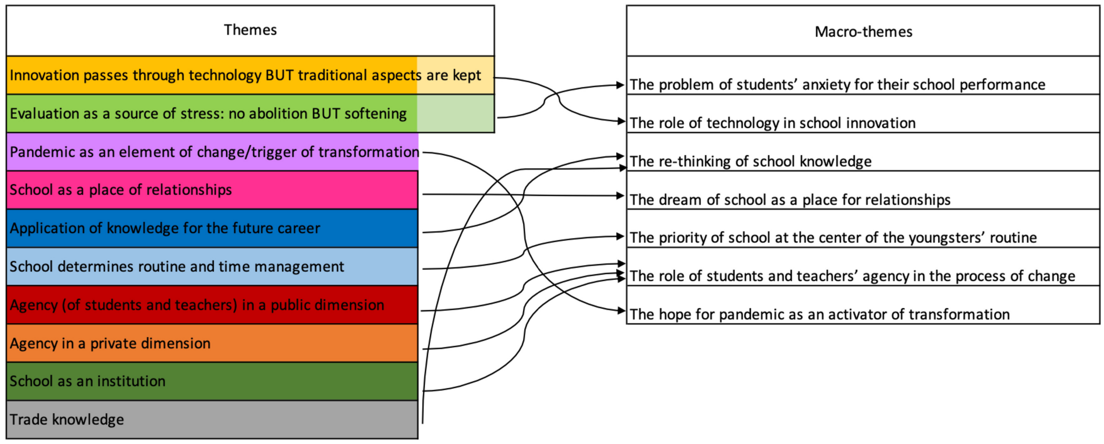

FIGURE 2 | Grouping of the themes in macro-themes.

To validate the analysis, in line with recommended practices (Anfara et al., 2002), the coding procedure was triangulated through peer debriefing with researchers in STEM education during specifically designed meetings. In particular, the richness of research sensitivities allowed to reach the set of macro-themes presented and the connections with the literature and the key issues of sustainability and agency.

DATA ANALYSIS AND RESULTS

Before presenting the results of the data analysis we provide an overview of the presentation of the seven groups. In **Table 2** we write, for each group, a short description of the problems chosen, the simulations used to tackle these issues, the scenarios identified, and the main features of the desirable futures obtained.

The Construction of Scenarios of Equilibrium for Complex Societal Issues

As summarized in **Table 2**, in the future-oriented activity, 5 groups out of 7 (groups 2, 3, 4, 5, and 7) imagined their preferred scenarios as strongly characterized by an idea of equilibrium. This equilibrium was interpreted in a different way by the groups.

Group 2 worked on the problem of overpopulation and, after having explored scenarios in which the population ran out of resources or was threatened by infectious diseases, imagined a scenario by interpolating the two extremes previously identified. Observing the graphics provided by the simulation, they noticed that a situation of equilibrium between resources and humans was achieved when the curve reached a plateau (they call it a "stable peak").

Group 3 addressed the issue of globalization and imagined a future with a diversity of cultures that live peacefully, side by side, avoiding that only one culture takes the lead on everyone. Even if the idea of a peaceful co-living of cultures, without any conflicts or cultural predominance could suggest the idea of a "fake equilibrium" as the "equilibrium of perfection", the context in which this scenario was formulated contradicts this interpretation. Indeed, when the students outlined the story that led to that future, they considered many conflicting interests and a diversity of stakeholders which continue to co-exist in the final un-globalized scenario.

The problems chosen by Group 4 were related to the school system: the predominance of antiquate teaching methods and the stress experienced by students. They imagined three main stakeholders for their futures: supporters of traditional educational methods, supporters of innovative methods, and students. After having outlined two extreme scenarios (only educational methods or only traditional ones are used in the schools), they think of a future in which it is reached an equilibrium between old and new teaching methods where each of them works as a counterweight for the other and only their mutual presence can guarantee the realization of the students' objectives.

Group 5 worked on the problem of air pollution in the Po Valley (Italy). They explored different scenarios, including the business-as-usual and the worst-case scenarios, evaluating them based on the graph of pollution in time. Having realized that it is very difficult to make pollution lower, they changed the parameters until they reached a plateau of the curve which they considered their desirable future. In this case, the idea of equilibrium consists in the fact that the plateau is reached through the balance of two factors i.e., the number of polluting agents (e.g., factories) and the trees planted.

Group 7 addressed the problem of the high levels of stress that the students experience today because of the school system. Even in this case, they formulated their desirable scenario "between" two extremes: the elimination of the students that are psychologically defeated by the stress and the absence of any obstacle for students. The desirable equilibrium between stress and students is recognized by the group in the periodic evolution of the graph displayed by the simulation.

On the opposite, the two groups that did not cite any equilibrium in their analysis ended up with naïve scenarios that did not seem plausible either to the students. For example, Group 6 worked on the problem of ethnocentrism and imagined a future

TABLE 2 | Summary of the problems addressed by the seven groups in their presentation, the simulations used, the scenarios envisioned, and the actions to be taken.

	Group 1	Group 2	Group 3
Problem	Unfair distribution of wealth and resources in the world	Overpopulation	Globalization and cultural flattening
Simulation	Cash flow	Wolf sheep predation	Voting (extended)
Scenarios	Wide rich-poor gap Increase of middle class 3) Increase of middle class and decrease of poor	Depletion of resources and death of population Spread of diseases and death of population	Complete globalization and cultural flattening Partial globalization with survival of cultural islands 3) Equilibrium among cultures without conflicts nor cultural predominance
Desirable future	Few poor people, many middle-class people	Stable peak of population	Equilibrium
Actions	Creation and strengthening of a central bank institute	International agreements and norms for sustainable development	Revolution, internet

	Group 4	Group 5	Group 6	Group 7
Problem	Predominance of antiquate teaching methods and stress experienced by students	Pollution in the Po Valley (Italy)	Racial discrimination	High levels of stress experienced by the students because of the school system
Simulation	Cooperation	Urban Suite—Pollution	Ethnocentrism; segregation	Wolf sheep predation
Scenarios	Equilibrium between traditional and innovative methods Predominance of innovative methods 3) Predominance of traditional methods	Increase of pollution and stop after 20 years Constant increase of pollution 3) Reach of a plateau and slight decrease of pollution	Return to nationalisms Business as usual 3) Elimination of races from the public discourse	Stress wins Students win 3) Equilibrium
Desirable future	Equilibrium	Plateau	Elimination of races from the public discourse	Equilibrium between stress and students
Actions	Mass movements, peer instruction, individual will	Use of technologies, unification of factories, incentives for sustainable development	Improvements in education and institutional actions	Public demonstrations, lobbying and personal hard work

in which no relevance is given to race in the society and no discriminations exist at all. But after their description of this ideal scenario, a student talks about it as a "utopian scenario" and then says it is "unreachable". Hence, it seems that the construction of desirable scenarios based on equilibrium produced more realistic scenarios that the students believed more feasible than "too perfect" futures that resulted to seem utopian because clearly far from a sense of reality.

Students' awareness about the types of equilibrium embedded in their scenario emerged in the last discussion of the course:

> *Instructor: Can you tell us something about the concept of scenario? And on the scenarios that you all have identified, on the type of scenarios you have used. You've all used a very similar strategy to think about scenarios.*
> *F15 (Group 3): Probably at least as far as my group is concerned, first of all, we took our ideal scenario and that had to be there... How I wish it were... even utopian, even if it was not feasible. And then the opposite scenario probably comes automatically in the sense that I have my utopian scenario and then if everything goes wrong, everything completely wrong what could happen, right? And then an in-between scenario, that is... what I want is not achieved, but neither it is possible to reach the most absolute catastrophe. At least, we have reasoned that way.*
> *M8 (Group 2): For group 2 on overpopulation... for scenarios 1 and 2 we took extreme cases. Even in the simulations, to try to have an obvious result, we exaggerated parameters so as to obtain results that were certainly as we expected. Then instead for the third simulation which was the one that we preferred and was a little more balanced...*
> *Instructor: This is the other word you have all used. An equilibrium that is not a thermodynamic equilibrium, but a particular equilibrium... Which equilibrium? It is a form of equilibrium that you have all identified... Which form of equilibrium? What does balance mean in these situations?*
> *M13 (Group 3): Well, it is a balance of a system that is not a physical system but also often a social one and which, however, reaches its own equilibrium and stops varying...*
> *Instructor: It stops varying in what sense? Is it all dead?*
> *M13 (Group 3): No, I mean... Oh my God... (laughs) It depends on the case.*
> *Instructor: At the extremes, yes, because we arrive at a balance where everything stops.*
> *M13 (Group 3): No well it depends on the circumstances... (laughs) defining it dead is perhaps a bit exaggerated but basically, yes, you get to a situation that then persists.*

Instructor: But what is it that allows the balance to persist? What's this? What persists?
F17 (Group 4): Actually, in my opinion, a balance will be reached that can be defined as dynamic, that is, hybrid. Now it makes me think of chemistry right away... but this balance, however, does not persist. Well as we saw in the Voting simulations. . . it is not fixed. . . more or less the parts are those, but it is a continuous change, a continuous movement.

Triggered by a question from the instructor ("Can you tell us something about the concept of scenario?"), four students reacted by explaining how in the groups they constructed their scenarios. F15 is the first to take the floor saying that the desirable future identified by her group (Group 3) was "an in-between scenario". Indeed, they started from two extremes, the utopian ideal scenario, and its opposite, the worst-case scenario. Between these two extremes, they found the desirable future where "what I want is not achieved, but neither it is possible to reach the most absolute catastrophe". A similar strategy, which starts from the extreme cases, is followed by Group 2, as M8 tells. He emphasizes the role of the simulation in defining these extremes: "to try to have an obvious result, we exaggerated parameters so as to obtain results that were certainly as we expected". Hence, extreme scenarios originate from extreme values of parameters, that lead to configurations of the system that are easy to interpret. When the extremes are clear, it can be identified an intermediate scenario that is "a little more balanced". This is the first time that in the discussion the word "balance" appears explicitly.

Then, citing the difference between this kind of balance with respect to the thermodynamic equilibrium, the instructor presses the students to focus better on the type of balance embedded in the scenarios ("Which form of equilibrium? What does balance mean in these situations?"). Here we have a little exchange of words between the instructor and two students from two different groups who have two very different ideas of equilibrium. The first student, M13, from Group 3, does not seem to have grasped the idea of thermodynamic equilibrium expressed by the instructor, indeed he says the equilibrium does not necessarily regard a physical system but a social one ("it is a balance of a system that is not a physical system but also often a social one"). Beyond this difference, he describes the equilibrium as something that is "reached" by the system and consists of the fact that the system itself "stops varying". Pressed by the instructor ("It stops varying in what sense? Is it all dead?"), M13 confirms that "it depends on the circumstances" but, anyhow, "you get to a situation that then persists". If his idea can be ascribed to a conception of *static equilibrium*, F17, from Group 4, cites the idea of *dynamical equilibrium*. She refers to a system characterized by a balance of elements that remain more or less the same but recognizes that something always changes and does not freeze ("more or less the parts are those, but it is a continuous change, a continuous movement").

The Priorities for the School of the Future According to the Students

To understand and describe how students imagined the future of the school, we analyzed the final presentations given by groups 4 and 7. We will present the results of the analysis developing a narrative that goes across the macro-themes identified, to give back a picture of the main problems that the students see in the school nowadays, the features of their ideal school, and the kind of transformation that needs to take place.

The Problem of Students' Anxiety About Their School Performance

The traditional methods of knowledge assessment and evaluation are perceived by both groups as a considerable source of stress for the students. In particular, the final exam of high school (in Italy, the "maturità"), is a sort of threat for the students during the whole school path.

However, in a perspective of maintaining a certain balance within the system (as discussed above), they do not propose abolition of texts, exams, and grades. Indeed, to a certain extent, forms of evaluation are believed to be a fruitful resource for the students and helpful for learning. To keep the motivation but reduce the stress connected to the marks, group 4 suggests, for the tests, to move from an evaluation in a 0–10 rank to a ranking with letters from A to F. They do not explain the advantages of using the letters as a ranking system, but we can suppose that there is in the students a certain pop-cultural fascination for what happens in the United States, as an example of innovation. More ideas are proposed by the students of group 7 who reflects on the possibility of a better organization of the workload to avoid too many tests in a too short period of time. The teachers appear as protagonists of the change of school from the very first sentences of the presentation. Later on, they will illustrate how their role is essential for the transformation they hope for. To reduce the anxiety for the final examination, they ask for an evaluation system that takes more into account the achievements throughout the whole school path, without basing only on the performance in the exam.

The Role of Technology in Science Innovation

The technological dimension has a relevant role in the innovation of the school system that the students advocate. Its use is foreseen to contrast the traditional teaching methods that the students consider "boring and not very interacting". They say that technological devices are already part of some teaching activities, and the process has recently accelerated because of the massive implementation of distance learning imposed by the pandemic. However, always in a logic of balance and gradual transformation, the students of both groups believe that technological innovation must not replace traditional learning tools. In particular, according to group 7, keeping textbooks made of paper is necessary in order to "organize the study". We can read, behind this apparently simple sentence, an implicit idea of the students: if new methods (represented by the "technology") can innovate school making it more entertaining, more pleasant and less boring for students, it's from traditional methods (represented by the "paper" and the "books") that comes a precise and solid form of organization of knowledge and this organization is what allows the students to orient themselves in all the pieces of information. Coherently with this interpretation, we also have group 4 which imagines use of technology that should allow closer interaction between teachers and students. This shows how technology itself needs to support the students in their learning processes but cannot replace the confront with the teachers as the repositories of organized, authentic, and validated knowledge. On the opposite, the platform that the students imagine is designed to facilitate the process of teachers' supervision of the students. Group 4 also reflects on the health issues related to the widespread use of technological devices, imagining that those tools will be used only starting from middle school.

The Re-thinking of School Knowledge

In front of what group 4 calls "the classical notional and frontal teaching method", the students do not only refer to technology as the solution to their problems. They imagine a variety of changes that need to be done to make learning, on one side, more pleasant for students and, on the other, more relevant for their personal future and careers.

One problem that the students experience is related to the frenetic rhythms of the classes, with a too intense concentration of information in a too short period of time. For group 4, knowledge requires time to be assimilated and understood, while the current organization of the school timetable and the curricula implies dense lessons in which a lot of information is given. They not only think about a change of the rhythms of the classes but imagine also that the type of knowledge provided should be rethought. The "notional" lessons are counterposed with the "concrete" character of knowledge they would like to learn. They believe that school should teach more about the applicative issues embedded in the disciplines to prepare the students for the world outside and after school. The students imagine a variety of activities with which the school curriculum should be enriched: courses in the afternoon, school trips, internships, university, and career orientation activities (they cite, for example, the PCTO activities, "Percorsi per le Competenze Trasversali e l'Orientamento" that are programs in Italy aimed to develop transversal competences and prepare for the university or professional choices after high school). All these are experiences that already exist in the school and that are present in the official curricula. The emphasis that the students give on them reveals their appreciation of engaging in activities that allow to widen the knowledge learned in the classroom, find application contexts for that knowledge and understand their attitudes.

Another difference between the school they experience and that they would like is related to peer instruction. The suggestion of introducing peer instruction in all schools can be interpreted as another dimension of change in the forms of how knowledge is constructed. According to students' ideas, the teachers will not be the only repositories of knowledge but there can be some spaces during the school routine in which some form of knowledge is developed thanks to the interaction with mates. This point will be furtherly discussed in the following paragraph.

The Dream of School as a Place for Relationships

An element that characterizes students' ideal school is the quality of relationships between the protagonists that live in the school in the first place: students and teachers. The ideal school dreamt by the students is centered around relationships. And there is more than that: we can read a sort of positive feedback that makes the school environment a carrier and support of relationships between students and between professors and students, but the quality of these relationships makes school learning more effective, and the school environment results enriched. These relationships are exploited in different activities. In the previous paragraph, we have already mentioned peer instruction, but there are other kinds of moments in which students can for example meet to study in groups or with a professor. In these activities in which the teacher participates in the moments of study, the students can "re-evaluate" the "image of the teacher", establishing a "bond" with them.

The Priority of School at the Center of the Youngsters' Routine

With the second and third macro-themes, we have already introduced some elements regarding the different organization of time imagined by Group 4. For example, they mentioned the idea of the fair amount of time needed to learn and appropriate disciplinary concepts, or the necessity of spending extra time at school in the afternoon to strengthen relationships with mates and teachers. They also mention that more time spent at school would reduce the time spent by students for their individual study. From the students' words, emerges the desire of the students to have back the time that in their routine they spend at home and devote to self-study. Later in the presentation, they sketch out a normal day in their ideal future: for these students, the school is the main place around which the youngsters' routine should be centered, with 8 hours spent there every day. School seems to be so important that includes in it almost every aspect of the students' life: the access to institutionalized knowledge (with the most traditional classes in the morning), the experience of fields of application of what they have learned (with the laboratory activities, meetings with experts or trips), the cultivation of meaningful relationships with teachers and mates (during the group study or lunchtime), the practice of recreational activities like sports. With the imagination of the future ideal routine, the students display the need for an almost fully institutionalized routine, where most dimensions of life are covered by the school program. However, it is thanks to this dense timetable that the school can contribute to free the time that the students have beyond school, like the "time for themselves" that the students claim to need as well as the relationships with friends and family.

The Role of Students and Teachers' Agency in the Process of Change

One of the most frequent macro-themes identified in groups' presentations was the importance of students' and teachers' agency in the process of realization of the desirable future. Their agency covers three main dimensions: the *public* (establishing a relationship with the institutions), the *professional* (involving the relationship with colleagues), and the *personal* dimension (carried out in the personal routine).

The public dimension is identified when the students talk about collective protests, marches, and petitions in which students and teachers take part or when they refer to awareness campaigns on social media or in the schools. All these forms of actions relate to the public dimension since they have the explicit goal to raise the government's attention about the situation of the school (petitions, marches, and protests) or to involve others in the movement (campaigns on media):

> *Then after the pandemic people realized how badly the school was managed due to the uncertain indications that always arrived late and subsequently thanks to the demonstrations and requests of the students their ideas were taken into consideration by adults. These events have made possible a greater dialogue between educational institutions and students. The attention from the government towards the school has also increased in fact financial investments have been made. [. . .] We have identified two main actions that we can do to improve the situation. The first is to manifest, both in the strict sense precisely with organized events about we have been talking a lot lately, and also a manifestation in a broader sense, in the sense of manifesting one's thoughts personally or even at a class level, to the school, so encouraging dialogue between students and teachers and the school organization. (Group 7)*
>
> *Because of this, it is necessary a sort of activism on the part of students and teachers who can therefore make petitions or even movements on social media to the mass media. In this way, many more people would come into contact with this thought and maybe it would also spread the fastest way since we can exploit a tool that is still very prevalent today in life, especially of young people. [. . .] Finally, an effort is needed on the part of everyone, especially the students. In fact, it is the students themselves who mobilize themselves to bring about a change in Italian education. Because of this, it is necessary to awaken in a certain sense the students from the passivity that lies in these days, in this period. More than passivity I would say indifference towards the school since now it is almost like torture many times. To this extent, we need movements that can reach everyone so that they realize that the school can change and they can do something to help. (Group 4)*

We can recognize that with the idea of agency in the public dimension comes the recognition of the roles of institutions with which, as said by group 7, a dialogue can be established. Moreover, the students realize that acting on a public dimension is not limited to the dialogue with the higher-level institutions (e.g., the government) but also involves mid-level actions of awareness-raising at the class or school levels.

If the public activism involves students and teachers who take part together in the transformation of the school, the second dimension of agency, the professional one, mainly regards the teachers. Especially group 4 focuses on the fact that, to trigger the desired transformation, the teachers need to take part in courses of professional development where they work together with their colleagues to figure out ways to innovate their teaching and, hence, school.

> *Furthermore, it is also difficult to find teachers willing to try new teaching methods. In this case, projects or courses could be set up for the teachers themselves so that they have the opportunity to discuss with each other to devise new teaching methods and perhaps even discuss them with the students in order to have their approval. (Group 4)*

The last dimension relates to the personal agency of students that covers the context in which they act without interacting with institutions and peers but in their personal lives and routines. Group 7, for example, focuses on the hard work of students in order to "get the work done" personally.

> *And the final thing and perhaps not the most important is the management by the students in their autonomy of the tasks and projects they have to carry out because it can manifest as long as you want, you can have a perfect school system but, in any case, you have to work and you have to get the work done to get results. (Group 7)*

The Hope for Pandemic as an Activator of Transformation

In the presentations, both groups referred to the role of the pandemic (that in their scenario of 2040 occurred twentyish years later) in the process of transformation of the school. From one side, the pandemic raised the issue of the importance of technology, which we already addressed with the analysis of the first macro-theme. But the importance of the pandemic was not only that of suggesting a way of change like the use of more digital devices but was also a trigger of transformation. Indeed, as group 7 points out:

> *Then after the pandemic, people realized how badly the school was managed due to the uncertain indications that always arrived late, and subsequently thanks to the demonstrations and requests of the students their ideas were taken into consideration by adults. These events have made possible a greater dialogue between educational institutions and students. The attention from the government towards the school has also increased in fact financial investments have been made. Finally, thanks to these investments there has been an innovation in the school system, schools, and equipment. All the things we said before have changed. (Group 7)*

Again, the importance of students' agency is underlined. Indeed, the group recognizes retrospectively the role of the protests that occurred during the pandemic in starting a durable change. The students' actions made a difference because the government decided to make more financial investments to improve the school system. In some sense, for both groups, the pandemic created the conditions for the realization of the desirable future.

Overview

After having presented the meaning of the different macro-themes, in **Figures 3**, **4**, we report, with two different visualizations, the distribution of the macro-themes in the two groups' presentations. In both figures, on the left, there are the

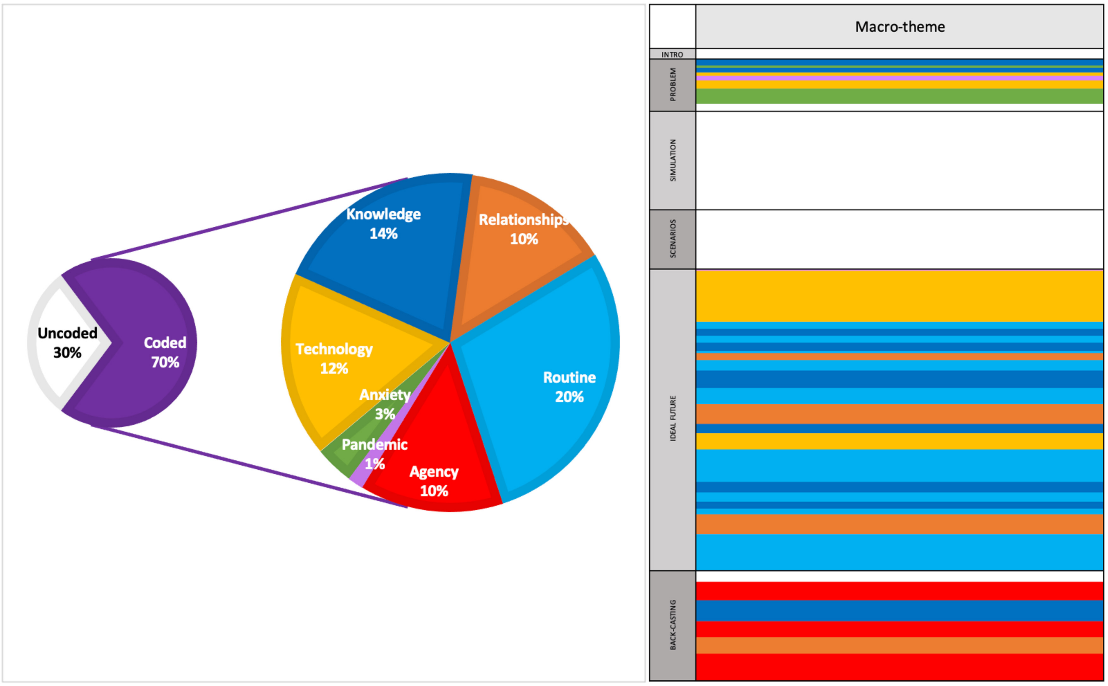

FIGURE 3 | Distribution of the macro-themes in Group 4's presentation.

pie charts for the frequency in the transcripts of the seven macro-themes. The pie charts contain a first graphic with the percentage of the coded and uncoded transcript (coding coverage) and then it is reported the details of the percentage distribution of the seven categories on the coded portion of the transcript. All the numerical values have been calculated using the number of words in each excerpt. The second visualization, on the right of **Figures 3**, **4**, consists in the miniatures of the transcripts of two presentations (the readable versions are reported in Barelli, 2022) with the distribution of the macro-themes. In this case, the height of rows is proportional to the number of words in the specific excerpt of the transcript.

The difference between the two kinds of visualization is that in the second we have the chronological articulation of the occurrence of the macro-themes across the development of the presentation. In particular, we have divided both presentations into six phases that corresponded to the tasks in which the activity was articulated: introduction, statement of the problem, introduction of the simulation, explications of the scenarios obtained with the simulation, presentation of the ideal future, and back-casting.

Even if the two presentations are very different for their extension (more than 2,300 words for group 4 and less than 1,000 for group 7), we can draw some common considerations about both.

A first observation is methodological and can be done by looking at the portions of the coded and uncoded transcripts. In both cases, we notice that there are significant parts of the transcript that could not be coded using the seven macro-themes. This percentage is 30% in group 4 and grows up to 42% in group 7. Apparently, this would mean that from the bottom-up phase of coding to the identification of the macro-themes, many excerpts of text could not be captured by the macro-themes. However, if we look at the right part of **Figures 3**, **4**, we can notice in which parts of the presentation there are the uncoded parts. For both groups, most uncoded parts are in three phases: the short introduction to the presentation, the phase of description of the simulation, and that regarding the scenarios obtained using the simulation. This is all but unexpected for us. The reason behind the absence of coding in the introduction is rather trivial: here, the students briefly summarized the content of the presentation, the name of their group, and outlined the general structure of the presentation, without entering the content of their investigation. We can easily explain the absence of macro-themes in the other two phases too: those parts of the presentation were interpreted by the students as the most technical ones, in which they had to "play the role" of scientists and experts of simulations, presenting the reasons for the choice of the model and showing its functioning. If we exclude these three sections by the count of the uncoded transcript, we notice that remain only a few excerpts. Both for Group 4 and 7, they are positioned at the joints between the sections and are sentences that connect one part of the discourse to the following.

A further comment is needed on the distributions of macro-themes related to agency and pandemic.

For both groups, we can notice that in the back-casting phase are concentrated the excerpts related to agency (in red, following the color coding). To explain this, we recall that in this part of the activity, and consequently in this part of the presentation, the students had to think about the possible events that could have

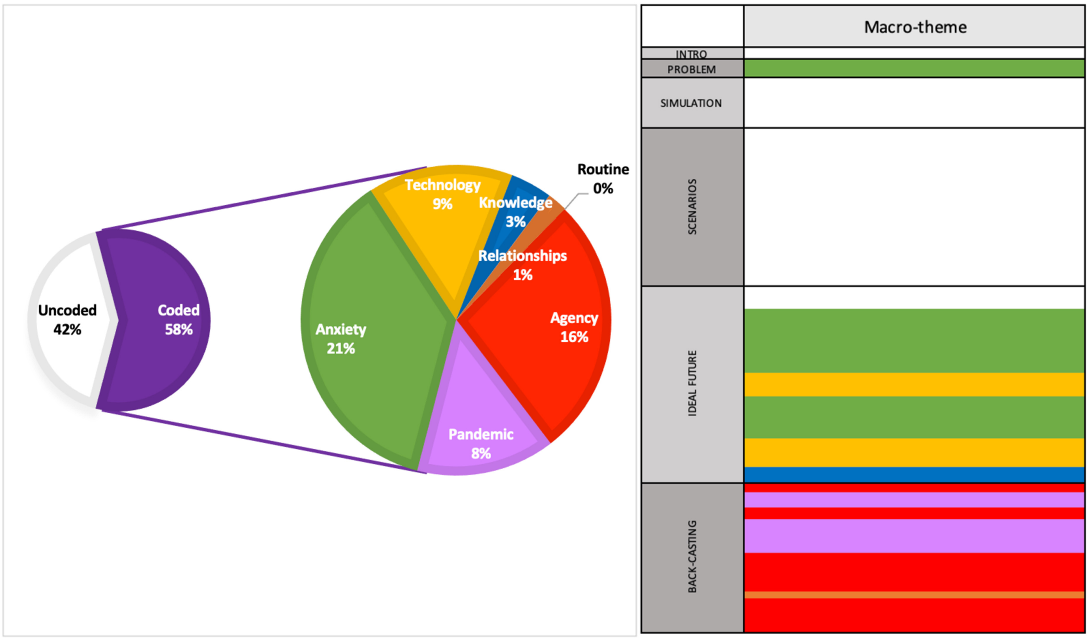

FIGURE 4 | Distribution of the macro-themes in Group 7's presentation.

led to the desirable future in 2040. Of the range of possible events and actions, the students emphasize the role of their own agency, as students, in changing the system.

We have already discussed how the students imagined the role had by pandemic on their possible and desirable futures and talked about this in the presentation. However, the two groups mentioned the pandemic in different parts of the presentation. Group 4 dedicate only a very small part of the presentation (around 1%) to this issue. In particular, they used the pandemic as the starting point to introduce the problem of their interest (the resistance of the school to innovate, also technologically, its methods) and then they mention it at the beginning of the description of their ideal future that is partially inspired to the use of technologies experienced in the on-going pandemic. For group 7, the reference to the pandemic is much more frequent (around 8% of the total presentation) and concentrated in the back-casting phase. This indicates that the students recognized the pandemic as a historical moment in which specific actions, such as public protests and petitions, have been possible: for them, the pandemic (and what happened during it, especially in terms of social awareness and agency) is part of the sequence of essential actions that can realize the desirable future.

The macro-themes related to agency and pandemic are the most connected with the issues on which RQ2 is focused. However, we want to conclude this section commenting other two macro-themes that appear with different frequencies in the two presentations, allowing to highlight the specificities of the groups of students in terms of the important changes to be made to reach the desirable school.

The biggest difference that can be noted comparing **Figures 3**, **4** is the appearance, in the figure related to Group 4, of the macro-theme of routine that is totally absent in that related to Group 7. This macro-theme covers around 20% of the whole presentation of group 4. This can be partially explained with the choice of Group 4 about how to structure the presentation. Indeed, the second half of the section about the explication of the ideal future was dedicated by the students to present their daily routine in the preferred 2040. This made explicitly recognizable the macro-category related to routine. However, the high frequency of the macro-category does not only depend on the choice of presentation because even in the first part of the section the category was highly present. This suggests that for Group 4 the revision of the times structure of school was of fundamental importance.

Another category whose frequency differs a lot between the two groups is that related to the issue of students' anxiety toward school performance. If in Group 4 this macro-theme covers 3% of the presentation, this percentage grows up to 21% in Group 7. Observing the position in the presentation of the macro-theme, we notice that for Group 4 it is part of the introduction to the problem, alongside many other themes related to the role of pandemic, of school knowledge, and of technologies. In the following sections of the presentation, the issue is not touched again because they mainly focus on addressing the issue of technological innovation as a response to the problem of teaching methods. On the opposite, for Group 7 this macro-theme is more organically present in the presentation. The only problem they mention is the students' anxiety toward school and it is not surprising that, in describing their ideal future, this dimension occupies large parts of the section.

DISCUSSION

The richness of students' presentations at the end of the future-oriented activity is suited to many different highlights. We will discuss mainly two points that relate to the main themes of the special issue of which this paper is part.

Analyzing the students' presentations, it emerged very clearly the importance that the groups gave to the idea of equilibrium in the construction of the different scenarios. This was surprising because, if for the futures studies the concept of equilibrium is at the basis of the formulation of authentic scenarios (Greeuw et al., 2000; Kosow and Gaßner, 2008), this is difficult to be identified by novices reasoning on future-oriented issues. Indeed, in previous experiences within the ISEE project, the desirable scenarios imagined by students were always very extreme (Barelli, 2017). Indeed, the imagination of a desirable scenario triggered attitudes of detachment from reality that resulted in fictional, idealized futures that were static pictures of a future without any possible conflicts between interests or people. On the opposite, it is intrinsic to the notion of future scenario the description of a state of future equilibrium of the system. The equilibrium state, to be realistic, must foresee differences among interests and stakeholders, and circular interactions between agents in the systems. In previous studies, students' desirable scenarios gave back, instead, a picture of, metaphorically speaking, "thermodynamic equilibrium" where conflicts, interactions, and differences among the stakeholders were minimized (Barelli, 2017).

Even in an experience carried out with university students (Barelli and Levrini, 2021), the type of scenarios obtained lacked this aspect of equilibrium and the students felt they were not reliable since they exaggerated specific aspects of a problem. On the opposite, in the course with high-school students, we have observed that an accurate work on simulations (carried out during lessons 3 and 4 with the analysis of three simulations of reference and then with the establishment of correspondences with real-life issues) made it very natural for students to imagine scenarios of equilibrium, even if this concept had not been introduced explicitly. In the implementation with university students (that covered 6 hours of teaching instead of the 18 hours of the course with high-school students), the participants had been only introduced to the features of equation- and agent-based simulations, then they were left rather free of exploring NetLogo models in groups during the future-oriented activity. In particular, the activities of interactive analysis of selected NetLogo simulations and of analogies' development were not carried out. Hence, we can hypothesize that an in-depth analysis of the models offered by the instructor followed by hands-on experiments in the virtual laboratory of simulations allowed the students to elaborate their desirable scenarios either as interpolations between two extreme scenarios or as representations of the equilibrium behaviors displayed by the simulations in specific conditions. The resulting scenarios of dynamical equilibrium were authentically *sustainable*. Indeed, they included tensions between the needs of the present and those future generations, between traditions and innovations, and between practical requirements and desires (WCED - World Commission on Environment and Development, 1987; Murphy, 2012). Moreover, envisioning a complexity of tensions, they seem to accept the irreconcilability of the conflict (Weber, 1958) which also makes the scenarios reliable: for those groups that eliminated every form of conflict from their future, it appeared meaningless because utopian and impossible to be realized.

The second point that deserves discussion regards the emphasis given by the students to their own agency in the process of transformation of the school toward the desirable scenarios. The structure of the future-oriented activity was explicitly designed to make students reflect on their role as agents of change, able to impact the present in the light of their desires for the future. For example, in the back-casting phase, they were asked to identify the actions, decisions, or policies that occurred in the imagined timeline. In particular, they had to make explicit their role as agents in the path of changes from the present to the future they foresaw, as professionals, members of society, and individuals in general. Not only the future-oriented activity included an explicit request for students to reflect on agency, but also the whole course with its focus on the agent-based simulations underlined the importance of the individuals and their actions in the interaction with others to produce certain evolutions of the system. In this sense, the way toward agency had been paved throughout the module, both from the conceptual, the epistemological, and the societal perspectives.

However, the results achieved by the participants went over the expectations. In the future stories elaborated by the students, we clearly identified three dimensions of agency: the *public* (establishing a relationship with the institutions), the *professional* (involving the relationship with colleagues), and the *personal* dimension (carried out in the individual routine). These can be conceptually associated with the three "spheres of transformation" (O'Brien and Sygna, 2013; O'Brien, 2018) that are the practical, the political, and the personal. In this model, the practical sphere is usually associated with the idea of transformation throughout expertise and in our case is connected to the professional dimension of agency. Then, the political sphere can be linked to the public agency, since in both cases an impact on institutions and societal structures is implied. Finally, we have the personal sphere which is the most blurred of the three. Indeed, following O'Brien, this is the sphere "where the transformation of individual and collective beliefs, values and worldviews occur" (O'Brien and Sygna, 2013, p.6). In our case, students' words to describe this change cannot be explicitly associated with values and worldviews, because they are more linked to an aspect of routine and to a very local agency made of concrete actions. In some sense, the personal dimension of agency could be interpreted as another shade of the practical sphere of transformation.

CONCLUSION

In this paper we have shown how the future-oriented activity was for some students an opportunity to reason about the school they desire. During the presentations of their work, the students pointed out well-known problems that the current organization of the school is facing. Thematic analysis has been carried out to identify the main macro-themes which emerged from the presentations and the interviews. From the analysis of the groups' presentations, we found that the students suffer a great problem of anxiety about their school performance and imagine that this can be mitigated in the school in the future. They see the importance of the role of technology in school innovation but also that no innovation is possible if school knowledge is not re-thought of its times and forms. The students dream about a school as a place for relationships and that can become at the center of the youngsters' routine. In particular, we have pointed out that the students deeply recognize the power of their own agency and that of their teachers in the process of school transformation, and hope that the tragedy of a pandemic can be transformed into an opportunity to trigger change.

However, the school that the students imagine as their desirable one is not idealized as a utopia: like most of the other groups working on different topics, the participants were able to see a scenario—even the preferred one—as a complex interaction of many stakeholders and as a tension between opposite interests that the different agents have regarding a topic. Experimenting with the NetLogo simulation, the participants observed both divergence scenarios, in which for example a class of agents totally defeated the other, and equilibrium scenarios where a dynamical balance assured the sustainability of the system and its credibility.

The students' enthusiasm in reasoning about the school of the future demonstrated in the implementation described in this paper led us to design further activities in which the students were explicitly required to select, as a future-oriented issue, a problem related to the current school system and to analyze it with a simulation. This activity has been carried out both with prospective teachers and with high-school students and the results appear promising.

In the incipit of the paper, we stated how the history of computational simulations began in war times and dramatically contributed to catastrophic events of the past. It has been comforting for us, especially in these days when the world is shaken again by the fear of war, to see how, through future-oriented science education, these computational objects can become tools to dream about the future, not in a naïve way but in a sustainable—hence actionable—perspective.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: http://amsdottorato.unibo.it/10146/ (Barelli, 2022).

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of Alma Mater Studiorum – University of Bologna. All data discussed in this paper were collected and analyzed in compliance with the European Union's Regulation for Data Protection (GDPR) as made explicit in the Ethics Requirements of the FEDORA Project in which this research is framed. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

EB conceived and designed the study, collected the data, performed the analysis, and wrote the manuscript.

FUNDING

This study has been funded by the FEDORA (Future-oriented Science Education to enhance Responsibility and Engagement in the society of acceleration and uncertainty) Horizon 2020 Project. FEDORA has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 872841.

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Exploring Primary Preservice Teachers' Agency and Systems Thinking in the Context of the COVID-19 Pandemic

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OPEN ACCESS

Edited by:
Olivia Levrini,
Alma Mater Studiorum - University of Bologna, Italy

Reviewed by:
Neni Hermita,
Riau University, Indonesia
Milan Kubiatko,
J. E. Purkyne University, Czechia

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Specialty section:
This article was submitted to STEM Education, a section of the journal Frontiers in Education

Received: *04 February 2022*
Accepted: *22 June 2022*
Published: *12 July 2022*

Citation:
Uskola A and Puig B (2022) Exploring Primary Preservice Teachers' Agency and Systems Thinking in the Context of the COVID-19 Pandemic. Front. Educ. 7:869643. doi: 10.3389/feduc.2022.869643

The science education curriculum has become increasingly focused on the study of complex systems and on the development of agency so that students make decisions on relevant issues. The current pandemic has underlined the need to look at health from a systemic "One Health" approach, but little is known about the knowledge, skills, attitudes, and actions necessary for individuals to successfully contribute to One Health. This study seeks to contribute to this knowledge, and explores preservice elementary teachers' agency and systems thinking competencies to propose actions for preventing future pandemics from the One Health approach. The participants were 47 preservice elementary teachers working on a set of activities about the COVID-19 pandemic, in which they were asked about ways to prevent future pandemics. Content analysis of individual written responses was applied for addressing the level of systems thinking and the sense of personal and collective responsibility toward the action proposed. Results show that the preservice teachers initially referred mainly to actions in the human health dimension, and that the systems thinking showed a higher level when they made the activity in groups after reading information. Collectively proposed actions showed a lack of agency or individual responsibility compared to individually proposed ones. The implications of the results for science teaching are discussed.

Keywords: agency, COVID-19 pandemic, health education, One Health, environmental problems, preservice elementary teachers, systems thinking

INTRODUCTION

Science education faces urgent challenges related to health and environmental problems, as the current pandemic shows. During the COVID-19 pandemic, citizens all over the world were called upon to take actions and make responsible decisions to stop the spread of the disease. However, little information was aimed at putting this pandemic in context with the situation of emerging infectious diseases (Jones et al., 2008) or at explaining the factors that may promote its emergence, including environmental ones (World Health Organization [WHO], 2021). Human impact on the environment is increasing the risk of emerging infectious diseases in humans, over 60% of which originate from animals, mainly from wildlife. United Nations (UN) Secretary-General António

Guterres recently noted in a message to UNEA5 delegates that "the world's top environmental body needed to generate global will for action and a transformation of our relationship with nature" (United Nations Environment Programme [UNEP], 2021, p. 4).

Science education should address this issue (Zeyer and Kyburz-Graber, 2012), as it aims to develop critical citizens who make informed decisions about the problems they face. In fact, the experts preparing the PISA assessment program for 2024 (Organisation for Economic Co-operation and Development [OECD], 2020) made a reflection and defined a vision "based on the principle that scientific knowledge and competencies are important and valuable for young people's futures, but that identity outcomes (and the extent to which young people feel meaningfully connected to science, as critical consumers and producers of science in their daily lives) are also crucial for supporting agency and active citizenship in a rapidly changing world" (p. 2). This led the experts to recommend the creation of three new knowledge areas, one of which is 'Socio-environmental Systems and Sustainability' and the addition of two new competencies, 'Using scientific knowledge for decision-making and action' and 'Using probabilistic thinking.' Consequently, science education should enhance students to build scientific knowledge from a systemic view and to develop critical thinking skills for decision-making and responsible actions. Furthermore, it should help to create an identity, to foster values and to promote agency.

Citizens are expected to make decisions and take actions in these complex systems, not only to cope with problems they are facing in the present, but to prevent problems in the future. Science educators have started to incorporate the development of futures thinking, agency and action competence in science education (Levrini et al., 2021). Besides, in response to the COVID-19 pandemic, science educators around the world are working together to find ways to develop health literacy and critical thinking to understand this emergent disease and to avoid the rise of disinformation (Dillon and Avraamidou, 2021; Puig and Evagorou, 2022).

Despite this pandemic showing us the need to understand the links between human health and global environmental change, few studies have addressed the interactions between environmental, animal, and human health or the causes of the increase of pandemics (Lakner et al., 2021). COVID-19 is an emergent disease, and as such it can be characterized as a socio-scientific issue (SSI) that demands not only responsible citizenship skills (Dillon and Avraamidou, 2021), but also a systemic view of the different factors involved in this problem. The factors involved are manifold and condition both the emergence of epidemics and pandemics and their management, and concern all social, cultural, political and ecological spheres. Equipping students and teachers for these goals requires engaging them in activities that show the complexity of health problems when considered from a One Health perspective. According to Christensen and Fensham (2012), "the urgency and responsibility of including key SSIs that relate to social and environmental health in school science is so great that they cannot be avoided on these grounds" (p. 15). This study aims to fill this gap by engaging preservice elementary teachers in diverse activities that require to use systems thinking and to develop agency.

Systems Thinking in Health-Related Problems: The One Health Approach

The notions of systems and systems thinking have been defined in a variety of ways, which is reflected in the views of biology educators (Gilissen et al., 2020). However, there are several factors common to the different definitions. Thus, a system is understood to be made up of several parts that interact interdependently, such that any change in one part affects the others, and with a common goal: the functioning of the system (Ben-Zvi-Assaraf and Orion, 2005). On this basis, systems thinking is characterized by, among other things, identifying the different parts or components of the system, their processes or behaviors and the functions or phenomena resulting from these interactions (Ben-Zvi-Assaraf and Orion, 2005; Snapir et al., 2017). Systems thinking has been developed in science education, but mostly applied to natural systems, such as ecosystems (Hmelo-Silver et al., 2017; Mambrey et al., 2022), human body (Snapir et al., 2017), or geological systems (Ben-Zvi-Assaraf and Orion, 2005).

Science education curricula have become increasingly focused on the study of complex systems (Less, 2006), for example those which imply interactions between natural and social systems. The pandemic has shown us the importance of introducing a systemic view when addressing socio-scientific issues such as COVID-19. In a world characterized by uncertainty, individuals will need to think in a more integrated way that avoids premature conclusions and recognizes interdependencies (Organisation for Economic Co-operation and Development [OECD], 2018). Students will need to apply their knowledge and skills in unknown and evolving circumstances, as the current pandemic shows.

The systemic and holistic view is necessary to address issues related to sustainability (United Nations [UN], 2015) and health. Indeed, the Food and Agriculture Organization of the United Nations, World Organisation for Animal Health, World Health Organization [FAO, OIE, WHO], 2019) where they developed the One Health approach, which looks at the environment–animal–human system and specifically at the interactions between the parts of that system, that make that the health of animals, of the environment and of humans be interconnected and interdependent.

For centuries, scientists have recognized the close relationship between human, animal, and environmental health (Hutchins et al., 2014). Globalization and the emergence of infectious and zoonotic diseases that cause pandemics put into clear focus the importance of collaboration between scientists, health professionals and educators from diverse fields. This is the idea behind the One Health approach that this study supports. The term "One Health" is defined as the collaborative effort of multiple disciplines working locally and globally to obtain optimal health for people, animals, and our environment. This concept means that human health and animal health are interdependent and bound to the health of the ecosystems in which they exist.

Inger Andersen, Executive Director of UNEP, observed: "To end the triple planetary crisis of climate change, biodiversity loss and pollution that threaten our peace and prosperity, we must understand that human, animal and planetary health go hand in hand. We must do more to promote transformative actions that target the root causes of nature's destruction" (World Health Organization [WHO], 2021). The goal of One Health is to foster interdisciplinary, interinstitutional, and interprofessional collaboration locally, nationally, and globally to advance the well-being of people, animals, and the environment.

The One Health approach implies systems thinking, but no studies have been found in the literature review on this topic in a teaching/learning context related to this notion. Perhaps this is because it is a relatively recent term. However, some studies in the context of environmental education and/or Education for Sustainable Development (ESD) have dealt with systems thinking. Authors such as Hofman-Bergholm (2018) advocate introducing systems thinking in education as one of the keys to achieving sustainability: "Perhaps systems thinking, and systems education could be the missing tools needed to develop the holistic thinking required in the work toward a sustainable future." (p. 3). The United Nations Educational, Scientific and Cultural Organization [UNESCO] highlighted the need for developing systems thinking in ESD activities and programs both in the final report of the UN Decade of ESD (2005–2014) (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2014) and in the roadmap for 2030 for the future of ESD (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2020). Indeed, several proposals to define the competencies for ESD that educators should have also make explicit reference to systems thinking (Sleurs, 2008; United Nations Economic Commission for Europe [UNECE], 2012). Nevertheless, teacher trainees have shown deficiencies in systems thinking. For instance, in Palmberg et al.'s (2017) study, three quarters of the 424 Nordic teacher trainees showed no evidence of systems thinking when relating species identification, biodiversity, and sustainable development. This study seeks to contribute to empirical research on systems thinking in the context of applying the notion of One Health to propose actions to prevent pandemics like COVID-19.

Action Competence and Agency

Funtowicz and Ravetz (1993) introduced the concept of 'postnormal' science and stated that in the case of socio-environmental systems, which entail high levels of risk and uncertainty, individuals' values are fundamental, not secondary, elements. In this scenario, experts and non-experts have a more balanced power of decision-making, given that there are no definitive solutions endorsed by science. In the face of an increasingly uncertain and complex world, both science education and environmental education can help students embrace the challenges we are confronted with, as the current pandemic shows. The OECD Education 2030 project (Organisation for Economic Co-operation and Development [OECD], 2018) contributes to the UN 2030 Global Goals for Sustainable Development, aiming to ensure the sustainability of people and the planet.

Education has a vital role to play in developing the knowledge, skills, attitudes, and values that enable people to contribute to and benefit from an inclusive and sustainable future. Students need to practice agency and to develop action competence in the science classroom. Agency is a term whose theoretical meaning is often defined too narrowly and unclearly (Oliveira et al., 2013). In this paper, we draw from the definition of agency provided by Levrini et al. (2021), who consider it as the capacity to take responsibility for global challenges, take part in decisions and consciously influence events and circumstances to realize the desired future scenario. Therefore, the notion of agency involves a sense of responsibility to participate in the world and, in so doing, to influence people, circumstances and events for the better.

Agency and action have gained prominence during the current pandemic; however, they have been an object of concern for environmental education for a long time. Several Danish environmental educators (Breiting, 1997; Jensen and Schnack, 1997) called for environmental education being directed toward training for action and considering the conflicts of interest entailed by every environmental problem. In this way, the abilities to think critically, to clarify one's own values, to put oneself in somebody else's shoes, to discern the data on which an argument is based, to decide, and to act in consequence become the fundamental educational objectives to be pursued. Jensen and Schnack (1997) fostered the concept of action competence, associating competence with the ability and desire to be a qualified participant, and emphasizing the intentionality of actions to distinguish them from behaviors, activities, and habits. They counterposed the search for action competence to the search for behavioral change, a primary objective of most current environmental education activities and programs. In behavior-changing activities, educators decide what is the best behavior for the good of the environment, basing their decision on the certainty of scientific analyses, without considering other factors, such as the values of the individuals involved. Researchers (Funtowicz and Ravetz, 1993) and educators (Bonil et al., 2004) concerned by the complexity of scientific issues indicate that if the activity is successful, the participants will demonstrate appropriate behavior, but it is unlikely that they will have developed the competence to act in response to new problems or to jointly construct a sustainable society.

In contrast, in the activities designed to train for action the educational process is more important than the product. From this perspective, the educator should not direct his or her efforts toward achieving a specific change in behavior, but rather he/she should facilitate scenarios that can develop students' abilities in a way that enables them to decide, using their critical thinking skills, what direction change should be taken in a democratic way. The aim, consequently, is to develop "a critical, reflective and participatory approach in which the future adult can cope with environmental problems in a democratic way, instead of prescribing to pupils certain behavioral patterns here and now that we believe contribute to solving current environmental problems" (Mogensen and Mayer, 2005, p. 14).

Building on the OECD 2030 Learning Framework (Organisation for Economic Co-operation and Development [OECD], 2018), we agree that science education should prepare students to be change agents, which implies that they can have a positive impact on the environment and anticipate the short and long-term consequences of what they do. According to Hodson (2003), action competency requires the mobilization of knowledge, skills, attitudes, and values to meet complex demands. Thus, students should learn how to engage and experience participation in action. Students' consciousness of a problem and the causes is based not only on their opinions and motivation, but also on their views and commitment (Chen and Liu, 2020). Pedagogical strategies for positioning students as agents vary widely with school subject, but are socio-culturally mediated, as Oliveira et al. (2013) pointed out. These authors propose a model of environmental agency in which agency is not strictly inside the mental processes of individuals, rather environmentally protective behavior emerges in students' sociocultural interactions with existing environmental social structures. Furthermore, research in action emphasizes the importance of distinguishing learning *about* action, *through* action, and *from* action. This study attends to the first perspective, although we support that the three can be enhanced. This study seeks to engage students in the process of proposing actions that can help to avoid/prevent future pandemics. We want to make students conscious of their own actions and reflect on the ones that alter positively or negatively human, animal, and environmental health. According to Hodson (2003), substantive knowledge, guided toward action, is crucial to understand the issue underlying a problem and to make informed decisions and arguments. In the context of proposing actions for avoiding future pandemics, we view knowledge on the One Health notion and systems thinking as critical, as explored in the previous section.

The research questions are:

RQ1. What actions proposed by preservice teachers to avoid future pandemics such as COVID-19 integrate systems thinking? To what extent do individual actions differ from collective actions regarding systems thinking?

RQ2. How do actions proposed by preservice teachers to avoid future pandemics such as COVID-19 reflect a sense of responsibility or agency? To what extent do those proposed collectively differ from those proposed individually?

MATERIALS AND METHODS

Context and Participants

The activities were designed and implemented in a course that started in September 2021. The participants were 47 pre-service elementary teachers – 28 females and 19 males – in the fourth year of their Primary Education Degree (typically undertaken at 22 years old) at a Spanish university. The number of COVID-19 cases was falling, and the majority of the population was vaccinated, although at the beginning of the course the teaching modalities were adapted so that half of the students were at home attending the classes by videoconference. At the time of the implementation of the activities, all students attended classes on site.

The activities on the origins of epidemics and pandemics lasted a total of 3 h and took place over the course of one session. First, preservice teachers answered an open-ended questionnaire about pandemics. Secondly, they were provided with information by means of popular science articles about the emergence of epidemics and the link between environmental problems and zoonosis. In small groups (11 groups, named A–K), they made a conceptual map of the origins of pandemics and proposed actions to avoid future pandemics.

Research Tools

For this study, the actions proposed by preservice teachers in two activities were considered, namely the individual answers of one question included in the initial individual questionnaire and the actions proposed by small groups. The question "*What can we do to prevent another pandemic? Describe in your own words the concrete actions we can take*" sought to get preservice teachers to situate their thinking in complex cause-and-effect relationships (Ossimitz, 2000; Ben-Zvi-Assaraf and Orion, 2005) and placed the question in what Ossimitz (2000) argues is one of the most fundamental elements of systems management; namely, thinking about which components of the system are possible subjects of direct change through changing one's own behavior, which is linked to agency.

All participants gave informed consent for their answers to be used as research data. The names used for preservice teachers are not their real names, but pseudonyms. Preservice teachers with a pseudonym starting with the same letter are from the same group.

Data Analysis

Given the nature of the research questions, the study was mainly based on the interpretative analysis (Erickson, 1986) of data of a qualitative nature. To address RQ1, individual and collective written responses were coded in two categories of systems thinking, according to Ben-Zvi-Assaraf's and Orion's (2005) proposal: (a) Components of the system (One Health dimensions) and (b) Interrelations between the components of the system (One Health dimensions). In this case, the phenomenon would be the increase in epidemics, and the interrelations, the processes of generation and release of new viruses, the processes of transmission of viruses (between animals, between animals and humans, and between humans), and the processes that make increase or decrease of the latter, such as deforestation, the movement of animals, the movement of people, or socio-economic activities, among others. Preservice teachers' answers regarding the establishment of interrelations were assigned to a level, considering the allusion to dimensions other than the human one (that is already implicitly included in the topic of pandemics), and the justification of the relationships between the One Health dimensions. These three levels were established:

Level 0: Includes the responses that only referred to the human dimension, which means that students were not able to identify environmental and animal as dimensions that need to be considered to prevent future pandemics.

Level 1: Includes the responses that alluded to other dimensions besides the human one. This could be done by explicitly referring to actions in various dimensions or by referring to the environment or animals when asked about human health-related issues. Although these answers did not explain the interactions between the dimensions mentioned, they implicitly interrelated them.

Level 2: Consists of responses that, besides fulfilling the criteria for being in level 1, justified the interrelations between the different dimensions (two dimensions or three) of the One Health notion.

The first author identified the One Health dimensions to which preservice teachers referred in their writings, and, after applying a constant comparison method (Lincoln and Guba, 1985) to the data, emergent categories were established into the dimensions. The second author revised the categories and results. Disagreements were discussed to reach a consensus.

To address RQ2, individual and collective proposed actions were categorized as Indirect actions and Direct actions. Indirect actions are considered actions one cannot take alone, since they depend on others, such as political agendas and institutions, to do so. Direct actions are actions that preservice teachers can carry out themselves, thus they do not depend on others. For instance, to wear a mask, to recycle, to eat less meat. Following Granit-Dgani et al. (2017), two subcategories were identified within this according to the sense of personal and collective responsibility toward the action proposed. For this, attention was on how the writing responses reflected the construal of identity by using the first-person single and/or plural. Thus, the category of direct actions was divided into (a) *direct implicit actions*, which corresponded to actions that did not show participants' explicit awareness of being agents for the action proposed as they did not use the first-person; (b) *direct explicit actions* includes actions proposed by preservice teachers using the first-person, which means that they showed an explicit awareness of being agents for the action.

RESULTS

Integration of Systems Thinking in the Actions Proposed by Preservice Teachers

The analysis of RQ1 *What actions proposed by preservice teachers to avoid future pandemics such as COVID-19 integrate systems thinking? To what extent do individual actions differ from collective actions regarding systems thinking?*, is developed in this section. First, we review data on the types of actions proposed individually and then we compare individual proposals with collective ones.

A total of 111 actions were proposed by preservice teachers in their individual responses: 81 (73%) related to the human dimension, 23 (20.7%) to the environmental dimension, and 7 (6.3%) to the animal one. Indeed, 90.7% of preservice teachers proposed at least one action linked to the human dimension, 27.9% to the environment, and 16.3% to the animal dimension.

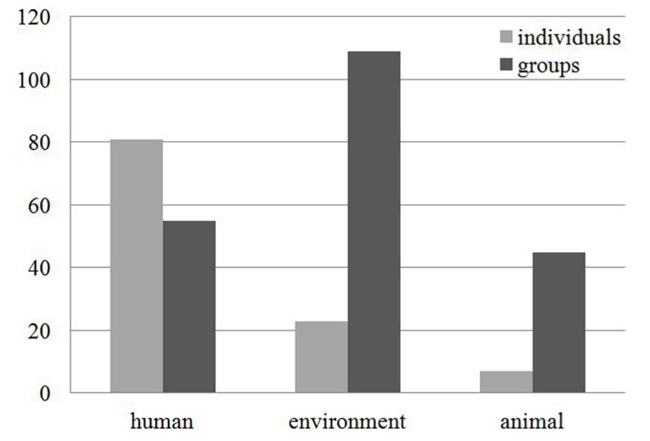

FIGURE 1 | Frequency of actions proposed individually and in groups by preservice teachers to avoid future pandemics, by the corresponding One Health dimension.

The excerpt below shows an example of the human dimension when a student, Jon, appeals to reducing socialization as a measure to avoid another pandemic such as COVID-19.

> "To avoid another pandemic, activities that promote the socialization of people must be reduced (...)." [Jon]

An example of two dimensions, environmental and animal, is reflected in the following response.

> "I believe that not everything is in our hands. Even so, reducing pollution, changing habits (using public transport or bicycles for example), taking care of the landscape and animals, etc. would partly prevent pandemics." [Blanca]

Blanca mentioned diverse factors including taking care of the landscape and animals, which is related to both dimensions. In her answer she referred to these actions as personal actions that can partially prevent pandemics such as COVID-19.

The distribution of individual and collective responses in the One Health dimensions is shown in **Figure 1**.

Actions proposed in small groups were higher in number compared to individual ones; 209 actions were identified. Besides, all groups proposed at least one action in all three dimensions (human, environment, animal). With respect to the consideration of interrelationships among the One Health dimensions, **Table 1** summarizes the results, both for individual and for group proposals.

Level 0. No interrelation: most individual responses were included in this level, since they did not mention other dimensions apart from the human one, implicitly included. We did not identify any group responses at this level. An example of an individual response is the one given by Carmen, which considered globalization and research in laboratories, both in the human dimension:

TABLE 1 | Percentage of individual and group proposals in each level of performance in interrelationship-identification among the dimensions of the One Health approach.

Level	Types	% preservice teachers	% groups
2 Justified interrelation	Total	0	18.2
	Animal	0	18.2
1 Implicit interrelation	Total	32.6	81.8
	Environment–animal–human	9.3	81.8
	Environment–animal	2.3	0
	Environment–human	14	0
	Animal–human	4.7	0
	Animal	0	0
	Environment	2.3	0
0 No interrelation	Only human	62.8	0

> "Reduce globalization, especially in unnecessary global activities. Take more care in research, especially research into diseases." [Carmen]

Level 1. Implicit interrelation: Most individual and group responses are included in this level, although some differences are identified regarding the capacity to integrate the three dimensions of One Health. All group responses mentioned the three dimensions, whereas just a proportion of students were able to do it individually.

The human and the environmental dimensions together are the most frequently mentioned by preservice teachers (14%), as **Table 1** shows. An example is the response of Daniel, who mentioned human dimension actions as experimenting with viruses, or reducing travel between countries, but also considered pollution and natural spaces:

> "Take care of natural spaces, don't pollute so much, reflect on our way of life, don't experiment with viruses. As soon as a new virus appears, stop tourism and relations between countries until it is eradicated." [Daniel]

Individual proposals that mentioned the three dimensions (environment–animal–human) were also present, and some are provided below:

> "I believe that to avoid any kind of pandemic, we have to act more responsibly, observing the consequences of our activities and trying to change them; recycle; use cars that pollute little; carry out awareness campaigns; teach the children who come after us to act responsibly; do not use animals for experiments. In conclusion, we must start taking care of the environment and we can start at home and in our neighborhood. In other words, we can do our bit." [Carol]

> "We need to recycle, and use litter bins; reduce air pollution, and use public transport; implement minimum hygiene measures; more testing of animals, especially wild animals; in case of illness, go to the doctor so as not to infect others; have safety measures in each country and ensure that people comply with them. For example, if masks are compulsory, accept to wear them even if we don't like them." [Irati]

Carol and Irati referred to environmental actions such as recycling, using cars that pollute little or public transport, and actions in the animal dimension such as not using animals in experiments. They also proposed human health measures such as using masks.

Although participants were able to mention the different dimensions individually, they were not able to justify the interrelations between them, as **Table 1** shows. The analysis of collective responses provides similar results; however, some groups did justify the interrelationship when formulating collective actions. For example, Group G when proposing an action linked to animals:

> "Reducing demand for and regulating international trade in live animals, meat and fish products in order to reduce species movements, disease transmission and the development of new pathogen-driver relationships." [Group G]

Students pointed to animal consumption and trade in live animals as potential causes of disease transmission, thus they proposed the reduction and regulation of international trade as measures for preventing future pandemics.

Agency in Actions Proposed by Preservice Teachers

In this section, RQ2 *How do actions proposed by* preservice teachers *to avoid future pandemics such as COVID-19 reflect a sense of responsibility or agency? To what extent do those proposed collectively differ from those proposed individually?* is addressed. Results obtained regarding direct and indirect actions and the integration of agency are first presented, and then individual and group responses are compared in these terms.

The analysis shows that most actions proposed by preservice teachers individually at the beginning of the task were *direct actions*. Particularly, 68.5% were direct actions ($N = 76$) whereas 31.5% ($N = 35$) were *indirect actions*. Considering the examples given above, appealing for controlling experimentation with viruses would be an indirect action, as it is not something they can do themselves, but reducing pollution is a *direct action*, as they can directly contribute to reducing pollution in their day-to-day actions.

Among the *direct actions*, 60% were *direct explicit actions*, since they were formulated using the first person, and the rest were *direct implicit actions*. The following examples illustrate these different types. Jon appealed for reducing socialization activities but Gorka places that same action within his sphere of responsibility.

> "To avoid another pandemic, activities that promote the socialization of people must be reduced (...)." [Jon]

> "At the individual level, we should strictly follow the steps of the scientists, such as avoiding crowds." [Gorka]

Similarly, Belen considered taking care of hygiene, but Gurutze made explicit which everyday actions she could take to maintain hygiene.

> "In the same way, it can also be useful to take better care of hygiene and health around the world, both for people and animals." [Belen]

> "To avoid a new pandemic, we have to take care of our hygiene first and foremost. That is, we should clean our hands before eating something or after touching something, before putting them to our face, and before putting them to our hands." [Gurutze]

It needs to be highlighted those results are different for each dimension. Regarding the human dimension, more than 2/3 of the actions were *direct actions* (57% of them explicit) and all of them corresponded to pandemic measures dictated by governments to prevent infection by COVID-19 and transmission. It includes wearing a mask (as seen in the Irati example), maintaining hygiene and keeping a safe distance:

> "We can do many different activities. On the one hand, we can take care of our habits, especially those related to hygiene. In fact, taking care of cleanliness can stop the spread of viruses like this one." [Borja]

Regarding the environmental dimension, all actions were direct (74% of them explicit) and made reference to recycling (as seen in Carol's and Irati's examples) or taking care of the environment.

In contrast with these results, for the animal dimension, the majority (71%) proposed *indirect actions* and appealed to not carrying out experiments on animals (as in the examples of Carol and Irati). Direct actions (29%), all formulated implicitly, referred to caring for the health of animals, as in the case of Belen.

> "In the same way, it can also be useful to take better care of hygiene and health around the world, both for people and animals." [Belen]

When we compare individual proposals to collective proposals some differences are identified. Particularly, in the case of the 209 actions proposed by the groups, 79% were indirect, much more than in the case of individual actions (31.5%). Besides, indirect proposals accounted for the majority in all dimensions (96% in the human dimension, 68% in the environmental dimension and 84% in the animal dimension). Some examples of *indirect actions* proposed by groups are shown below, such as accelerating the energy transition (Group A), facilitating telework (Group C), changing the production of food (Group E), investing in infrastructures (Group G) or giving grants to low-income countries (Group J), all of them outside their field of action:

> "Accelerating the energy transition to a carbon-free economy." [Group A]

> "Install broadband networks that facilitate telework and telemedicine to help us build a society where we do not accumulate in unhealthy spaces and where income is not related to geography." [Group C]

> "Changing the way, we produce food." [Group E]

> "Increase investment in animal and health infrastructure, care, information and coordination." [Group G]

TABLE 2 | Percentage of preservice teachers and groups that proposed actions of each type.

		% preservice teachers (*N* = 43)	% groups (*N* = 11)
Direct explicit actions	Any dimension	55.8	36.4
	Human	44.2	9.1
	Environment	23.3	36.4
	Animal	0	0
Direct implicit actions	Any dimension	44.2	100
	Human	37.2	9.1
	Environment	11.6	100
	Animal	4.7	63.6
Indirect actions	Any dimension	55.8	100
	Human	48.8	100
	Environment	0	100
	Animal	11.6	100

> "Grants to low-income countries to prevent new infections and find solutions to infections such as vaccines, medicines, ..." [Group J]

With respect to direct actions, only 11% were coded as *direct explicit actions,* written in first person.

Table 2 shows the percentage of preservice teachers (initial) and groups (collective, after reading) that proposed actions of each type. Since all types of actions given by each individual or group were counted, the sum is greater than 100.

Table 2 shows that the percentage of preservice teachers in each type was around 50%. Slightly under half of preservice teachers proposed *direct implicit actions*, and just over half proposed indirect actions and *direct explicit actions*. In the case of groups, all groups proposed *indirect actions* and *direct implicit actions* whereas just over one third of the groups proposed *direct explicit actions*, which accounted, as previously mentioned, for 11% of the total of 209 actions.

DISCUSSION

Regarding RQ1, the results of the individual initial actions proposed by participants show that initially referred mainly to actions in the human health dimension. Among these, most preservice teachers mentioned wearing masks, keeping distance, etc. They made reference to the cultural aspects and differences worldwide that actions such as maintaining social distance or changing eating habits imply. Nevertheless, they hardly mentioned actions linked to environmental or animal health. These results are consistent with the guidelines provided by governments to citizens to act against the current pandemic and reflect the low media coverage and studies disseminated to the general population on these dimensions in relation to the emergence of pandemics (Lakner et al., 2021).

It is significant that the results obtained in this study are very similar to the ones obtained 1 year before with another group of preservice teachers from the same university (Puig and Uskola, 2021). Indeed, we could say that they tend to be even more marked toward the human dimension, showing a very simple vision about the pandemic, compared to the complex systems thinking implied in the One Health notion. Indeed, the preservice teachers performed at a beginner level according to the levels of systems thinking proposed by Hmelo-Silver and Pfeffer (2004), who categorized low-level systems thinking by novices as thinking focused on structural components, particularly the visible ones, which in the case of our study would correspond to those of the human dimension, which corresponded to 73% of the actions proposed initially. Moreover, the 32.6% of preservice teachers that linked human health to environmental or animal health only mentioned the dimension (component) but did not justify the interrelation. Other studies that analyzed systems thinking of students about the human body (Snapir et al., 2017), the rock cycle (Kali et al., 2003), or other geological (Ben-Zvi-Assaraf and Orion, 2005; Baztri et al., 2015) or biological systems (Hmelo-Silver and Pfeffer, 2004), showed better results, which suggests that the context of the pandemic was challenging for participants. Our results are similar, although lower, to those obtained by Palmberg et al. (2017) with preservice teachers. The context, tasks and analysis tools had differences but in sum both studies point to the difficulties shown by pre-service teachers with systems thinking. The report made by United Nations Educational, Scientific and Cultural Organization [UNESCO] (2014) pointed out the challenges of ESD in primary-secondary education and the lack of ESD educator competencies, one of which is systems thinking (Sleurs, 2008; United Nations Educational Scientific Cultural Organization [UNECE], 2012).

The analysis of actions proposed by groups after they have accessed information shows that the groups performed at a higher level than the individuals initially. Thus, all groups included the three dimensions of the One Health notion. They were also able to justify the interactions between them. This reveals that working in small groups and discussing information on the environment, animal and human health improves students' ability to make relationships between them, making it possible to overcome the difficulties inherent in explaining the interrelationships among diverse dimensions, and explaining causal relationships between actions and their consequences (Hmelo-Silver and Pfeffer, 2004). The importance of working in teams for systems thinking was also highlighted by Gray et al. (2014). Nevertheless, the percentage of groups that justified the interrelations was still quite low at the end, which shows that the systems thinking of preservice teachers has much room for improvement in terms of being aware of and explaining the mechanisms and how they lead to the phenomenon.

In relation to RQ2, the actions proposed by preservice teachers to avoid future pandemics such as COVID-19 reflected a sense of responsibility or agency at the beginning of the task before information on COVID-19 was provided. Most of them proposed *direct explicit actions* related with the human and environmental dimensions, but not for the animal dimension, in which a sense of agency did not emerge from their individual responses. They seemed to understand animal actions as measures that do not depend on them, but on others, since they only mentioned experimentation with animals as an activity to avoid future pandemics.

Actions proposed by groups were higher than individual ones, but in contrast with them, the majority were *indirect actions* or *direct implicit actions*, which reflects a lack of agency or individual responsibility. These results might be influenced by the information provided, which makes reference to the environment and animal dimensions. Groups did not mention human health measures such as wearing masks, avoiding crowded places and keeping a safe distance, as they previously did individually. Instead they focused attention on the information from the texts provided. Furthermore, it needs to be acknowledged that this information suggested indirect actions since it referred to a higher investment in health infrastructure and changes in economic models that depend on companies and institutions, among other issues. That is, political and economical factors where salient in the information, and it seems that preservice teachers perceived them as external more than internal. Another factor that might explain these differences between individual and group proposals might be the effect of dilution of responsibility and identity when working in groups. Students might think about common responsibilities and identify themselves with the group rather than with their own views. Besides, the student that wrote the final response might have adopted the role of secretary of the group, thus he/she did not transfer their own identity to write in first person. We acknowledge that the use of the first person can be conditioned by such circumstances and that this is a limitation of the study, but we consider that its use denotes a greater personal implication than the use of the third person or impersonal forms (Granit-Dgani et al., 2017).

In summary, the information provided and working in groups helped students to consider more dimensions and to link them; however, the level of responsibility or agency reflected in their answers was low or even absent.

CONCLUSION AND IMPLICATIONS

According to the OECD Framework 2030 (Organisation for Economic Co-operation and Development [OECD], 2018), science education should prepare students to be change agents, which requires equipping teachers for this purpose. This study was carried out within a project about how to best equip pre-service teachers to develop agency and the notion of One Health to address health and environmental problems such as COVID-19.

The analysis of RQ1 allows us to conclude that students were able to integrate and justify the three dimensions of the One Health notion when information was provided and discussed in groups. This means that systems thinking can be promoted under these circumstances. We share the reflections of other authors on the need to change some aspects of teacher education. Rosenkränzer et al. (2017) studied the impact of different interventions for fostering pedagogical content knowledge for teaching systems thinking and their conclusion was that a technically oriented course without didactical aspects seemed to be less effective. They propose a course with mainly didactical content and an intervention with a mix of technical and didactical content. One of the recommendations is introducing activities that facilitate overcoming the traditional organization of the curriculum in the form of separate academic disciplines (Gray et al., 2014; Hofman-Bergholm, 2018). In addition, activities that require group or teamwork (Gray et al., 2014) should have a strong presence in teacher education, as the results of this and previous research suggests this facilitates systems thinking.

Regarding the presence of agency in students' proposals to avoid future pandemics, it is remarkable that group proposals, after the analysis of information, reveal a lesser sense of agency compared to individual ones at the beginning of the task. To help students to enable agency, educators must attend to the different factors that influence its exercise and learning; for instance, the interactions and relationships among students that help them to progress toward the identification of actions to influence people and circumstances for the better. A concept underlying the OECD Learning Framework (Organisation for Economic Co-operation and Development [OECD], 2018) is "co-agency," defined as the interactive, mutually supportive relationships that help learners to progress toward their valued goals. We consider that the sense of co-agency could be mediated by students' identities, values, and attitudes (e.g., empathy, respect for other opinions and views), so these aspects need to be considered when designing activities that engage students in the development of agency through action proposals.

The results of this study point to the need for designing activities that stimulate students' engagement in co-agency (Reis, 2020) when working in small groups. Developing the sense of co-agency might favor students' engagement in actions to protect human, environment, and animal health. Promoting students' agency requires developing from them a sense of responsibility, as Levrini et al. (2021) proposes.

This paper attends to the first steps of a wider project about primary pre-service teachers' training on health and environmental problems such as COVID-19 from the One Health approach. Research regarding teachers' training for this goal is in progress and it requires different cycles of data collection. The current pandemic of COVID-19 emphasizes the need to incorporate co-agency, which aims to make students take responsibilities on the decisions and actions that affect human, animal, and environmental health.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee for Research on Human Subjects of the UPV/EHU CEISH-UPV/EHU [M10_2021_161 research project, approved 20 May 2021 (138/2021)]. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

FUNDING

This research was developed within RODA research group (Ref. ED431C2021/05) and was supported by ESPIGA project, funded by the Spanish Ministry of Science, Education, and Universities, partly funded by the European Regional Development Fund (ERDF) (Grant Code: PGC2018-096581-B-C22).

ACKNOWLEDGMENTS

We acknowledge the contributions of all participants.

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frontiers | Frontiers in Education

TYPE Original Research
PUBLISHED 08 August 2022
DOI 10.3389/feduc.2022.850016

OPEN ACCESS

EDITED BY
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SPECIALTY SECTION
This article was submitted to STEM Education, a section of the journal Frontiers in Education

RECEIVED 07 January 2022
ACCEPTED 27 June 2022
PUBLISHED 08 August 2022

CITATION
Lloyd D and Paige K (2022) Learning science locally: Community gardens and our future.
Front. Educ. 7:850016.
doi: 10.3389/feduc.2022.850016

Learning science locally: Community gardens and our future

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The wholistic nature of gardening is an approach to learning that provides opportunities to place science education in a context that also values other ways of knowing and draws on the cognitive, the affective and the spiritual—knowing, feeling, connecting. This paper offers a case study of teaching gardening to primary students at The Old School Community Garden (TOSCG), in the Adelaide Hills, South Australia. As experienced science educators, we find that engaging young people in gardening provides them with the opportunity to see the world as a whole, learn science concepts while also addressing local issues such as organic food production. Our focus in this project is the use of the garden as a learning place for Year 1 students (aged 6–7) working with Year 4 students (aged 9–10). We also argue that nature teaching is part of the answer to liveable futures in this time of climate change, pandemics, and the possible crossing of other Earth boundaries. These challenges require educators to focus on futures thinking and transdisciplinary approaches in order to develop the dispositions needed to live in the present with a well-formed idea of where we want to go. Learning the science of gardening is clearly a central aspect—soil science, biological science, ecosystem management and a sustainable food supply.

KEYWORDS

science education, futures thinking, community gardens, transdisciplinary, eco justice

Introduction

The value of community parks and gardens throughout history, and particularly in present and future times, has been well documented (Roseland, 2012; Murphy, 2014; Lloyd, 2015). They can be sites of cultural and social activity as well as places of practical small-scale food production which contribute to the sustainability, resilience, and flourishing of communities (Franklin et al., 2011; Gaylie, 2011; Payne, 2015). The development of the Old School Community Garden (OSCG) is taking place at a time of globalization, where our planet is reaching social, environmental, and economic limits. This is a situation which we may not be able to solve in an ideal way, but which we may survive. Eckersley (2012) encouragingly suggests that "there is still plenty to dream of, and to strive for" (p. 22).

To achieve a sustainable society in harmony with Earth's ecosystems, educators and educational policymakers will have to rethink the curriculum and adopt a different approach to teaching and learning (Bentley, 2010; Barker and McConnell Franklin, 2017). We need to develop curriculum and pedagogy that integrates humans more fully with the rest of nature and that develops a disposition for living in the present while planning for sustainable futures. As Berry (1999) argues, "We are not here to control. We are here to become integral with the larger Earth community" (p. 48). It is important for science education, and for transdisciplinary learning more broadly, to promote educative experiences where students contemplate the beliefs, interests, and feelings of others impacted by environmental socio-scientific issues. "Learners can form an intrinsic connection with nature, in the sense that nature should be afforded similar intrinsic value and justice, that is extended to people" (Herman et al., 2018, p. 2). Given the opportunity, students will see themselves as part of their nature world–likely more affectively and spiritually, than cognitively. Such an approach to science and environmental education is often hard to achieve, moving past, while drawing upon, the knowledge work of the disciplines that have more traditionally comprised science education. Participating in community gardening offers a significant opportunity for developing and illustrating the complexity of a futures-oriented science education.

The Old School Community Garden (TOSCG) is a public garden developed on the former site of the Stirling East School, in the Adelaide Hills (Mt Lofty Ranges), South Australia. This paper is built around the experiences and learning of young students who have been visiting the garden as part of their schooling in order to grow vegetables and plant indigenous trees and shrubs, with the primary aim of preparing them to care for and restore Earth's degraded and exploited ecosystems.

We start by drawing on our own experiences as educators, gardeners, and parents. Together, we bring over 100 years of experience in environmental science education. Our own stories describe what impacted on us in our early years, and what experiences have contributed to our passion for an eco-active curriculum. Clandinin and Connelly (2000) argue that "life is filled with narrative fragments, enacted on storied moments of time and space, and reflected upon and understood in terms of narrative unities and discontinues" p. 17. It is for this reason we have woven our early life and education stories through this paper. As "elders," our intention is to reflect on our evolving understanding and journey, and to leave a legacy for those picking up the baton for the future. We work from the ethical position that our generation should leave a world worth passing on to our grandchildren and theirs.

The authors are two "retired" academics from the University of South Australia with environmental science and futures studies backgrounds. We have taught pedagogical courses for science and mathematics, including environmental science and integral studies. We have worked particularly with pre-service teachers aiming for careers in primary and junior secondary education.

David Lloyd

I was born in Ormskirk, a market town in Lancashire, England, during the Second World War—a time when community gardens (allotments) became a necessity. After the war, my family immigrated to South Australia, where I attended schools in the metropolitan area. A teaching scholarship enabled me to complete Education and Science degrees which led to a career teaching secondary school general science and chemistry. After further study (MSc and PhD), I spent fifteen years lecturing at the University of South Australia. Throughout my schooling, I developed a love for the natural world through adventures in Adelaide's Mt Lofty Ranges. Later in life I enjoyed caravanning and camping with my family and friends and, of course, vegetable gardening for my family at home. I became an enthusiastic member of TOSCG and have worked with local primary school teachers who visit the garden with their classes. My academic work, and my understanding of the importance of living as part of nature through my connection with it, motivated me to explore many aspects of our environment and I became concerned with the way it is being used and (mis) managed. My grandchildren have a lot of work to do to repair natural ecosystems and to hopefully live in a vibrant, sustainable, and nature-filled world.

Kathryn Paige

I was born and raised in Berri, a rural agricultural town along the River Murray, South Australia. This river system is a major source of domestic and environmental water and, while the rhetoric was that there was sufficient for everyone, I remember brown water baths and being constantly mindful of the preciousness of water and the precariousness of the river flow. As a well-educated white woman of privilege, I am conscious that my "lot" have used more than our share of Earth's resources. The 70s were the times of Vietnam war, hippies and living simply. At Teachers College, our ecology lecturer inspired us to participate in frog counts (as a measure of healthy water systems) and to march down the main street of Adelaide chanting "ban the can" in a campaign that resulted in a deposit scheme for soft drink cans which remains to this day. Through my 17 years teaching in primary classrooms and 25 years educating future primary/middle teachers, I always strived to "walk the talk," reducing my carbon footprint through recycling, replacing single use items with reusables, cycling rather than driving wherever possible, planting trees, and gardening (later guerrilla gardening).

It is these educational and life experiences we bring to this community garden project. Using the community garden as a case study, we explore sustainable and transdisciplinary educational practice with two classes of school students who regularly engage with gardening. As experienced science educators, we find that engaging young people in gardening provides them with the opportunity to see the world as a whole, learning science concepts while also addressing local issues such as organic food production. Our focus in this project is the use of the garden as a learning place for Year 1 students (aged 6–7) and Year 4 students (aged 9–10) as they learn to live locally and make wider community connections. Data from primary students and teachers involved in learning in the community garden provide insights into their experiences. It orients also to a set of eco-justice principles which are then used to inform a curriculum structure for liveable futures and for teacher educators to develop.

Science education for environmental and futures learning

Children's understanding of science is acquired from early interaction with the world. Through play and their everyday experiences children are developing the own ideas about how the world works (Howitt, 2022). Building on children's natural curiosity in nature and embracing sustainability and futures thinking is an approach to science education many teachers are adopting. Sustainability is not just another issue to be added to an overcrowded curriculum but a gateway to a different view of pedagogy, of organizational change, of policy and particularly of ethos (Sterling, 2001; Gilbert, 2016).

In the Australian Curriculum, Science is one of eight learning areas. It has three substrands, Science understanding, Science Inquiry Skills, and Science as Human Endeavor. It is intended that these three substrands are interwoven together and science in the community garden is the perfect vehicle. It is the Science as Human Endeavor Substrand that highlights the importance of science in contemporary decision-making and problem-solving, as well as cultural, ethical and social implications to be taken into account (Australian Curriculum Assessment and Reporting Authority [ACARA], 2022). In addition to the learning areas Australian Curriculum has two other components, General Capabilities and Cross Curriculum Priorities which includes sustainability. Pedagogies which advocate for educating for sustainability include envisioning a better future, systemic thinking, critical thinking and participation in decision making (Australian Research Institute for Environment and Sustainability [ARIES], 2005; Skamp and Preston, 2021). This approach aims to shift the study of "science" beyond a eighteenth century and twentieth century view of progress, and technical know-how, and of narrow versions of objectivity and links well with the pedagogy modeled in the community garden (Brennan and Widdop Quinton, 2020).

A necessary process in conceiving a community garden is that how we understand and "value" the future will determine how we proceed in the present. Our global and local economies are destroying Earth's natural support systems, putting us on a path of decline and collapse. Current literature on sustainable futures identifies the challenges for a safe and liveable environment. These challenges include climate change, ocean acidification, chemical pollution, nitrogen and phosphorus loading, freshwater withdrawals, land conversion, biodiversity loss, air pollution and ozone layer depletion (Flannery, 2015; Jickling et al., 2018; Figueres and Rivett-Carnac, 2020). Earth is heading for an uncertain future with the likelihood of dramatic changes–a good reason to be concerned (Norberg-Hodge, 2020). If Earth is to remain liveable, we need a futures vision that can turn things around. Futures thinking is about exploring possible futures that are evidence based and investigating how trends will affect us and our community, promoting decisions on what action needs to be taken to either fulfill the future scenario or work to prevent negative aspects.

At the personal level our minds have the faculties of memory and prevision (de Jouvenel, 1967; Cornish, 1977) and we have no choice but to have images of possible futures. They are a central aspect of our worldview (Kelly, 1963; de Jouvenel, 1967; Damasio, 1994; Loye, 1998; Eckersley, 2002; Bowers, 2017). Images of possible futures are mental tools that deal with possible future states and are composed of a mixture of concepts, beliefs and desires that affect our choices and guide decision making and actions. They are flexible, changeable, and personal in nature and are mental constructions dealing with possible future states (Ziegler, 1991; Rubin and Linturi, 2001). Images of possible futures are important and life forming, and prediction is both intuitive and learned, and can be improved when acknowledged and attended to Loye (1998). Hicks (1996), says that "One of the main concerns of environmental education is the need to create a more ecologically sustainable future," and that images "of possible futures seem to be important at both the personal and community levels" (see also Hicks, 1994, 1996; Hicks and Holden, 1995; Slaughter, 2012; Kopnina et al., 2018). Schools as community groups need practical ways to express and build their hope and agency for the future.

The following extract is from a positive future story using a guided fantasy to get participants thinking about the world in 20 years, in this example, an adult:

I spend my day working in my small garden and glasshouse with my vegetables and fruit. I enjoy the society of the main street, the library. I take interest in the public orchard I helped plant 10 years ago. The freeway is quieter, there are two train tracks where roads were; people now find the new train to the city more convenient. There is much more local cultural life, films, music, and local sociability (Lloyd, 2013).

The choice of preferred futures identifies what the author would like their Earth to be like. Many would like to see a future based on greater environmental awareness and personal and community action for sustainable futures as argued by Slaughter (1991, 1995, 1998) and many other authors (e.g., Boulding, 1996; Gidley, 2016). There is ample evidence in these articles that having positive expectations for the future, emerging from active engagement in the present, has a positive effect on our world view and wellbeing. We believe that what student images of possible futures reveal about their interests and concerns provides a primary justification for a more explicit futures perspective in education (Lloyd, 2005; Paige and Lloyd, 2016; Paige et al., 2018b). They constitute prior knowledge that can influence motivation, conceptual development, and what is valued as knowledge.

Climate change, brought about by human behavior, is currently the Earth's primary challenge. Climate change is exacerbated by deforestation, a major cause of biodiversity loss and carbon dioxide removal (Rockström et al., 2018). A further significant challenge is the destruction of our natural environment–the homes of so many native plants, animals and insects. In Australia, overfishing and illegal fishing, introduction of exotic species, pollution, and infrastructure development add up to degradation of the natural environment (Australian Government Department of Agriculture, Water and the Environment, 2022). Environmental degradation is evident at even well-managed sites. At TOSCG rabbits–an introduced pest–want our fruit and vegetables, leaving nothing for humans!

Toulmin (1990, p. 2) explains that "futures scenario are available futures, not just those that we can passively forecast, but those that we can actively create." This position enhances considerably the need for community parks and gardens that can provide spaces for the non-human residents (plants and animals) and the growing of organic food for humans (Kolbert, 2006; Lindenmayer, 2007; Spratt and Sutton, 2008; Lloyd, 2015; Raskin, 2016).

Community gardening for connections and wellbeing

The use of parks and gardens to improve health is known as *social and therapeutic* horticulture (Goleman, 1996; Armstrong, 2000; Arvay, 2018). As well as promoting physical and mental health benefits, social and therapeutic horticulture has also been shown to help improve people's communication and thinking skills. The University of Hull's Center for Systems Studies is researching ways community gardening can boost wellbeing for people, societies and the wider world (Metcalf et al., 2021). They have, since 1998, been maintaining trees, shrubs and wildlife areas, growing vegetables and salad crops, and holding crafting activities. Similarly, TOSCG runs workshops on how to mulch, build wicking beds, as well as plant propagation. We must not forget social events such as barbeques and picnics–often occurring after a hard day of digging, weeding, and planting. Spending time in the outdoors, taking time out of the everyday to surround yourself with greenery and bird life we have found to be one of life's great joys.

Norbert-Hodge sees a need to "work to renew ecological, social and spiritual wellbeing by promoting a systemic shift away from economic globalization toward localization" (Local Futures—Building economies that restore community and nature). Community gardens are an expression of localization that respects nature, justice, and real democracy, rebuilding local economies and communities, and restoring cultural and biological diversity.

When it comes to food, the value of local production is paramount:

The logic of local food production is unassailable: locally grown food is fresher, and therefore tastier and more nutritious, than food transported over long distances. It is also likely to contain fewer preservatives and other artificial chemicals, because when the producer knows the consumer personally and not only as a faceless target market, he or she is less likely to take risks and liberties with the consumer's health (Norberg-Hodge, 2020, p. xxiv).

Gardening can directly improve our wellbeing and encourage us to adopt healthier behaviors through physical activity, collaborating with friends, relaxing, or meditating in a quiet and beautiful place, coming to a better understanding of plant growth, soil properties and the ecology of gardens (Payne and Wattchow, 2009; Nettle, 2010). Growing food, for own use and for local distribution or sale, is often the motivating purpose of community gardening. For example, surplus food from TOSCG goes to people in need and is distributed by The Hut Community Center, operated by local government. Unlike growing food in private gardens, community gardening requires an element of cooperation and collective planning. Working together toward shared goals can create a real sense of community. And in a garden, a feeling of connection may develop, not just with other people, but with the living world. For example, Australian magpies are often our companions at the garden, particularly if turning over soil–they find food for lunch or tea for themselves and their children.

Community gardens connect people to nature and help towns and cities to move toward local, healthy, less expensive food with a reduced carbon footprint (Costanza et al., 2013). Learning about our environment and how to live sustainably within it is critical for a liveable future for all species including humans, so understanding, valuing, behaving, and taking action to care for our natural environment–for ourselves and for future generations–is our greatest challenge for sustainability (Walker, 2019).

Individual wellbeing and societal wellbeing are inextricably linked. Community gardens support this connection in part by placing people in nature. They can demonstrate that it is possible to make spaces inclusive and accessible. Wicking beds and paved pathways, for example, can improve access for wheelchair users.

Community gardens such as TOSCG highlight the importance of nature places and the many benefits they can bring for people, society and the other-than-humans.

Community gardens can also play a significant role in conserving biodiversity through developing wildlife pockets and corridors across towns and cities. Gardens can also help to mitigate climate change: their vegetation captures carbon dioxide and improves air quality, provided there is enough of them to use the carbon dioxide we generate for them. Tree and shrub roots absorb water and help stop flooding and erosion but also reduce evaporation, a very important local consideration in South Australia's hot, dry summers.

Community gardens: A context for sustainable educational practices

The Old School Community Garden was once a primary school, hence the name. Located in the township of Stirling, approximately 15 km from the Adelaide city center, the land is government-controlled and is managed by the district council. In 2013, the council leased the site to a group of local people who wanted to develop a community garden (Lloyd, 2015). The garden is two hectares in size and has a flat area suitable for growing vegetables, and an undulating area ideal for growing indigenous flora. Koalas are starting to find their homes in the trees and native birds of many species are at home in the garden.

The original OSCG community team, all interested in gardening and/or growing food, also saw the site as a community meeting space, for both health and economic reasons and, in particular, the local production of food which was seen as becoming an increasingly higher priority for communities. During early consultations, with the community, the managing committee established six objectives for the garden (Lloyd, 2015):

1. A Meeting Place
2. A Growing Place
3. A Learning Place
4. A Healthy Place
5. A Sustainable Place
6. A Beautiful Place

Environmentalists such as Edward O. Wilson support these objectives, as seen in his "biophilia hypothesis" (Wilson Edward, 1984). Wilson spoke about the "human urge to affiliate with other forms of life," in other words, about our connection with nature. It is a connection that has evolved over millions of years. Human beings come from nature. We have been formed by our interaction with nature. We should therefore be considered a part of nature, just like all other life forms (Arvay, 2018, p. 3). In this paper, the educational value of TOSCG (Objective 3) is our primary concern. We focus here on the use of the garden as a learning place for Year 1 students (aged 6–7) and Year 4 students (aged 9–10). As Gaylie (2011) and Lloyd (2013) note, many schools already have their own food gardens as strategies for developing sound nutritional practices and cooking skills, encouraging outdoor physical activity, and preparing students for living locally food-wise. It is hoped that this generation of young people, with the opportunity to learn how to grow food, will be better prepared for a likely challenging future (Cattaneo et al., 2012; Ehrlich and Ehrlich, 2012; Stevenson et al., 2013).

The explicit objective 4 of making TOSCG "A Healthy Place" objective has four main aspects–cultural inclusion, eco-system health, and personal mental and physical wellbeing. Student visits to the garden promote social interactions, physical exercise, and ecological knowledge. This is a complex space for diverse kinds of learning, socializing and being with the environment. Text book biology, physics, chemistry, and geology take on real meaning when applied to an understanding of the needs of plants and animals and of the needs of the humans who manage the garden.

It is important to recognize that the cognitive, scientific and conceptual work, has to take account of the emotional dimensions of relating to the rest of the world, other humans and to oneself, not customarily a feature of science education. Awareness of local and global issues is not generally the result of the school curriculum but rather emerges from television and other forms of mass media (Hutchinson, 1996; Oscarsson, 1996). Many young people intuit the dangers of our time and are "deeply cynical, alienated, pessimistic, disillusioned, and disengaged" as well as "uncertain of what the future holds" (Eckersley, 1997, p. 244). Eckersley (1995) argues that the lack of confidence that youth have in futures may be due to cultural failures, loss of key values, and the rapid pace of change. Goodall and Abrams (2021) in their "Book of Hope" highlight "ego-grief":

I read a report by the American Psychological Association found that "the climate crisis can cause people to experience a whole range of feelings including helplessness, depression, fear, fatalism, resignation, and what they are now calling eco-grief or eco-anxiety" (p. 73).

Because people's relationships with the living world affects their behaviors toward it, taking part in community gardening can also help people, old and young, be environmentally conscious, and responsible (Sobel, 2017*).* The mature gum trees and those we are planting at TOSCG provide food and shelter for koalas. The creek that runs through the garden provides a home for animal species such as frogs, lizards and Australian wood ducks (see **Figure 1**).

There are so many positives gained through community gardens that their popularity is likely to rise as we learn how to live more locally. There are challenges such as suitable sites in towns and cities, but as one of us discovered in their narrative,

FIGURE 1
A shared space for humans and wildlife.

in times of need such as the Second World War, suitable places for community gardens can be found. We suggest that they are necessary for sustainable and flourishing communities. The many benefits of community gardens include:

- Workshops that ensure our continuous learning for sustainable futures, for example building wicking beds to reduce water use; native bee workshop (Lloyd and Deans, 2017; Paige et al., 2020).
- Supporting inner wellbeing
- Connecting to community and its culture
- Living a life in harmony with the natural world
- Developing knowledge about indigenous plants that support local species[1]

These garden experiences fit well with objectives 5 (A sustainable place) and 6 (A beautiful Place). This is reflected in the pleasure that community including children take in being in the garden working toward a sustainable place appreciating the beauty of native plants and animals species.

The study

We report on the year when two classes and their teachers were involved in the community garden. A Year 4 class of 20 students and their buddy class of Year 1s visited the garden over the growing period for vegetables. They walked to the community garden from school and back, taking about 15 min each way. This provided opportunity for talking, building friendships, and noticing what was happening around them. For example, seeing koalas in the trees. They visited TOSCG once a week for a 3-h morning or afternoon session. But many also visited in their own time, often with their parents.

An in-depth, purposeful case study (Merriam, 1998; Stake, 1998; Yin, 2016) was undertaken using a participatory methodology, alongside the teachers and students around sharing the gardening experience. Both researchers had current working with children checks. Data collected over an extended period of time included observations and notes from conversations with students and teachers, student writing, illustrations, and future thinking, reports by the teachers and photographs of learning experiences. With young children especially, and the complex learning experiences offered through the gardening, we needed a range of qualitative methods to capture aspects of their multiple ways of knowing and being in the garden. We include two photographs of the community garden illustrating vegetable plots, wicking beds (**Figure 2**) and shared space for humans and wildlife (**Figure 1**).

The teaching foci came from the teachers asking students to write about their experiences, with one teacher giving them the *sentence starter "I love the garden because*. . .Their responses included their environment, the plants, seasons, and sustainability. The teacher wrote, *'They loved their time in the garden and really enjoyed finding out about their place. As you can see the garden makes an impact in many ways'.* The data used in this paper has been collated from the comments of young people reflecting on their community garden experiences.

FIGURE 2
Community Garden wicking beds.

1 https://greenleafcommunities.org/the-many-benefits-of-community-gardens/

Transdisciplinary learning in the community garden

The garden is an ideal site for young people to learn about their local environment and how to manage it sustainably. In the Australian Curriculum, the concept of sustainability is a "cross-curriculum priority" from Reception to Year 10 and this, in itself, is indicative of the transdisciplinary nature of learning for sustainable and harmonious interaction with the environment.

For teachers bringing their students to TOSCG, the pedagogy used is transdisciplinary, connected to place, and consistent with the agreed garden objectives (Balsiger, 2015; Mochizuki and Yarime, 2016; Paige et al., 2018a). The activities are also transgenerational. The teachers and students work with senior members of TOSCG team, including David Lloyd, one of the authors of this paper. The older Year 4 students act as mentors for the younger Year 1 students.

The central activity for students is planting vegetables in wicking beds, and planting trees at the site as well as at school and home (see **Figure 2**). In the process, students plant seeds and learn to identify the needs of the plants. They work in twos and threes to dig holes or trenches and then space their seedlings or seeds equal distance as indicated on the seed packet information. We explain that plants, just like us, need nutrients and we introduce them to community garden generated mulch and purchased fertilizers that have explanations on how and how much to use for vegetables. They are thinking mathematically when measurements are made using calibrated spoons and for liquid fertilizers, how to dilute if required. An important piece of chemistry is pH—acidity, alkalinity and neutrality. They connect to these ideas through their own eating—bitter, sour and neither—alkaline, acidic and neutral. We introduce students to pH meters which they can use to measure acidity and alkalinity. At the garden we explain that some plants like acidic soil but most vegetables like alkaline or neutral soil which leads onto soil management and the needs of particular vegetables. The students cover their garden beds with netting to keep out the feral rabbits and white butterflies that lay eggs on their plants. Snails also need to be managed, although snail races are not uncommon, and students love the worms! Back at school the teachers connect this process to students' own diets, explaining that all living things need feeding and the vegetables they eat provide them with what their body needs to live and to grow. Plant nutrition is connected to human nutrition through the in class curriculum. Making the connections between the needs of human, plants and animals, while talked about at the garden is addressed more thoroughly in class.

As a "Learning Place" (Objective 3), TOSCG promotes multiple ways of knowing (Gardener, 1983) including the development and sharing of values and visions–a cultural perspective. Through their participation in TOSCG, the students learn more about living sustainably, as the TOSCG team demonstrate, practice, and promote the sustainable use of resources. Participants are provided with rich opportunities for learning including organic gardening, plant propagation, pest control/weed control, composting, and wicking bed construction. There is also a focus on biodiversity and local knowledge–specific to the Adelaide Hills conditions and microclimates—as part of the curriculum in Year 4. Engaging students in the decision-making process has added to the democracy agenda. As students aren't often aware exactly how their food is produced and where it comes from, growing and cooking food have been welcomed and are now integrated into the school curriculum.

Student experiences at the garden are taken back to school, interrogated and further researched. The produce is either taken home or cooked and eaten at school, providing an opportunity for cooking lessons. Students continue their garden studies in the classroom to develop their literacy skills by researching and writing stories about their garden experiences. These stories are shared with fellow students, teachers, instructors, and parents. The student experiences are supportive in connecting them to Earth, their curriculum, and the interconnectedness of the subjects they do at school–transdisciplinary learning (Brown et al., 2017). The learning is good for your body, mind, soul, and spirit. TOSCG is a place of rest, reflection and physical exercise, a place of connection to nature, and a place for companionship, discussion and collective decision making.

Participant reflections

As part of their learning back at school the teacher assisted students to reflect, record, write, and illustrate their experiences in the community garden. These were collected and a copy was forwarded to the research team. Permission was granted by the parents to use the work samples and pseudonyms have been used to de-identify the children. The researchers analyzed the work samples for common themes and these are used to organize the children's personal comments on their community garden experience (provided in **Table 1**). What is interesting is the variety of reasons students give for being at the garden. Common themes include (1) the science of gardening e.g., learning about growing plants, planting seeds, putting out pea straw, and pulling out weeds. A second theme is helping people less fortunate, for example growing food for people in need. Thirdly, being outside, walking to the garden, and spending time with their buddies. Both the learning and social aspects were identified by the students.

Student stories, comments and notes can be seen as young people preparing themselves and their community for a sustainable future, not necessarily in a deliberate way but by students seeing the value of community gardens.

TABLE 1 Students' comments on the value of the garden.

Connection to nature/gardening	Francis: "I love going to the community garden because it helps us become connected to nature." Frankie: "I think that the community garden is a great place if you don't have a garden" Faye "I love going to the community garden because we get to water the plants"
Food production	Estia: "More people should visit the Community Garden because people can get vegetables." Veronica: "I like going to the garden to learn how to grow fruit and vegetables to eat and so they don't have to pay money for it."
Companionship	Faye "I love going there with my buddy"
Contributing to wellbeing (personal/community)	Anna: "I like going to the garden because I like being able to plant whatever I want and be able to help the community. I think our class trips to the garden are fun and also, we can get more exercise walking there"
The whole story	Bianca: "I like going to community garden; we get to take the vegetables we have planted. I am learning how to plant. We got to go with our buddies. We would pull out the weeds and put them in the big mulch pile. I think this will help the community if we plant our own vegetables and don't use packaging, so it is better for the environment"

One of the teachers commented on the important role of children mentoring younger ones and the interdisciplinary nature of the learning, identifying both mathematics and science. "As the Year 4 class are working with Year 1s, they are able to develop mentorship skills, model social skills as well as learning all the benefits of participating in a local sustainability enterprise. They acquire knowledge about soil preparation, seedling growing and seed germination. They will gain the expertise of caring for their plants and later will reap the rewards and will be able to cook and eat their produce. It is also beneficial for the students to get to know an older citizen guiding them through the process."

Learning to live locally

TOSCG is very much about connecting to place–to the local. Many readers will be familiar with playing in the backyard when younger, or going to the park with friends, or to the garden, to play or just relax. TOSCG has become a second home for some locals particularly when needing a break from the "dishes." Aizenstat (1995) puts it well: "The rhythms of nature underlie all of human interactions: religious traditions, economic systems, cultural and political organizations. When these human forms betray the natural psyche pulse, people and societies are sick, nature is exploited, and entire species are threatened" (p. 93).

TOSCG can nurture a unique and special sense of place, and students can find an outlet for their biophilic needs (Orr, 1992; Gruenewald, 2003; Louv, 2008, 2011; Suzuki, 2010; Camerona et al., 2011; Arvay, 2018). Barrows (1995, p. 107) hypothesizes that "the attraction children have for fairy tales set in nature and populated with animal characters may be explained by children's instinctually based feelings of continuity with the natural world." The garden is symbolic of a desired and holistic community–for both the local and the global, economically and environmentally–in striving for a sustainable world (Assadourian, 2012, 2017; Cardinale et al., 2012; Buxton and Butt, 2020). This links students' environmental connection to place to their economic needs in particular access to organic food. In support Berry (1999, p. 160) argues "As regard economics we need. subsistence economies where the variety of human groups become acquainted with the other species in the local bioregion" and "It would be philosophically unrealistic, historically inaccurate, and scientifically unwarranted to say that the human and the Earth no longer have an intimate and reciprocal emotional relationship," p. 175). Bowers (1995) adds that "This bio-conservatism is concerned with the forms of community, agriculture, work, and art that improve the quality of human life by living more in harmony with natural systems" (p. 39).

Connecting to place isn't a trivial disposition. Familiar pleasant places provide for relaxation and exercise, but can also act as outlets for the cognitive, the affective and particularly the spiritual. The wonder of our Earth becomes distinct to us when resting under a tree or in a shelter at any time of the year–although perhaps not when a bushfire warning siren is heard!

In our support in creating naturally sensible systems of schooling, Bekoff argues our psyche is, souls, and bodies cannot heal without also healing our ecosystems and our relationship to other species. Similarly, planetary healing cannot be achieved without healing ourselves (Arvay, 2018, p. xi). We have been formed by our interaction is nature. We should therefore be considered a part of nature, like all other forms. The same life force in us also operates in animals and plants. We are a part of the "Web of life," as Wilson expressed it (Arvay, 2018, p. 3).

Eco-justice principles and sustainable communities

The term eco-justice is used in this paper as a form of justice that considers the rights of organisms and the natural environment in addition to those of human beings. Drawing on research and shared practices in science teacher education, we (Paige et al., 2016) identified eight principles that underpin eco-justice education. The community gardening experience illustrates how such principles can be learned through social action.

- *Listen, learn and challenge* worldviews and behaviors.
- Develop a *community of learners:* with knowing and valuing with compassion natural and human systems (the cultural

TABLE 2 Practical examples for community gardens and science education.

Eco-justice principles	Examples of practice and action	
	Community garden	Science education
Listening, learning and challenging current world view values and behaviors.	Locally grown food Planting and managing native flora Empathizing with and loving native flora and fauna Friendships with people and environment Living locally when possible	Reducing ecological footprint (water, energy, food, clothing, etc.). Reducing waste. Studying and supporting native Australian bees. Re-attaching humans to Earth.
Develop a community of learners with a disposition to value with compassion natural and human systems (the cultural commons) in the geosphere and biosphere, and elements of the noosphere supportive of natural systems.	Undertaking physical exercise Learning and teaching gardening with the young, the older, and the old	Active in the interests of all Earth citizens, humans and other-than-humans Looking after local environments Such as wetlands and river systems. Boundary crossing, e.g., school and community collaboration on community gardens and local native environments
Engage collaboratively toward creating socially and ecologically just and sustainable communities.	Sharing food with those in need Protecting natural places, plants and animals Sharing grown food with neighbors	Place-based experiences such as volunteering for "Trees for Life" Environmental pledges Inclusive of all aspects of knowing, feeling and doing
Develop students as role models who value the commons, partnerships, quality of life, creativity, and material adequacy.	Schooling at the community garden—environmental behavior, growing and harvesting and cooking self-grown food	Observational drawing, environmental sculptures. Visiting/taking part in environmentally connected businesses/institutions. Managing school and community recycling. Activist role Application of learning as members of community, charity and environmental groups
Foster eco-social wisdom—ways of thinking, feeling and acting within places which they inhabit.	Connecting to the animals and natural and grown plants. Understanding and appreciate the needs of plant, and animals—the ecology	Citizen science projects. Spending time in the natural world with humans and other-than-humans Rewilding: using senses Guerrilla gardening
Develop respect for long-term rather than short-term thinking through historical and futures studies.	Take to heart the history of the land and its human past and develop utopic scenarios for its future	Historical studies of the places we live Futures scenarios to explore possible, probable and preferred futures Transdisciplinary learning and acting
Provide opportunities for critical reflection	Evaluate the season's successes and failures and plan for the next season	Slow pedagogy Planning, enacting and engaging knowledges, including Indigenous narratives
Prioritize culturally responsive pedagogies and Indigenous perspectives.	Decide on at least one method of improving growing conditions and one different or variant vegetable to grow next season	Plan for a long-term view of building relationships and trust with communities, allowing Indigenous communities and Elders to share their knowledge and narratives of local histories and environments on their own terms Learning in local places

commons) in the geosphere and biosphere, and elements of the noosphere supportive of natural systems.

- *Engage* collaboratively toward creating socially and ecologically just and sustainable communities.
- Develop as *role models* who value the commons (including Indigenous perspectives), partnerships, quality of life, and material adequacy.
- Foster *eco-social wisdom*—ways of thinking, feeling and acting within places which they inhabit.
- Develop respect for long-term thinking through historical and *futures* studies.
- Provide opportunities for *critical reflection on student learning*.
- Prioritize *culturally responsive* pedagogies and Indigenous perspectives

The principles focus on enhancing socially and ecologically just communities, include challenging assumptions around growth and development, valuing natural and human systems, promoting knowing our place, developing a respect for long-term (futures) thinking, being culturally responsive, and taking an activist role. These principles, already used with undergraduate teacher education students, provided direction for planning student activities at TOSCG and at school.

These principles combine with the objectives of TOSCG to provide a focus for further planning and introducing new members to sustainability values. Unpacking the principles can become valuable conversation starters at garden meetings and in science education in classrooms. These discussions can help advance sustainability, futures and science education aims, as discussed above.

Bowers (2009) points out that "while many indigenous cultures have understood for hundreds of years the need to adapt cultural practices to what is sustainable over the long term, it has only been in the last thirty or so years that the exploitation of the environment has become the concern . . ." (p. 114). As we illustrate here, community gardens can create conversations of hope and action for liveable futures.

In **Table 2**, we invoke eco-justice principles and align them with practical examples and actions that are able to be enacted in the community garden and thus included in science curriculum.

The examples show how educators and community members can provide experiences critical for connecting children to the natural world through science, such as growing plants, harvesting, cooking self-grown food and connecting to animals. All of these are recognizable in the garden activities and student reflections. The experiences build on how we currently understand humans should be thinking and acting in order to bring about sustainable futures. The 6th principle in particular relates to futures by focusing on the long-term rather than short-term thinking through historical and futures studies. This is an evolving set of understandings and actions that will very likely change as we shift toward living more in harmony with Earth.

Developing desired futures images, working with eco-justice principles, and enacting them ensures sustainable environments. Psychological/cultural and material/natural-social systems are integrated in such future visions and plans. Integral wellbeing and sustainability are intimately connected in this process. Futures planning requires:

- Connecting to place and nature
- Respecting Earth's boundaries and
- Caring for country with the assistance of new understandings and the wisdom of the past.

Raskin et al. (2002, p. ix) argues that by developing students' understanding of community gardens and futures scenario writing they will be able to plan for sustainable futures and work toward them. These are described as a work of analysis, imagination and engagement. As analysis, it describes the historic roots, current dynamics, and future perils of world development. As imagination, it offers narrative accounts of alternative long-range global scenarios, and considers their implications. As engagement, it aims to advance one of these scenarios. By identifying strategies, agents for change and values for a new global agenda (p. ix).

Conclusion

We have attempted to illustrate through the case study how primary science learning can be done when studied as part of a transdisciplinary curriculum in the community garden. We argue that transdisciplinary learning can contribute to enabling us to live in harmony with a whole Earth system and that, as pointed out by Snoek (2003, np):

- Humans are in a better place with the opportunity to gain experience from pandemics,
- Reflections on the impact of futures thinking and its place in environmental science education can create futures thinkers and actors
- Humans can create a world worth living in for their grandchildren

The educative focus provides a vehicle for students to connect science learning to their personal, community and their future professional lives. The learning, knowing, behaving, cooperating, and valuing of TOSCG, and community gardens all over the world, provides a motivating and highly important area of learning and sustainable community living. The learning is local and necessary for productivity. It is an integral learning area, particularly needed for an understanding of the biology, geology and chemistry of plant growth and can be readily connected to other areas of the curriculum –a transdisciplinary/interconnected learning. Hence the decision to include our voice and illustrate our commitment as citizens and educators through our short biographies.

Many teachers and students are, to a large degree, illiterate when it comes to an understanding of ecology and the lives of individual members of the ecosystem. This community garden study aimed to help teachers and students acquire an understanding of the basic ecology of plants and animals such as bees and snails in their local area and their value/place in the ecosystem. The teachers were empowered to take their students' learning about their environment into the outdoor classroom and were excited by the students' enthusiasm and energy for science learning and connection to the natural world. It was a memorable experience for teachers and students. The garden project has provided an opportunity for like-minded community groups and schoolchildren to work together to enhance the social and environmental resilience of the human and broader natural environments to "enable future generations of humans and non-humans to meet their own needs" (Kopnina, 2014, p. 6). The time spent learning science in a natural laboratory enables teachers and students to explore scientific concepts in context. This is an example of meaningful science education where the outcome is for students to be informed and knowledgeable which will contribute to an utopic view of the future and active participation in constructing a liveable world.

Another group involved in this life project is primary middle pre-service teachers who enroll in a science and mathematics professional pathway course in their final year. Throughout the course they undertake assessment and between workshop tasks that endeavors to prepare them for teaching science using the eco-justice principles. One example is planning a transdisciplinary unit of work which include using an environmental issue to plan student learning across several learning areas including mathematics and science. There is an expectation that they include Aboriginal and Torres Strait Islander perspectives, place based experiences, authentic assessment tasks, pledges of green and journaling (Paige et al., 2019). Through planning the transdisciplinary unit of learning pre-service teachers become familiar with embedding the cross curriculum priority of sustainability with the science understanding substrand of the Australian curriculum (Australian Curriculum Assessment and Reporting Authority [ACARA], 2022). It is important preparation for beginning teachers to be confident planning meaningful experiences for their students. As Ferreira et al. (2019) argue the curriculum and pedagogical processes of embedding education for sustainability (EfS) in teacher education are both structural and organic. The importance cannot be overemphasized of on-going collaborative inquiry and critical reflection as teacher educators develop knowledge of and practices in EfS along with their understandings of the impact of these practices on pre-service teachers.

On a final note, community gardens, as illustrated in the case study TOSCG, can become part of the solution of transitioning to a low energy economy that can adapt to, and assist in the mitigation of, climate change and other challenges such as over-population, environmental degradation, adequate quality food, ozone depletion and social inequality (Hopkins, 2008, 2010; Urry, 2013; Lloyd, 2015). In the future, sustainability will be integrated in all aspects of our lives. It won't be an afterthought or something we do on the side. We'll have more sustainable companies, products, and even towns and cities. The vision is to develop a sustainable community with leadership coming from today's well-informed students, teachers and pre-service teachers. We hope this vision will include local food growing, as well as home gardens and new community gardens. The broader vision is long term: to support the transition of the community to a low carbon, self-managing, and steady state economy within vibrant, resilient, and sustainable communities and a 1,000-year future. This vision cannot come about unless there is a change in understanding of a stable Earth and behaviors that connects us to place. For such a transition, education from birth and schools and community gardens, have a central role to play. The encouraging thing is that students endorsed "the community garden as a place of happiness, production, and companionship."

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

Both authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Education

TYPE Original Research
PUBLISHED 06 September 2022
DOI 10.3389/feduc.2022.911052

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to
STEM Education,
a section of the journal
Frontiers in Education

RECEIVED 01 April 2022
ACCEPTED 18 July 2022
PUBLISHED 06 September 2022

CITATION
Barelli E, Tasquier G, Caramaschi M, Satanassi S, Fantini P, Branchetti L and Levrini O (2022) Making sense of youth futures narratives: Recognition of emerging tensions in students' imagination of the future. *Front. Educ.* 7:911052.
doi: 10.3389/feduc.2022.911052

Making sense of youth futures narratives: Recognition of emerging tensions in students' imagination of the future

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In this era of great uncertainty, imagining the future may be challenging, especially for young people. In science education, the interest in future-oriented education is now emerging, research needs, however, to keep eyes on youngsters' future perceptions and on the development of a *future literacy*. In this article, starting from a sample of individual students' narratives about their future daily life in 2040, we aim to delineate which ways of grappling with the future can be observed in the essays and which methodological tools are suited to operationalize their identification and characterization. The analysis led to the definition of "polarization" and "complexification" attitudes that represent the ways in which the students' narratives are positioned with respect to a bunch of dichotomies: personal–societal, functional–aesthetics oriented, good–bad, natural–artificial, and certain–uncertain. Moreover, with this study, we provide a contribution to the methodological reflection that deals with the collection and analysis of data, when students' future perceptions need to be investigated. Discussing the limits of the current data collection tool, we introduce the design of a SenseMaker® questionnaire which contributed to feeding a collaboration with #OurFutures project, recently launched by the European Commission to collect future narratives all around Europe.

KEYWORDS
science education, *futures literacy*, secondary schools students, agency, sensemaking

Introduction

In this era of threatening societal challenges, the issue of how the youngsters perceive the future is becoming of paramount importance. Even before the COVID-19 pandemic, we were already in a period that sociologists called the "society of uncertainty and acceleration" (Rosa, 2013), in which communities were experiencing profound and accelerated changes that, as Rosa states, led to a situation of disorientation. As the Italian sociologist Carmen Leccardi argues (2009), the acceleration of social rhythms has produced, in everyday life, a widespread cult of urgency capable of eroding the possibility of control by individuals, forced to measure themselves against an epochal trait of uncertainty and ungovernability of the future. The relationship with time has therefore profoundly transformed and is changing the way individuals construct their daily experiences. Indeed, this is also combined with the perspective raised by the South Korean-born Swiss-German philosopher Byung-Chul Han, who said that we are experiencing a society flatted on the present where "we are individuals afloat in an atomized society, where the loss of the symbolic structures inherent in ritual behavior has led to overdependence on the contingent to steer identity" (2019, p.11). About the importance of rituals, Han argues that "they represent for the time what the house is for the space" (2019, p.12), but the current accelerated and consuming society is progressively losing them. He continues saying that the absence of rituals also has wicked consequences on how humans relate to each other and with objects. Indeed, if rituals let humans be users and take care of their relationship with people and objects, in this accelerated society where we are losing these caring practices, the relationships of humans with others, and the objects become only in terms of consumers (Han, 2022).

Contemporary sociologists and philosophers are warning of a discrepancy in time, where the future has disappeared and the supremacy of the present, as well as the consumption of the contingency, is deeply affecting not only individuals' daily life but also our relationships as humans (Gancitano and Colamedici, 2018). For example, as a society, we are facing a widespread phenomenon of polarization that touches, among others, the political, ideological, and behavioral dimensions. Even facilitated by the inherent mechanisms of social media interactions (Del Vicario et al., 2016), people are increasingly led to perceive "Us" in opposition to "Them", this resulting in a threat to social cohesion and democracy (McCoy et al., 2018; Baldassarri and Page, 2021).

A fundamental contribution to the management of uncertainty of the future comes from the so-called *Futures Studies*. As Barbieri (1993) describes, since the late 1970's, at a time of energy crisis, Futures Studies has outlined a new modality to address the problem of decision-making and facing the future. This discipline was not interested in predicting specific events, but in pointing out alternative ways to imagine the future. Specifically, the Futures Studies approach consists of a methodical examination of possible, probable, and preferable futures starting from a certain current condition, to open multiple possibilities toward the future.

Educational research has manifested a strong interest in understanding how to provide the young generation with abilities for imagining their future, in a manner that supports different ways of acting in the present with an eye on the horizon. This interest has grown not only within academic institutions: no-profit organizations, like Teach the Future (TTF[1]), have been established with the goal to introduce Futures Studies into education, preparing next generations with future-thinking skills and supporting educators in the process of teaching but also science education research tried to accommodate the Futures Studies approach to future thinking within STEM disciplines' teaching and learning (Carter and Smith, 2003; Jones et al., 2012; Paige and Lloyd, 2016; Branchetti et al., 2018; Levrini et al., 2021a,b).

A recent Horizon2020 project called FEDORA (Future-oriented Science EDucation to enhance Responsibility and engagement in the society of Acceleration and uncertainty, Grant Agreement no. 872841) was established with the intention of conveying research efforts to foster youngsters' ways of coping with images of the future through science education. Indeed, it was highlighted that a strong misalignment in the school system exists between the a-temporal or historically oriented teaching approaches and the need to support the young to construct visions of the future that empowers actions in the present.

The study presented in this article is situated within the FEDORA project and aims to explore students' perceptions of the future. In particular, we aim to unpack two critical issues that previous studies in science education brought to light (Levrini et al., 2019, 2021a): (1) the "polarization attitude" toward socio-scientific issues (SSI) and complex themes; and (2) the "bubble effect." The "polarization attitude" is manifested when students, also dealing with SSI, tend to reduce the dynamics between the individual and collective dimension to its extremes, either a mere personal/individual issue or a social-big issue. As per the "bubble effect," the pandemic situation emphasized both the relevance of daily life and school rituals as ways to manage anxiety toward the future and the tendency to search for comfort zones through the activation of special personal and social routines and rituals that "close the systems" around the individual, rather than opening toward other societal actors (Levrini et al., 2021a). Moreover, we desire to give a contribution to the methodological reflection that deals with the collection and analysis of data with this study, when students' future perceptions need to be investigated, in particular, we aim to understand which modality used to collect data can best suit avoid push the students, also indirectly, to emphasize a polarized situation.

1 www.teachthefuture.org

Theoretical framework and background

This work builds upon three theoretical backgrounds: (1) the study referring to the definition and recognition of *future-scaffolding skills* (FSS) (Levrini et al., 2021b); (2) the study about the phenomenon of the Present-shock analyzed by the lenses of science education (Levrini et al., 2021a); and (3) the sociological constructions of the society of performance and the palliative society (Gancitano and Colamedici, 2018; Han, 2021).

The concept of FSS was coined and operationally defined within the Erasmus + project I SEE — Inclusive STEM Education to enhance the capacity to aspire and imagine future careers.[2] The project, inspired by the sociological construction of the society of uncertainty and acceleration (Leccardi, 2009; Rosa, 2013), touched upon the great difficulties encountered by young people in imagining their futures. As one of the main outcomes of the I SEE project, some operative markers were identified and defined to describe the change in students' perception of the future, as well as to recognize the development of FSS, which are extensively described in Branchetti et al. (2018), Levrini et al. (2019), Levrini et al. (2021b) and Tasquier et al. (2019). FSS is intended as skills to construct visions of the future that support possible ways of acting in the present with an eye on the horizon. They consist of structural skills, which represent the abilities to recognize temporal, logical, and causal relationships; build systemic views; and dynamical skills, which represent the abilities to navigate scenarios, relating local details to global views, past to present and future, and individual to collective actions (Levrini et al., 2019, 2021b; Tasquier et al., 2019).

Other parallel studies in science education born within the I SEE project (Rasa and Laherto, 2022; Rasa et al., 2022) have pointed out the fact that development in science and technology can have great desirable and undesirable societal implications. This issue is at the core, for instance, of research in STSE – science, technology, society, environment (e.g., Bencze et al., 2020), SSI – socioscientific issues (e.g., Zeidler et al., 2005), and the various visions of scientific literacy (e.g., Sjöström et al., 2017). However, despite those fields exploring large holistic, value-centered approaches to evaluating technoscientific issues related to environmental aspects toward decision-making (e.g., Sadler et al., 2007; Tasquier et al., 2022), they omitted to explicitly address future thinking.

As Rasa et al. (2022) argue, technology is deeply connected to young people's fears and future views (Carter and Smith, 2003) and also to their hopes for sustainable futures (Cook, 2016). Indeed, the technological dimension deeply influences young' sense of future and agency and, thereby, it has important implications for future-oriented science education.

As a follow-up of the *I SEE* project, the study on the Present-shock (Levrini et al., 2021b) aimed to investigate students' perception of time induced by the pandemic and to create a new baseline to reflect on the role of science education in supporting the young as they navigate through fast-changing space-time structures. The study, elaborating on the sociological dichotomy between alienation from time and time re-appropriation (Rosa, 2010, 2013) from the perspective of science education (Levrini et al., 2015), coined and defined the construction of the Present-shock as that feeling, emphasized by the pandemic, of re-appropriating the meaning of daily rituals and perceiving a new sense of directionality. The survey about whether young students were really re-appropriating their time and how such reappropriation looked like unveiled an interesting phenomenon: school science tends to create "bubbles of rituals" that detach learning from societal concern.

The third and final backgrounds used for this part-study concern the sociological constructions of the society of performance and the palliative society (Gancitano and Colamedici, 2018; Han, 2021). Gancitano and Colamedici recently assert that we are living in a society where each person is forced to have a performer's public and inauthentic image, which they must build and enhance, and which could be either their salvation or their ruin. In this kind of society, working time and free time are no longer really separated, and this makes it impossible to have a true contemplative life, to make choices that are free. The entanglement between the working space and the free time forces the transformation of the sacred space related to the personal space into a public space. But, above all, into a merely and banally shared space. This does not represent a real sharing that should be characterized by the ability of entering together within a community that shares values and meaning, but it is rather the transformation of daily moments into moments of apparent value. This social, cultural, economic, and political system provokes two major reactions: performance anxiety and a sense of guilt. More recently, the Korean philosopher and sociologist, Byung-Chul Han, argued in his recent publication how today's society is terrified by suffering. The fear of pain appears to be so pervasive and widespread that people are forced to give up even personal freedom in order to avoid suffering. According to Han, the risk is closing ourselves in reassuring fake confidence that turns into a cage, because it is only through pain that we open ourselves to the world. The search for removing and denying the pain in front of an apparent sense of calm, self-realisation, and happiness, ensures people's capacity to perform and induces them to focus on a more private, introspective, and psychological relationship with the self instead of thinking at the collectivity and addressing any critical societal issues. Those two sociological constructions are in line with the phenomenon of the creation of isolated bubbles observed and analyzed in the Present-shock study.

2 www.iseeproject.eu

Research questions and method of analysis

Framed within the studies outlined in the section above, the present study aims at answering the following Research Questions:

> RQ1) What pattern can be observed in students' narratives about the imagination of the future?
> RQ2) What methodological tools can be outlined to operationalize the identification and characterization of these patterns?

The data and the methodology through which we addressed these questions are outlined below.

Data and data sources

The data considered for the analysis were 223 individual essays. They were written by students, aged between 17 and 19 y.o., during the courses for university orientation organized by the Department of Physics and Astronomy of the University of Bologna from 2018 to 2021 within the PLS project (National Scientific Degrees Program, *Piano Lauree Scientifiche*). The topics of these courses were scientific, that is, *Climate Change*, *Simulations of Complex Systems*, *Artificial Intelligence*, *Seismic Risk*, and *Quantum Computing*. Consent forms were signed by all the students or their legal guardians, depending on the students' age. In writing the essays, the students followed the task of describing an ideal day in the future in twenty years. The tasks were refined throughout the years but the general structure could be summarized as follows:

> *"Imagine a winter day in 2040 and try to think about where you would like to live. Describe in a few lines (about half a page): (i) the place where you imagine you live; (ii) the kind of life you are leading; (iii) the types of problems that you, in your daily life, in your community of people and, in general, in your society are discussing and/or facing; (iv) the possibilities and new opportunities you can seize; (v) the technology, objects, the house, the city and the environment that surround you; (vi) the type of social life you lead.*
>
> *Complete the following sentences: (i) A dream I have is. . .; (ii) My ideal city includes. . .; (iii) My ideal world includes. . .; (iv) My main fears and concerns are. . ."*

Analytical approach

Given the sample and the research issues, we opted here for a semi-qualitative methodology of data analysis rooted in *Grounded Theory* (Glaser and Strauss, 1967). As part of this, a *thematic analysis* was carried out across all data sources (Braun and Clarke, 2006; Nowell et al., 2017). In particular, we assumed the approach of *reflexive thematic analysis* where a mixed inductive/deductive approach is used, combining both data-driven clusterings – coming from a bottom-up analytical process made on the essay – and theoretical hypothesis – merging and corroborating results coming from related research (Braun and Clarke, 2019).

From Grounded Theory, we derived the guiding principle for the immersion into data in all the stages of the analysis: the starting point was not a purely coding procedure but an iterative process in the search for *sensitizing concepts* (Glaser and Strauss, 1967; Charmaz, 2003). In this way, the researchers got attuned to the participants' perspectives, hence enabling themselves to capture and describe students' worldviews and narratives about the future, so as to guide further rounds of increasingly structured implementations. Coherently with the methodological framework of reference, the data were analyzed through an iterative process that included bottom-up debriefing phases designed to identify emergent themes and generate interpretative ideas.

To reach an acceptable level of internal validity, the analysis was conducted through a triangulation process that, in line with recommended practices (Anfara et al., 2002), included member check and peer debriefing with researchers in science education and some collaborators of the network. In particular, the group of analysis was composed of a core group of four scholars who dived into the analysis and a group of external scholars, among which the other authors of this contribution, who guaranteed the other levels of triangulation and checking. In the next paragraph, all the methodological phases are described and discussed.

Methodological phases

Essays organization and pre-processing

Data analysis started with a process of data organization and cleaning. A database has been constructed, into which all essays have been collected, anonymized, and pre-processed, in order to obtain a list of 223 word file documents. At the end of this step, they did not contain sensitive information that could allow tracing back to the authors and were ready to be analyzed. The documents were named in order to keep track only of the year and month when the essays were written, the gender of the authors (as declared by students themselves in the application form), and the PLS course they attended (a generic name is like Sxyz_year_month_course_StudentGender.docx and a real example could look like S004_2018_FEB_AI_M.docx). All essays (text only) are available in an official and public dataset.

Preliminary reading and immersion into data

After MC skimmed 50 essays randomly picked up from the dataset, she suggested the reading of 5 essays – particularly rich (i.e., touching many dimensions requested by the task, fairly long, detailed, and well-articulated) – to the research group, composed of 9 independent readers. Three of these essays were by females and two by males who attended the PLS course on *simulations of complex systems* in 2021. The readers brainstormed a list of macro-areas (technology and science, nature, relationships, emotions, time, routines, and rituals) and a list of transversal perspectives (e.g., individual/collective, static/dynamic vision) that were not only touched by the students in the essays but also emerged as an important point in reading the literature, as stressed in the theoretical frameworks. These macro-themes and perspectives have been shared as initial lenses through which to focus the following phases of analysis.

First analytical phase

The first analytical phase was based on the hypothesis that polarization attitude could occur when the themes or the perspectives mentioned above were touched in an essay from a single, specific perspective, depicting, in fact, a polarized image of the future. For this reason, the aim was to explore better how the macro-themes were manifested into the data. We performed a qualitative analysis of 44 additional essays (stratified according to gender, years, and courses). From this stage, the analysis team was restricted to 4 researchers who first worked independently and then discussed together to triangulate their results. In this phase, we annotated into an Excel file how the different sentences of the essay matched the macro-themes and transversal perspectives previously sketched (ref paragraph preliminary reading). The main result of this phase was an analytical grid structured in macro-themes, sub-themes, and perspectives, schematized in **Figure 1**. The combination of top-down and bottom-up approaches led to a rather complex structure of themes and sub-themes. The macro-themes extend our initial categories into: "Science and Technology," "Nature," "Relationships," "Relationship Role," "Emotional states," "Emotional Factors," "Time, Routines and Rituals," "Values," and "Otherness." Most of them contain sub-themes: for example, we found "technology and/or science for personal use" and "science and technology as a job" as sub-themes of the first main theme. Also, a sub-theme of "Otherness" is the "subject's attitude in judging against others." The grid also presents transversal perspectives, such as individual, collective, agency, or devolution, which can be transversal features of many themes.

The essays analyzed through this tool seemed to show different structural patterns. For example, there were essays in which the coding was grouped into one or few themes and others were very spread. However, this categorization of essays into vertical and transversal ones resulted ineffective for our purposes because it could not directly capture our theoretical ideas of polarized and complexified attitudes.

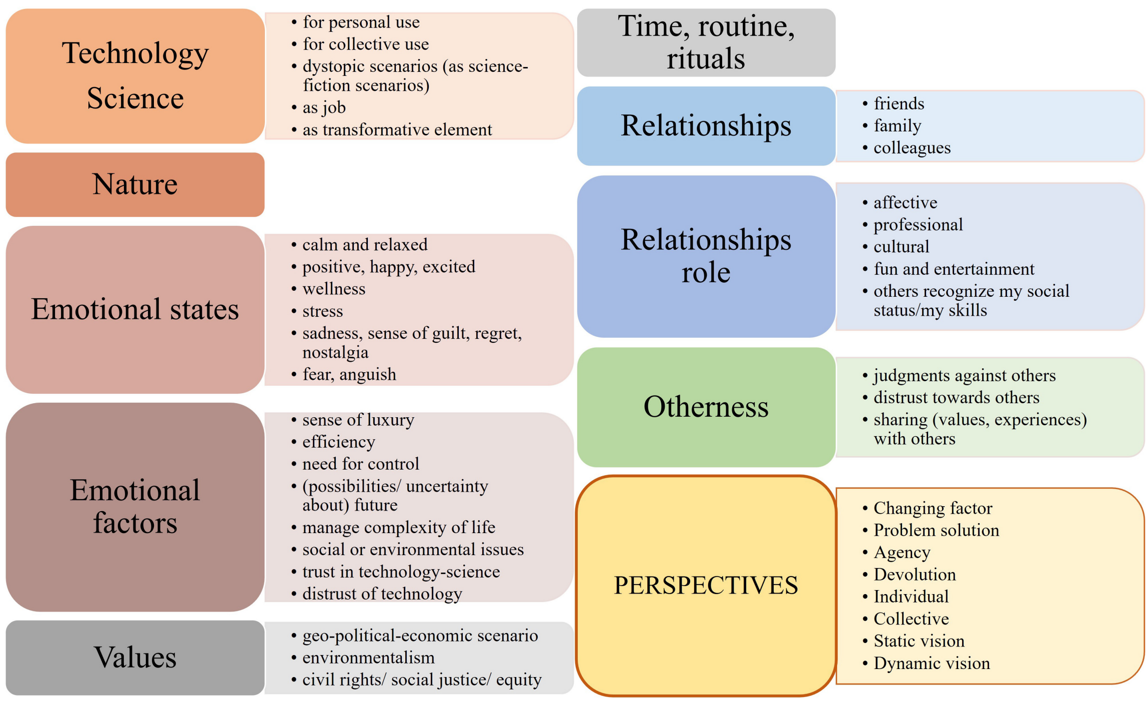

FIGURE 1
A representation of the macro-themes, sub-themes, and perspectives of the grid used in the first analytical phase.

TABLE 1 Set of dichotomies (columns) as projected onto the macro-areas (rows).

		Dichotomies				
		Personal-Societal	**Functional-Aesthetics oriented**	**Good-Bad**	**Natural-Artificial**	**Certain-Uncertain**
	Science and technology	Personal use of S&T - Societal use of S&T	Humans rule on machines -Machines rule on humans	Negative - Positive impact of S&T	Nature as the priority - Technology as the priority	Certain - Uncertain of S&T scenarios
	Relationships	Self-centred circle of family and friends - Societally-oriented relationships	Useful for wellbeing - Generative of delight	Extreme harmony - Difficulty of cultivating relationship	Authentic face-to-face relationships - Relationships mediated by technology	Fixed and established - Undefined or in continuous transformation
Macro-areas	**Emotions**	Self-determined - Societally-determined emotions	Determined by a functional-oriented life - Determined by aesthetics-oriented life	Pessimism - Optimism	Visceral - Artificially induced emotions	Need for control - Refusal of control
	Time and space routines	Self-determined - Societally-determined routines	Determined by the search of performance - Determined by the search of delight	Routine increases the quality of life - routines are oppressive	Routine immersed in nature - Routine dominated by technology	Fixed routines - Vague or absent routines
	Occupation	Individual career - Career with social impact	Performance - Aspiration	Good role in someone's life - Bad or absent role in someone's life	In contact with nature - Totally immersed in technology	Already decided career - Unimagined career

Second analytical phase

At this stage, the analyzers felt they were sufficiently immersed in data, but still not capable to distinguish if an essay could be considered as an example of text containing a polarized attitude or complexified attitude. This was because some essays were markedly polarized over many themes, while other essays seemed to touch many themes but without giving a marked orientation for all of them. Here, the second analytical phase started, the results of which we will describe in the Data Analysis and Results section.

Instead of looking for themes and their sub-themes to construct a grid as we did in the first analytical phase, we went directly in search of the polarized or complexified attitudes not only over the different *themes* but also over a set of *dichotomies* that represented alternative ways of looking at a particular issue. The dichotomies were listed through an iterative process of data analysis that progressively enlarged the empirical base up to the reach of saturation. They are formulated as couples of poles, i.e., opposite, very generic adjectives that do not contain any reference to the specific themes. The five dichotomies have been identified are personal–societal, functional–aesthetics oriented, good–bad, natural–artificial, and certain–uncertain.

However, to analyze the essays, these general dichotomies were not enough. Indeed, we needed something closer to what the students actually mentioned in their essays, but at the same time, we wanted to avoid the risk of a too precise mapping that made us lose the possibility of observing the polarized or complexified attitudes of the students, as we did in the first analytical phase. To do that, we reconsidered the previously identified themes and reformulated some of them arriving at the following set of macro-areas: vision of science and technology, relationships, emotions, time and space routines, and occupation. Then, we realized that all the dichotomies could be projected onto each macro-area to obtain specific dichotomies that were closer to the data and ready to be used to look at the students' essays. For example, the personal–societal dichotomy, when projected onto the science and technology theme, became a dichotomy that contrasted a personal use of science and technology and a societal one; when projected onto the theme of relationship, the personal–societal became a counterposition between a restricted circle of people around oneself versus societally oriented relationships. The complete list of the specific dichotomies obtained from the projection of the general ones onto the macro-areas is reported in Table 1.

Once we obtained the area-specific dichotomies, we were ready to see how the students' essays embodied them. From previous readings and analyses, we expected, for each specific dichotomy, to find three possible behaviors, schematically represented in Figures 2–4:

- **Case 1 - Neutral**: The students do not mention explicitly any pole of the dichotomy or touch them in an inconsistent way (Figure 2).
- **Case 2 - Polarized**: The students position their description on one pole of the dichotomy, ignoring or explicitly rejecting the other (Figure 3).

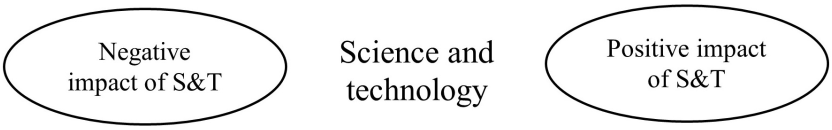

FIGURE 2
Schematic representation of neutral behavior.

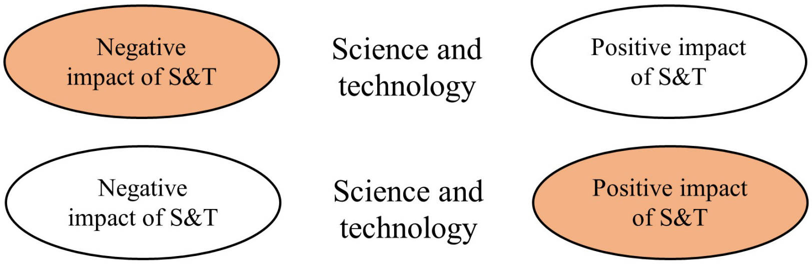

FIGURE 3
Schematic representation of two opposite polarized behaviors.

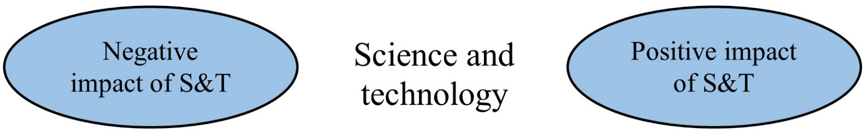

FIGURE 4
Schematic representation of complexified behavior.

- **Case 3 - Complexified**: The students "keep the dichotomy alive" including in their description a tension between the two poles without a collapse on only one of them (**Figure 4**).

To analyze the essays, we used a table identical to **Table 1** for each student, in which we added a column to take note of whether the student wrote about a macro-area or not. If a polarization was observed over a certain dichotomy (case 2), we colored the cell in orange; if otherwise a complexification was observed, we marked it in blue (case 3); the cell was left white in case of neutral behaviors (case 1). In a separate file, we reported a general synthesis of the essay and the specific sentences that made us recognize the dichotomy and the related polarized or complexified behavior.

From the resulting tables, we could observe several patterns. There were essays markedly polarized (orange) or complexified (blue) over several macro-areas and several dichotomies; others that projected the same general dichotomy on all macro-areas and others that mixed complexified with polarized behaviors. To give back a picture of the multiplicity of students' attitudes with respect to the macro-areas and the dichotomies, we chose 4 essays to be analyzed in detail. We report them in the **Annex**, while we discuss our interpretation in the Findings section.

Findings

To construct the narrative of polarization and complexification, we chose four profiles that well represent the variety of students' essays. Of the 12 essays analyzed with the grid in **Table 1**, we selected four that represent the two types of behavior observed in the data, i.e., polarization and complexification. Two case studies will be analyzed in detail, with precise references to the students' words, one as an example of polarization and the other as complexification. After this detailed presentation, two further cases will be presented as other possible manifestations of the phenomena. This will allow us and the readers to enrich the empirical basis on which defining the polarization and complexification behaviors.

Lucy: A case of polarization

The first essay considered was written by S113 (in the following we will name her Lucy), who attended the course on Quantum Computing in February 2019. Below, all findings emerged from the analysis of Lucy's essay will be described and visible in **Figure 5**.

S113_2019_FEB_QC_F		Macro-area mentioned (1) or absent (0)	Dichotomies				
			Personal-Societal	Functional-Aesthetics oriented	Good-Bad	Natural-Artificial	Certain-Uncertain
Macro-areas	Science and technology	1	Personal use of S&T - Societal use of S&T	Humans rule on machines -Machines rule on humans	Negative - Positive impact of S&T	Nature as the priority - Technology as the priority	Certain - Uncertain of S&T scenarios
	Relationships	1	Self-centred circle of family and friends - Societally-oriented relationships	Useful for wellbeing - Generative of delight	Extreme harmony - Difficulty of cultivating relationship	Authentic face-to-face relationships - Relationships mediated by technology	Fixed and established - Undefined or in continuous transformation
	Emotions	1	Self-determined - Societally-determined emotions	Determined by a functional-oriented life - Determined by aesthetics-oriented life	Pessimism - Optimism	Visceral - Artificially induced emotions	Need for control - Refusal of control
	Time and space routines	1	Self-determined - Societally-determined routines	Determined by the search of performance - Determined by the search of delight	Routine increases the quality of life - routines are oppressive	Routine immersed in nature - Routine dominated by technology	Fixed routines - Vague or absent routines
	Occupation	1	Individual career - Career with social impact	Performance - Aspiration	Good role in someone's life - Bad or absent role in someone's life	In contact with nature - Totally immersed in technology	Already decided career - Unimagined career

FIGURE 5
Polarized and complexified dichotomies found in S113 essay's analysis.

In the essay, all the macro-areas are touched by the student and are intertwined throughout the whole story.

The pace of the narrative is marked by a very precise temporal rhythm that follows the pace of the day with a precise description of daily rituals. The protagonist of the story is the student's "personal and health assistant," named Bobby, that helps its owner in all the routine aspects and mediates her needs for control in the routine, as well as the emotional aspects. The role of the assistant is related to the personal life of its owner and it only improves it.

The emphasis on the personal dimension of the future imagined by the student (as opposed to the societal perspective) and on the optimistic and positive attitude toward it sketches the two prevalent and coherent dichotomies that we recognized in Lucy's essay.

Concerning the personal–societal dichotomy, as already mentioned, the presence of Bobby – named the *personal* assistant – reflects a vision of technology as something devoted to responding to individual needs. Indeed, this is confirmed by the absence through the essay of any implication of technology on society at large. Moreover, the assistant also gives back a picture of the relationship between humans and technology, where machines are always conceived as something at the service of humans, functional for the exploitation of everyday actions, and guarantors of personal support and well-being. Bobby is her "guardian angel" that "refreshes her memory of what she needs to do at work," cooks the lunch for her, and welcomes her home "with a blanket and a cup of tea." The personal emphasis is also well-evident not only in the use of technology but also in the self-determination of daily rituals, careers, and emotions, which excludes any reference to society at large and to the surrounding community. The openness beyond individual issues is only present when Lucy mentions her relationships with her inner circle of friends and colleagues, where she finds contexts to discuss relevant societal issues ("I really missed him a lot, but above all I missed talking to him: you can go from politics to bloopers in a very short time, and never lose significance. In particular, we start talking about the current political situation in Italy, our country of origin, which is more fragile than ever in this period").

About the good–bad dichotomy, the essay is strictly centered on the "good" pole across all macro-areas. Technology is never problematized but is a herald of positive implications only ("In the driveway I find Bobby [.] I thank him and as I throw myself on the bed I think he has been the best investment in recent years"). Job is experienced with a deep sense of accomplishment and satisfaction of continuous successes. Relationships are experienced by her in an extreme harmony and throughout daily routine, she reports only positive emotions ("I get up smiling and thinking that finally a new day has arrived arm in arm

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S220_2021_FEB_SC_M		Macro-area mentioned (1) or absent (0)	Dichotomies				
			Personal-Societal	Functional-Aesthetics oriented	Good-Bad	Natural-Artificial	Certain-Uncertain
Macro-areas	Science and technology	1	Personal use of S&T - Societal use of S&T	Humans rule on machines -Machines rule on humans	Negative - Positive impact of S&T	Nature as the priority - Technology as the priority	Certain - Uncertain of S&T scenarios
	Relationships	1	Self-centred circle of family and friends - Societally-oriented relationships	Useful for wellbeing - Generative of delight	Extreme harmony - Difficulty of cultivating relationship	Authentic face-to-face relationships - Relationships mediated by technology	Fixed and established - Undefined or in continuous transformation
	Emotions	0	Self-determined - Societally-determined emotions	Determined by a functional-oriented life - Determined by aesthetics-oriented life	Pessimism - Optimism	Visceral - Artificially induced emotions	Need for control - Refusal of control
	Time and space routines	1	Self-determined - Societally-determined routines	Determined by the search of performance - Determined by the search of delight	Routine increases the quality of life - routines are oppressive	Routine immersed in nature - Routine dominated by technology	Fixed routines - Vague or absent routines
	Occupation	1	Individual career - Career with social impact	Performance - Aspiration	Good role in someone's life - Bad or absent role in someone's life	In contact with nature - Totally immersed in technology	Already decided career - Unimagined career

FIGURE 6
Polarized and complexified dichotomies found in S220 essay's analysis.

with new opportunities and possibilities," "I fall asleep, finally, thinking that tomorrow is a beautiful new day"). This optimistic view of life seems to be triggered by a satisfied need for control over the uncertainties and contingencies of life to which the personal assistant responds.

David: A case of complexification

The second essay considered was written by S220 (in the following we will name him David), who attended the course on Simulations of Complex Systems in February 2021. The macro-areas and dichotomies found in David's essay are visible in **Figure 6**.

Almost all the macro-areas are touched by David, only the emotional level is not addressed. Stylistically, the essay does not have a structure of the daily routine's narration but rather follows – also graphically through the division of paragraphs – the list of issues suggested by the task (see above paragraph "Data and data sources"). However, the time and space dimensions are an important part of the student's picture of the future even if his description overcomes an idea of time as bounded by routine constraints and time boxes, which is very typical of other essays. Hence, we recognize in David an example of the possibility of overcoming the certainty–uncertainty dichotomy in relation to time. In particular, for this macro-area, this is represented by the complexification of the opposition between a strict stay within a very fixed and determined routine (fixed pole) and the vagueness and blurry perception of time in the future (vague pole). Indeed, David recognizes the intrinsic difficulty of imagining the future due to many variables that can occur ["It is difficult to say how my day will be organized since I do not know the schedules of what my work will be, certainly, there is that most of the time I will have lunch in the company of friends/colleagues (if the work will occupy both the morning and the afternoon) and probably often have dinner in the company of someone."]. Also in the technological macro-area, David imagines a future in which humans are able to live in an extraterrestrial space thanks to scientific advancements and discoveries and people's trust in it. Rather than something certain, static, and pre-determined, he describes these changes as an open scenario that he problematizes over many perspectives (e.g., ethical and juridical, technical, scientific, and technological research).

Remaining on the technological macro-area, he also overcomes the natural–artificial and the functional–aesthetics dichotomies. Specifically, the presence of technology throughout the whole assay is mitigated by the importance given to the natural pace of life and vice versa ("I imagine

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the house is of medium size, just over 100 m^2 at most, and precisely in the province and therefore in a situation of all things considered tranquility, but home automation is certainly present in my idea of a future home."). Moreover, the value and power of science and technology are neither limited to the functional solutions of everyday issues (functional pole) nor the contemplation of useless instruments (aesthetical pole) but are perceived as something valuable for pursuing both the pleasure of knowing and concrete outputs of research ("The opportunities that I most easily imagine will be presented to me are international research projects, however, if you really need to think big, you could also imagine having the opportunity to study some physical phenomena in space").

Another form of complexification can be recognized when David describes his relationships in the future scenario. Indeed, he imagines a rich spectrum of people around him that does not include only people similar to him, with his same interests and values, but also diverse people that he could encounter during his life ("I imagine a very active social life, I don't take it for granted that I will have a partner but I don't even exclude it, in my circle of close friends I don't only see people with the same interests as me but also those who are my current friends."). In this way, we interpret his vision as an example of complexification, because both the poles of personal-societal dichotomy are considered in his view.

In summary, the open, balanced, and complex vision permeates the whole essay. This is exemplified by the presence of affirmative sentences, then mitigated by others like "but it could go in another way.", "but I do not exclude I would...", "but I don't know...", and "but I don't take it for granted". However, this inhabitation of the dichotomy does not make the essay sound problematic nor struggled from an emotional point of view: the student seems to experience well the openness described.

Enlarging the span of cases of polarization and complexification behaviors

After having analyzed two case studies in detail, we want to show two further examples to show how polarization and complexification attitudes can be displayed differently in the various essays. In Table 2, we give a graphical overview of the four selected cases.

TABLE 2 Overview of the selected cases of polarization and complexification.

S113_2019_FEB_QC_F		Macro-area mentioned (1) or absent (0)	Dichotomies				
			Personal-Societal	Functional-Aesthetics oriented	Good-Bad	Natural-Artificial	Certain-Uncertain
Macro-areas	Science and technology	1	Personal use of S&T - Societal use of S&T	Humans rule on machines -Machines rule on humans	Negative - Positive impact of S&T	Nature as the priority - Technology as the priority	Certain - Uncertain of S&T scenarios
	Relationships	1	Self-centred circle of family and friends - Societally-oriented relationships	Useful for wellbeing - Generative of delight	Extreme harmony - Difficulty of cultivating relationship	Authentic face-to-face relationships - Relationships mediated by technology	Fixed and established - Undefined or in continuous transformation
	Emotions	1	Self-determined - Societally-determined emotions	Determined by a functional-oriented life - Determined by aesthetics-oriented life	Pessimism - Optimism	Visceral - Artificially induced emotions	Need for control - Refusal of control
	Time and space routines	1	Self-determined - Societally-determined routines	Determined by the search of performance - Determined by the search of delight	Routine increases the quality of life - routines are oppressive	Routine immersed in nature - Routine dominated by technology	Fixed routines - Vague or absent routines
	Occupation	1	Individual career - Career with social impact	Performance - Aspiration	Good role in someone's life - Bad or absent role in someone's life	In contact with nature - Totally immersed in technology	Already decided career - Unimagined career

Lucy. Example of polarization over all the macro-areas with a prevalence of the dichotomies of personal–societal and good–bad (female)

S011_2018_FEB_AI_M		Macro-area mentioned (1) or absent (0)	Dichotomies				
			Personal-Societal	Functional-Aesthetics oriented	Good-Bad	Natural-Artificial	Certain-Uncertain
Macro-areas	Science and technology	1	Personal use of S&T - Societal use of S&T	Humans rule on machines -Machines rule on humans	Negative - Positive impact of S&T	Nature as the priority - Technology as the priority	Certain - Uncertain of S&T scenarios
	Relationships	0	Self-centred circle of family and friends - Societally-oriented relationships	Useful for wellbeing - Generative of delight	Extreme harmony - Difficulty of cultivating relationship	Authentic face-to-face relationships - Relationships mediated by technology	Fixed and established - Undefined or in continuous transformation
	Emotions	1	Self-determined - Societally-determined emotions	Determined by a functional-oriented life - Determined by aesthetics-oriented life	Pessimism - Optimism	Visceral - Artificially induced emotions	Need for control - Refusal of control
	Time and space routines	1	Self-determined - Societally-determined routines	Determined by the search of performance - Determined by the search of delight	Routine increases the quality of life - routines are oppressive	Routine immersed in nature - Routine dominated by technology	Fixed routines - Vague or absent routines
	Occupation	1	Individual career - Career with social impact	Performance - Aspiration	Good role in someone's life - Bad or absent role in someone's life	In contact with nature - Totally immersed in technology	Already decided career - Unimagined career

Max. Case of polarization across macro-areas with a spread distribution over dichotomies (male)

S220_2021_FEB_SC_M		Macro-area mentioned (1) or absent (0)	Dichotomies				
			Personal-Societal	Functional-Aesthetics oriented	Good-Bad	Natural-Artificial	Certain-Uncertain
Macro-areas	Science and technology	1	Personal use of S&T - Societal use of S&T	Humans rule on machines -Machines rule on humans	Negative - Positive impact of S&T	Nature as the priority - Technology as the priority	Certain - Uncertain of S&T scenarios
	Relationships	1	Self-centred circle of family and friends - Societally-oriented relationships	Useful for wellbeing - Generative of delight	Extreme harmony - Difficulty of cultivating relationship	Authentic face-to-face relationships - Relationships mediated by technology	Fixed and established - Undefined or in continuous transformation
	Emotions	0	Self-determined - Societally-determined emotions	Determined by a functional-oriented life - Determined by aesthetics-oriented life	Pessimism - Optimism	Visceral - Artificially induced emotions	Need for control - Refusal of control
	Time and space routines	1	Self-determined - Societally-determined routines	Determined by the search of performance - Determined by the search of delight	Routine increases the quality of life - routines are oppressive	Routine immersed in nature - Routine dominated by technology	Fixed routines - Vague or absent routines
	Occupation	1	Individual career - Career with social impact	Performance - Aspiration	Good role in someone's life - Bad or absent role in someone's life	In contact with nature - Totally immersed in technology	Already decided career - Unimagined career

David. Case of complexification with a predominant articulation over the macro-area of technology (male)

S152_2020_FEB_QC_F		Macro-area mentioned (1) or absent (0)	Dichotomies				
			Personal-Societal	Functional-Aesthetics oriented	Good-Bad	Natural-Artificial	Certain-Uncertain
Macro-areas	Science and technology	1	Personal use of S&T - Societal use of S&T	Humans rule on machines -Machines rule on humans	Negative - Positive impact of S&T	Nature as the priority - Technology as the priority	Certain - Uncertain of S&T scenarios
	Relationships	0	Self-centred circle of family and friends - Societally-oriented relationships	Useful for wellbeing - Generative of delight	Extreme harmony - Difficulty of cultivating relationship	Authentic face-to-face relationships - Relationships mediated by technology	Fixed and established - Undefined or in continuous transformation
	Emotions	1	Self-determined - Societally-determined emotions	Determined by a functional-oriented life - Determined by aesthetics-oriented life	Pessimism - Optimism	Visceral - Artificially induced emotions	Need for control - Refusal of control
	Time and space routines	1	Self-determined - Societally-determined routines	Determined by the search of performance - Determined by the search of delight	Routine increases the quality of life - routines are oppressive	Routine immersed in nature - Routine dominated by technology	Fixed routines - Vague or absent routines
	Occupation	1	Individual career - Career with social impact	Performance - Aspiration	Good role in someone's life - Bad or absent role in someone's life	In contact with nature - Totally immersed in technology	Already decided career - Unimagined career

Alice. Case of complexification: emphasis on emotions; coherent on the dichotomies when overcome. Example of a robust complexification over many macro-areas but still presenting polarization in the technological macro-area (female)

S011_2018_FEB_AI_M		Macro-area mentioned (1) or absent (0)	Dichotomies				
			Personal-Societal	Functional-Aesthetics oriented	Good-Bad	Natural-Artificial	Certain-Uncertain
Macro-areas	Science and technology	1	Personal use of S&T - Societal use of S&T	Humans rule on machines -Machines rule on humans	Negative - Positive impact of S&T	Nature as the priority - Technology as the priority	Certain - Uncertain of S&T scenarios
	Relationships	0	Self-centred circle of family and friends - Societally-oriented relationships	Useful for wellbeing - Generative of delight	Extreme harmony - Difficulty of cultivating relationship	Authentic face-to-face relationships - Relationships mediated by technology	Fixed and established - Undefined or in continuous transformation
	Emotions	1	Self-determined - Societally-determined emotions	Determined by a functional-oriented life - Determined by aesthetics-oriented life	Pessimism - Optimism	Visceral - Artificially induced emotions	Need for control - Refusal of control
	Time and space routines	1	Self-determined - Societally-determined routines	Determined by the search of performance - Determined by the search of delight	Routine increases the quality of life - routines are oppressive	Routine immersed in nature - Routine dominated by technology	Fixed routines - Vague or absent routines
	Occupation	1	Individual career - Career with social impact	Performance - Aspiration	Good role in someone's life - Bad or absent role in someone's life	In contact with nature - Totally immersed in technology	Already decided career - Unimagined career

FIGURE 7
Polarized and complexified dichotomies found in S011 essay's analysis.

Max: Another case of polarization

S011 shows another example of a polarization attitude. He attended the course on Artificial Intelligence in February 2018, and we will refer to him as Max. This can be grasped at first sight by looking at the **Figure 7**, in which only orange cells are marked. Similarly to Lucy (case study 1), even in this case, the text is very rich, touching almost all the macro-areas, only the relationship dimension is not touched by the student. However, the structure of polarization is very different from that displayed by Lucy. In that case study, the polarization is mainly displayed vertically in the grid, reflecting the fact that the text is guided by two central dichotomies (personal–societal and good–bad) that are projected over all the macro-areas. On the opposite, this vertical structure of the table is not so present in Max's essay that shows a distribution of polarizations across all the macro-areas touched, with a predominance of that related to emotions, in which four dichotomies are touched. Even if not so marked as in the case of Lucy, Max also shows a prevalent dichotomy (functional–aesthetics oriented) with a polarization on the functional extreme.

Alice: Another case of complexification

Like David, even S152 is a case of a quite rich and extended essay in its description, indeed almost all the macro-areas, but relationships, have been touched. S152 attended the course on Quantum Computing in February 2020, and we will refer to her as Alice. Looking at **Figure 8** globally, we can see that it is a case of complexification, even spreader with respect to David, even if there are two aspects of polarization that are present in the technological macro-area, where instead David showcases a deeper level of complexification. Here, Alice manifests a negative aspect of technology that touches the personal dimension.

In this case study, the emotional macro-area, completely absent in David, is the most expanded. Indeed, four out of five dichotomies are overcome by showing a complexified attitude. In the emotional macro-area, the only "neutral" dichotomy is that related to the personal–societal one. A possible interpretation is that indeed the personal–societal is the only dichotomy that the student does not overcome in any area and, on the opposite, exhibits a polarization about this in the technological macro-area.

S152_2020_FEB_QC_F		Macro-area mentioned (1) or absent (0)	Dichotomies				
			Personal-Societal	Functional-Aesthetics oriented	Good-Bad	Natural-Artificial	Certain-Uncertain
Macro-areas	Science and technology	1	Personal use of S&T - Societal use of S&T	Humans rule on machines -Machines rule on humans	Negative - Positive impact of S&T	Nature as the priority - Technology as the priority	Certain - Uncertain of S&T scenarios
Macro-areas	Relationships	0	Self-centred circle of family and friends - Societally-oriented relationships	Useful for wellbeing - Generative of delight	Extreme harmony - Difficulty of cultivating relationship	Authentic face-to-face relationships - Relationships mediated by technology	Fixed and established - Undefined or in continuous transformation
Macro-areas	Emotions	1	Self-determined - Societally-determined emotions	Determined by a functional-oriented life - Determined by aesthetics-oriented life	Pessimism - Optimism	Visceral - Artificially induced emotions	Need for control - Refusal of control
Macro-areas	Time and space routines	1	Self-determined - Societally-determined routines	Determined by the search of performance - Determined by the search of delight	Routine increases the quality of life - routines are oppressive	Routine immersed in nature - Routine dominated by technology	Fixed routines - Vague or absent routines
Macro-areas	Occupation	1	Individual career - Career with social impact	Performance - Aspiration	Good role in someone's life - Bad or absent role in someone's life	In contact with nature - Totally immersed in technology	Already decided career - Unimagined career

FIGURE 8
Polarized and complexified dichotomies found in S152 essay's analysis.

We can also say that passing across the different macro-areas, in each of them, there is at least one dichotomy that has been complexified.

Looking at the picture per column, this complex behavior appears even stronger, since there are three dichotomies that seem to be strongly overcome (due to the showcase of their complexification in more than one macro-area), those are the functional–aesthetics oriented, the natural–artificial, and the certain–uncertain.

Discussion

We started our study by asking ourselves what we could *see* in the students' narratives when they were asked to imagine the future twenty years later. As we explained in the methodological section, the process that led to finally seeing something in the data was not straightforward. Students' essays were rich and articulated, and the lenses with which we looked at the data had to be progressively refined. However, the data analysis allowed us to answer the research questions we stated at the beginning, leading to an identification of both the phenomena that can be observed in students' narratives about the imagination of the future and of the methodological tools to reach a characterization of these phenomena.

In this article, we characterize these phenomena as polarization and complexification attitudes through the analysis of how the students' narratives are positioned with respect to a bunch of dichotomies that can be manifested across several thematic macro-areas covered by the text. Through the detailed analysis of four case studies, we recognized polarization patterns when the students, across several macro-areas, exhibited a flattening of the description of their future that covered only one pole of the dichotomy. On the opposite, complexification patterns are recognized when the students, instead of focusing on a pole of a dichotomy, develop a richer argumentation that moves across the two dichotomous poles keeping both "alive" and considering both of them as important to reach a sensible description of the future. We named the second phenomenon "complexification" since the multiplicity of perspectives that embeds recalls an issue that is crucial for the science of complex systems; indeed, the perspective of complexity allows us to overcome sharp distinctions between local and global phenomena or between the individual agents and the societal system. As science educators, we believe that embedding in science teaching perspectives on the science of complexity could help the students recognize the complexity of reality and go beyond dichotomous thinking that seems pervasive at many levels.

The complexification patterns can be individuated as a second issue which is also crucial for the science of complexity, i.e., the concept of equilibrium and sustainability (Barelli, 2022a,b). Being able to stay in the tension between opposite poles recalls the states of dynamical equilibrium that are observed in many complex systems. This particular type of equilibrium is very distant from the thermodynamic notion and includes a cyclical movement across states. As population dynamics models show, ecological sustainability is achieved not because a system perseveres in an immutable state but, on the contrary, because there is an overall evolution of the system obtained as the oscillation around different "poles." Hence, we emphasize that, again, the perspective of complexity could be a heritage of concepts to allow the students to move from fixed and static pictures of the future – hence unrealistic – to more dynamic ones that create spaces to envision authentically sustainable narratives.

The ways in which students perceive themselves as agents of their narrative are very different between essays exhibiting polarization and those that manifest complexified patterns. Indeed, even the actions described by the students seem to reflect the overall phenomena. In cases of polarization, the actions envisioned by the students are certain, already determined, well-established and with a precise outcome that has been already predicted. In cases of complexifications, we see that some actions are still imagined but they take the form of a cone of possible things to be done if some circumstances could happen. This echoes the certain–uncertain dichotomy: the complexification patterns show an overcoming of this Manichean distinction and accept the existence of a spectrum of possibilities, which do not exist in the polarized cases.

Conclusion and further steps

The analysis carried out in this study somewhat confirmed the societal phenomena highlighted by recent sociological and philosophical studies concerning the perception of time and the related consequences, like the need to rebuild rituals and the increasing difficulties in humans' relationships (e.g., Rosa, 2013; Han, 2019). Moreover, the analysis went in the direction to see the form of manifestation of what philosophers are recently calling the society of performance and the palliative society (Gancitano and Colamedici, 2018; Han, 2021). Indeed, the need to create "bubbles of rituals", where the time seems to live in a parallel world and where the emotions are kept low, defines a space time of isolation that expresses in some way a rooted feeling of the young generation to be separated from the crude reality. However, the analysis also shows that there are still interesting ways in which the young overcome the polarized effects and are able to imagine more complex futures, which are not stuck in bubbles.

Furthermore, the analysis also shows the predominant role that technology occupies in the future imagination and how this is a support and accompaniment to actions. This is in line with the findings of the Standard Eurobarometer (European Commission, 2021): Europeans expect that technology (together with science and innovation) will contribute to many important issues in the near future (e.g., health, jobs, education, environment, energy supply, security) and that this contribution will be bigger than those given by humans' actions.

Despite framing within the overall general picture, the original contribution of this analysis consisted in focusing on two specific phenomena that have been rarely explored within the research field of science education, the polarization, and the bubble effects, as well as finding an operative way to recognize them into students' narratives of their futures. Another contribution of this article was to understand whether the phenomena are induced by the type of narration required or if they are attributable to students' attitudes.

Indeed, in the whole article, we have been very careful in saying that the phenomena we observed were typical of the students' narratives, without assuming that polarized or complexified was the students' visions of the future. For the type of data we collected, this would have gone beyond our purposes. From this study, we began a follow-up investigation in order to check whether the students had some form of polarized or complexified views of the future, or if these phenomena were emerging patterns triggered by the tool of data collection. To do that, we got inspired by SenseMaker® questionnaires,[3] developed by Dave Snowden. These questionnaires are based on the ideas of complexity, sensemaking, and narratives (Snowden and Boone, 2007). They collect the first-hand narratives from respondents and combine these with quantitative data and pattern visualization. These quantitative data are created by the respondents who self-define the narratives they have provided, answering questions that require positioning the narratives in a space of possible choices. This process of "self-scoring" is made possible because all the quantitative questions are built on the so-called "signifiers," i.e., concepts that anchor the plotting of respondents' micro-narratives in space (Van der Merwe et al., 2019). A questionnaire has already been designed and submitted in synergy with #OurFutures, a project launched by the European Commission and aimed to use SenseMaker® to collect future stories all around Europe. In further studies, we will check if the students' sensemaking of their narratives will confirm our interpretation in terms of polarization or complexified attitudes, or if new phenomena will emerge.

This study is in line with what the EU context is urgently calling for. Education, and moreover science education,

3 https://sensemaker.cognitive-edge.com/

can give a fundamental contribution to enabling learners to develop competencies and acquire knowledge, skills, and attitudes needed to take action toward a sustainable transition of our society. Indeed, as it is stated in the recent Green Competence Framework (Bianchi et al., 2022), "through *futures literacy*," learners can anticipate, prepare, and invent as changes occur. *Futures literacy* encourages learners to (i) use their imagination when thinking about the future, ii) tap into their intuitions and creativity, and (iii) assess the possible steps needed to achieve their preferred future.

Data availability statement

The data supporting the conclusions of this article is contained in the open access dataset, available at the following URL: http://amsacta.unibo.it/6964/.

Ethics statement

All the data analyzed for this manuscript were collected after consent forms were signed by all the students or their legal guardians, depending on the students' age. The module for consent form and the whole process of data collection and analysis have been reviewed and approved by the Ethical Commission of the University of Bologna within the FEDORA project.

Author contributions

OL coordinated the whole group and contributed to the setting of the study and the revision of the manuscript. GT coordinated the processes of data analysis and writing of the manuscript. EB and GT co-shared the responsibility of the writing and they have been put as the first authors of the manuscript in alphabetic order. MC coordinated the process of preparation of the manuscript and submission phases and took the main responsibility of the construction of the dataset. SS, PF, and LB contributed to the collective discussion for the evolution of the ideas argued in the manuscript. EB, GT, and MC represented the core group of scholars who mainly worked on the analysis. To reach an acceptable level of internal validity, the analysis was conducted through a triangulation process that, in line with recommended practices, included peer debriefing with researchers in science education and some collaborators of the network. In particular, the group of analysis was composed of a core group of three scholars (MC, GT, and EB) who dived into the analysis and a group of external scholars, among which the other authors (SS, PF, LB, and OL) of this contribution, who guaranteed the quality of the results *via* other levels of triangulation and checking. All authors contributed to the article and approved the submitted version.

Funding

This research was conducted within the FEDORA (Future-oriented Science EDucation to enhance Responsibility and engagement in the society of Acceleration and uncertainty) project that has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement no. 872841.

Acknowledgments

The data discussed in this article were collected by the Bologna research team coordinated by OL and have been analyzed and processed by the authors of this article. The results were discussed with FEDORA partners working within WP3 and contributed to the design of deliverable 3.1 of the FEDORA project. The discussion of these results contributed to the refinement of a SenseMaker® questionnaire produced by the HorizonEU project #Our Futures (https://knowledge4policy.ec.europa.eu/projects-activities/ourfutures-images-future-europe_en). We would like to especially thank Erica Bol for this opportunity.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Annex

Lucy's essay (S113_2019_FEB_QC_F)

The sun shines and crosses my bedroom window, I see its light with my eyes still half closed, but then I look at the clock: it is already 6.00. I jump up smiling and thinking that finally, a new day has arrived arm in arm with new opportunities and opportunities, even if the more time passes, the more difficult I find it to leave my Ultimate Bed.

To wake up, nothing is better than a little exercise, a shower, and a cappuccino, without forgetting the subject! Luckily I have Bobby, my Guardian Angel, more commonly referred to as "personal helper and health care worker," who is refreshing my memory right now with what I have to say in a few hours at work. I go down the stairs and arrive at the garage, where I find my beautiful Mustang, which I soon discover has some problems with the battery, probably due to the radio being on all night. but it does not matter (!), It is an excellent opportunity to take a good walk. or run, since now it is done!

Finally, I arrive at work (at the hair, but I arrive), I hold a magnificent conference together with a couple of my colleagues, who, satisfied at least as much as I am at the end of it, decide to invite me and our whole department for a dinner this evening, and I see absolutely no reason why I should refuse, far from it! I accept smiling, and I walk home with my head in the clouds. I arrive in about 20-min, just in time for lunch (which fortunately Bobby has already taken care of) and for an episode of my favorite TV series. After that, I put on some music and start getting on with work, aware that the next few days I will spend at my parents' house without doing anything from a work point of view since I have not seen them for a while.

After 3 h without interruption, I turn off the music and my computer, turn on the phone, and find too many notifications for my taste, but there is one that catches my attention: my dearest friend, practically a brother, has decided to make a stopover here in Dublin so that I can say goodbye before leaving for Sudan for work. I call him and, strangely, he answers right away. He has always hated being on the phone, so I make it short and invite him for an aperitif before going to dinner with my colleagues.

Just half an hour later we are in my favorite bar. I really missed him a lot, but above all, I missed talking to him: you can go from politics to ducks in a very short time, and never lose meaning. In particular, we start talking about the current political situation in Italy, our country of origin, which is more fragile than ever in this period. it was probably lucky to find work so early here in Dublin, even if every day I hear the lack of my old friends and my family. But you have to make choices in your life, and I have chosen my future. and it is not that I never see them: I often go down to Bologna during the holidays to have the opportunity to greet everyone, as I will do this weekend, on the other hand.

Unfortunately, time passes very quickly, and he and I both have to go down different paths again, but it is worth it, at least I hope. I greet him and quickly catch up with my colleagues: it is a pleasant evening and we are able to compare and present our ideas regarding different topics, including Bobby, who I find to be appreciated by a large number of people, all that he is bringing with it the ExitBrexit, thanks to which the United Kingdom could return to be part of the European Union definitively and completely, and the new techniques on mind reading, in which I still do not fully believe.

A few hours and a glass of wine later I walk home, and the more meters I walk, the more I realize how much I need to get my beautiful red metallic car back, but I will think about it later: for now, I need to go home and get me a good sleep.

On the driveway, I find Bobby who was waiting for me with a blanket and a tea that has now turned cold, I thank him and as I throw myself on the bed I think he has been the best investment in recent years. I fall asleep, finally, thinking that tomorrow is a wonderful new day and that I will finally be able to talk and spend time with someone who really knows me, also because those few minutes spent with my "almost brother" had managed to make me feel crazy.

See you soon, my beloved and complicated Italy.

Max's essay (S011_2018_FEB_AI_M)

I wake up tired, the night before I was in the small hours; a few months ago I reached forty but my relationship with the bed has not changed one iota, I'd kill for an extra hour under the covers. At breakfast, I take an extra pill than usual, in addition to the usual one that increases my concentration I decide to also ingest a stimulant: an important day today, and I cannot let the morning sloth inside me affect my performance. As I get dressed I turn on the neural chip I installed somewhere in my skull, I'm too busy to remind myself of such trifles - not that I like passing all my private information to a company that makes the biggest bid, but the modern world has happily said goodbye to your privacy with Facebook and Google decades ago - I have other things running through my head: today I and the other 23 members of my quality check team have to run the latest batch of important AI tests that will revolutionize yet another turn the modern world. I let myself be overwhelmed as the wave of information runs through my neural connections: I like the feeling of having everything under control. Among other things, I am pleased to note that the value of the New Lira has risen again. With a thought, I discover that that night I received 17 unanswered calls, and I am delighted to have turned off the chip a few hours earlier; nowadays almost the entire population leaves their own on. It is not possible to live in modern society without it, but sometimes I regret the good old analog era. . . it is amazing how a few years' difference can affect so much. I like to think that people like me have seen the sunset of the analog, the advent of the digital, and the beginning of the neural. Leaving the house I find a capsule that, like every day, is waiting for me to accompany me to work. Ironically, after all these years we still go to work; probably a life locked up in your own home would not be much progress. The last time I drove a car was at the age of thirty-four, when the first AI for transport control was implemented nationwide: a couple of years earlier the new industrial revolution had begun, and now much of daily life revolves around artificial intelligences. It almost looks like an Asimov book, it is not bad.

David's essay (S220_2021_FEB_SC_M)

In 2040, I imagine I will live more or less where I live now or in the province of Bologna but I do not exclude that I will often be forced to travel for work. I imagine the house is of medium size, just over 100m2 at most, and precisely in the province and therefore in a situation of all things considered tranquility, but home automation is certainly present in my idea of a future home.

My expectation is to have a lifestyle that is not completely sedentary, in fact, I hope to be able to carve out some time to devote to physical activity and also above all to have time for social relationships, which I particularly have a heart.

It is difficult to say how my day will be organized since I do not know the schedules of what my work will be, certainly there is that most of the time I will have lunch in the company of friends/colleagues (if the work will occupy both the morning and the afternoon) and probably often dined in the company of someone. What will mark my time will therefore probably be work.

Surely the environmental issue will still be a very important issue, given the objectives of the Artemis space program, I also like to imagine that the issue linked to the regulation of space will be central, both as regards what belongs to whom, and the laws in force in extraterrestrial space, in end it is highly probable, since I would like to do my job with it, that physical debate will be my daily bread.

The opportunities that I can most easily imagine will be presented to me are international research projects, however, if you really need to think big, you could also imagine having the opportunity to study some physical phenomena in space (again thanks to the Artemis program) but I still see this very difficult, I believe that it takes more than 20 years for it to become almost normal.

I imagine a very active social life, I do not take for granted that I will have a partner but I do not exclude it either, in my circle of closest friends I not only see people with the same interests as me but also those who are my current friends.

Alice's essay (S152_2020_FEB_QC_F)

When the evening falls in the cold of Baltimore, the memories of my maturity surface. it will perhaps be that dry and pungent air, already breathed in different places and times that leads me to reflect on the times of a life in which the present escapes and fades, mingling with a past that I still feel close to.

In the forties of the 2000's, I was in New York, the city that in my youth had fueled my candid fantasy of making concrete the great aspirations that I had long hidden behind a humility that was anything but sincere. New York would have made it possible, I thought, since nothing is unfeasible where the explosive encounter between the microcosms of our planet takes place.

On the threshold of my forties, however, I had to realize that I had overestimated the centrality of the influence of a place, however, promising it might appear, on my ability to cultivate a brilliant present full of opportunities. It must be said I was there following the purchase of some completely automated suburban supermarkets: the only human intervention was in fact maintenance, at most two times a year. After all, the profits from the business made me largely independent and free to manage my time, mostly spent in the exasperated exercise of an empty eclecticism, in the hope of finding something I was really made for.

So I was always looking for what that land could offer me: the opportunities to undertake new careers in the most disparate fields were not lacking, however, I felt a sense of discouragement in the absence of real external stimuli: far from the richness of diversity between people, between their attitudes and the uniqueness of places, which were not necessarily artificial, metallic and cold constructions of glass and concrete.

I did not know whether to trace the cause of this condition of alienation back to the first twenty years of the century, when the first symptoms were already beginning to make their way into my habits: even then I began to consider with some seriousness the implications to which an excessive and unhealthy I use those devices, which were already revolutionizing our relationship with knowledge and emotions, and of which, in spite of myself, we were already addicted.

They were handheld computers, similar to tablets, which with the passing of the years had become thinner and thinner: until they could be wrapped around themselves, until they were incorporated into our muscular system and nervous system: enhancing their physical performance and capabilities cognitive. In this regard, a question that hammered my mind concerned the man himself: I wondered what he actually had left of him. What wealth had actually been left to him by what was thought to be called "progress"? What had become of his independence?

In my own way, I carried on my ethical battle, despite the professional contradiction at the base (I had to support myself), trying to preserve the roots of my identity as a human being while remaining open to the positivity of the advancement of science and technology.

frontiers | Frontiers in Education

TYPE Original Research
PUBLISHED 04 October 2022
DOI 10.3389/feduc.2022.871102

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to STEM Education, a section of the journal Frontiers in Education

RECEIVED 07 February 2022
ACCEPTED 08 September 2022
PUBLISHED 04 October 2022

CITATION
Rap S, Blonder R, Sindiani-Bsoul A and Rosenfeld S (2022) Curriculum development for student agency on sustainability issues: An exploratory study.
Front. Educ. 7:871102.
doi: 10.3389/feduc.2022.871102

Curriculum development for student agency on sustainability issues: An exploratory study

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Despite unprecedented global challenges to the environment, research show that many young people are pessimistic about their ability to address these challenges. This paper explores one approach designed to guide middle-school teachers and their students to develop and practice agency about sustainability issues: *via* a curriculum that challenges students to solve problems by analyzing real-world data and developing scientific arguments, as a basis for engaging in activism. The paper begins with an overview of the United Nation's Agenda 2030, its Sustainable Development Goals (SDGs), the related aims of Education for Sustainable Development (ESD), and a review of what is meant by student agency. Next, the goals and design features of a curricular initiative, "Speak to Me in Numbers," are presented with a brief presentation of two units, each based on a different SDG. The paper's research questions are (1) How were the design features of the curriculum perceived by the teachers? and (2) What were the preliminary outcomes of the curriculum in terms of student and teacher argumentation skills and student activism? To address these questions, we present an exploratory study: observations and comments from in-service teachers and participating students regarding preliminary outcomes of the curriculum that might be related to the development of student agency. In our concluding discussion, based on these findings and relevant literature, we suggest that a promising pedagogy to strengthen student agency on sustainability issues is a data-driven pedagogy that focuses on the development of scientific argumentation, mathematical thinking and activism.

KEYWORDS

education for sustainable development, data-driven pedagogy, argumentation, activism, student agency, sustainable development goals (SDGs)

Introduction

The world today faces global challenges that include complex environmental, social, and economic issues. Nearly 800 million people live in hunger (Von Grebmer et al., 2016), and 1.2 billion live in extreme poverty (Suresh et al., 2015). More than half of the world's agricultural land is overexploited, undermining the livelihoods of over 1.5

billion people (United Nations [UN], 2011). Climate change affects human well-being everywhere, and even threatens basic human survival in certain regions. Countries and islands may be flooded due to rising sea levels. Unprecedented droughts or changing precipitation patterns are expected to result in migrating populations.

The United Nation's sustainable development goals

To address these and other complex global challenges, the UN Council adopted the resolution "Transforming Our World: The 2030 Agenda for Sustainable Development" (United Nations [UN], 2015), adopted by close to 200 countries and based on the 17 Sustainable Development Goals (SDGs).

The roots of the SGDs initiative lie in a shared global vision for a better future economically and socially. Sustainable home for the planet and for present and future generations (Halisçelik and Soytas, 2019). The SDGs have been designed with the intention of having them achieved by 2030. The primary responsibility for monitoring and testing achievement is at the national level.

Sustainability education and environmental citizenship

What is the United Nations' vision for how the world can achieve the 17 SDGs by 2030? According to the UN, achievement of each of the SDGs objectives is dependent on the collaboration of each country's local civic organizations, along with its educational system (e.g., Lidstone et al., 2015). Educators, students and teachers, business professionals and members of civic associations are all important stakeholders and players in the process of achieving each country's SDG goals (Blanco-Portela et al., 2017). Thus, these ambitious goals are only a common reference point. Their achievement needs to take into account each country's social, environmental and economic capital, including its educational system, on both the national and local levels (Svanström et al., 2012).

The effort to translate the UN's SDGs into sustainability education was undertaken by UNESCO in its Education for Sustainable Development (ESD) initiative. The vision of UNESCO is that ESD: empower learners of all ages with the knowledge, skills, values, and attitudes to address the interconnected global challenges we are facing, including climate change (Mandler et al., 2012), environmental degradation, clean water (Mandler et al., 2014), loss of biodiversity, poverty, and inequality. Learning must prepare students and learners of all ages to find solutions for the challenges of today and the future. Education should be transformative and allow us to make informed decisions and take individual and collective action to change our societies and care for the planet (UNESCO, 2019).

Another effort to educate the world's youth to address global sustainability challenges relates to the emerging field of Environmental Citizenship, defined as the responsible pro-environmental behavior of citizens who act and participate in society as *agents of change* in the private and public sphere on a local, national, and global scale, through individual and collective actions in the direction of solving contemporary environmental problems, preventing the creation of new environmental problems, achieving sustainability and developing a healthy relationship with nature (Hadjichambis and Reis, 2020).

This emphasis on the developing the agency of citizens–including students–is reinforced by Dobson (2010), who defines Environmental Citizenship as "pro-environmental behavior, in public and in private." This behavior is driven by a belief in the fairness of the distribution of environmental goods, in participation and in the co-creation of sustainability policy. Thus, Environmental Citizenship relates to the active participation of citizens in moving toward sustainability.

Student agency and activism

As seen in the approach of both the UN's Education for sustainable development and the field of Environmental Citizenship, one of the main objectives of sustainability education is the development of student agency. What is meant by this concept?

The concept of "student agency" is a complex multidimensional concept that has recently emerged in pedagogical discourse. According to the OECD, there is no global consensus on the definition of this concept. In fact, student agency is perceived and interpreted differently in different countries; in some cultures, there is no direct translation for the term. Nonetheless, student agency is central to the OECD Learning Compass 2030, where it is defined as "the capacity to set a goal, reflect and act responsibility to effect change. It requires the ability to frame a guiding purpose and identify actions to achieve a goal. It is about acting rather than being acted upon; shaping rather than being shaped; and making responsible decisions and choices rather than accepting those determined by others" (OECD, 2019).

Student agency relates to the development of an identity and a sense of belonging. When students develop agency they rely on motivation, hope, self-efficacy and a growth mindset (the understanding that abilities and intelligence can be developed) to navigate toward well-being. This enables them to act with a sense of purpose, which guides them to flourish and thrive in society (OECD, 2019).

The concept of student agency is informed by Bandura's theory of human agency (Bandura, 2001). In social cognitive theory (SCT, Bandura, 1986), agency "is present in the ability of people to regulate and control their cognition, motivation, and behavior through the influence of existing self-beliefs (i.e., self-efficacy). SCT considers the self-as-agent to encompass four core features of human agency–intentionality, forethought, self-reactiveness (self-regulation), and self-reflectiveness (self-efficacy)." (Code, 2020). It is also important to note that environmental hope is linked to agency thinking (Kerret et al., 2020).

How to develop student agency? According to the OECD (2019), the process implies relationships with others.

Parents, peers, teachers, and the wider community influence a student's sense of agency, and that student influences the sense of agency of his or her teachers, peers and parents–a virtuous circle that positively affects children's development and well-being. Thus, "co-agency," often referred to as "collaborative agency," implies the influence of a person's environment on his or her sense of agency.

Research and development efforts to develop and measure the multidimensional aspects of student agency are emerging. Efforts to develop student agency in regard to sustainability issues have included youth-led action projects focused on individual and collaborative change in both formal and informal educational contexts (e.g., Trott, 2020). In regard to the evaluation of student agency, a questionnaire tool that has been developed is described by Code (2020) and a number of qualitative research to evaluate students agency have been reported (e.g., Lehtonen, 2015).

A related construct to student agency is activism, a term that traces its roots to the writings of the early sociologists (e.g., Parsons, 1937) who understood activism as social action directed to achieving a common communal goal. Whereas student agency reflects the development of a long-term personal identity and taking initiative, with the capacity to act responsibility to effect change, activism reflects the engagement in short-term activities that require collective action aimed to achieve a common good. We understand these two terms to be complementary: one relates to the development of a student's personal initiative while the other relates to action collectively taken to effect a change in the student's local environment.

In our study, we were interested in knowing to what extent, if any, an innovative interdisciplinary curriculum called "Speak to Me in Numbers" develops student agency relating to global sustainability challenges, where activism is a design feature to help develop student agency. In the following sections, we present the design features of the curriculum and how they were expressed in two curricular units. Next, we present the study's methodology, the data and findings, leading to a discussion about the relationship between the curriculum's design features and possible outcomes, including the development of student agency.

Design features of the "Speak to Me in Numbers" curriculum

Design features are "guidelines expressing the goals for the learning outcomes, the classroom activities and the teaching strategies" (Jiménez-Aleixandre, 2007). Each unit in the "Speak to Me in Numbers" curriculum is based on several design features:

1. A Sustainable Development Goal (SDG),
2. Data-based challenges requiring the use of mathematical literacy to address them,
3. Student construction of evidence-based scientific arguments, and
4. A concluding student activism activity.

In this exploratory study, we applied a design-based research approach by collecting continuous feedback from the participating teachers and students. In the paper we will present the design features and preliminary evidence collected that relates to the curriculum development process.

A sustainable development goal

Each of the "Speak to Me in Numbers" units is based on one of the United Nation's Sustainable Development Goals (SDSs). The SDGs chosen as topics for the different units were chosen because they can be well-integrated into a ninth-grade enrichment program. Each SDG has many important objectives. An effort was made to focus the curriculum on those objectives that are most relevant to the students and that can be well-integrated into the science syllabus, e.g., objectives that relate to the carbon cycle, acid-base solutions, and alternative energy sources. In some cases, science content was included in the units that is not part of the regular science syllabus.

Data-based challenges requiring the use of mathematical literacy to address them

After an introduction to the relevant SDG, students receive relevant data–presented in graphs or data tables that relate to a particular problem or challenge. By performing a mathematical analysis of the data, students reach data-based conclusions and make data-based arguments. It is important to note that the mathematical knowledge and skills needed for this analysis are not new for the 9th grade students, but that the applications of the knowledge and skills to the context of sustainability issues are new. This approach can be characterized by the term "mathematical literacy" which can be understood as an individual's capacity to formulate, employ and interpret mathematics in a variety of contexts (Istiandaru et al., 2018). Such contexts include personal, societal and scientific contexts (Tabach and Friedlander, 2008; OECD, 2022).

Student construction of evidence-based scientific arguments

The data-based challenges are the foundation for another design feature of the curriculum: the construction of evidence-based arguments (Osborne et al., 2004; Simon et al., 2006). In this way, the curriculum fosters a classroom culture of argumentation discourse regarding sustainability issues.

While the research literature provides many different ways to define what is meant by a scientific argument (e.g., Driver et al., 2000), we have adopted the Toulmin model of argumentation (Toulmin, 1958), as described in greater length in section "Students and teacher data-based argumentation skills" below.

The general goals that incorporate characteristics of an argument focus on empowering students to speak and write science, as well as supporting their connection to science communities and developing epistemic criteria for evaluating knowledge. Studies dealing with arguments relating to the understanding of scientific epistemology have found that students need to be in teaching-learning contexts in which they make explicit epistemic decisions in order to understand scientific methods (Mork, 2005). In the "Speak to Me in Numbers" curriculum, the student construction of evidence-based arguments focuses on "how we know what we know" regarding specific sustainability issues, as the basis for understanding "what we know" regarding those same issues.

A concluding student activism activity

At the end of each unit, the students are challenged to plan and carry out an activism activity. This activity is also data-driven and challenges the students to make a plan to "take action," based on the data. These activities are usually set in the context of the students' local environment. This activity causes the students both to take action regarding a specific sustainability issue, as well as to "speak in numbers," i.e., in a manner that improves their scientific and mathematical skills, organizes their thoughts, builds good scientific arguments and creates awareness for the need to change in their immediate environment.

The processes of curriculum development and implementation

Given the above four guiding design features, the curriculum was developed and implemented by an interdisciplinary staff of content specialists from the sciences (particularly chemistry and biology) and mathematics, along with several teachers of these disciplines for middle school students.

In the curriculum development process, the staff first chose a science-rich SDG on which to focus (e.g., SDG 3: Good Health and Well-Being). Next, the science content specialists outlined the relevant science principles and concepts (e.g., health issues involving the COVID-19 pandemic and virus). Afterward, both the science content and mathematics content specialists looked for data that could be analyzed by middle school students, in order to develop evidence-based claims involving the relevant science principles and concepts. Given these data sets, activities were developed, focusing on the application of mathematical knowledge and skills by these students in the context of the SDGs. It is important to note that the relevant mathematical knowledge and skills were already known to the middle school students. The emphasis was on students developing mathematical literacy (OECD, 2022). As part of the development process, science and mathematics teachers on the staff tried out the activities with their students, feedback was provided, and necessary changes were made in the activities.

In the curriculum implementation process, the project staff first led Professional Development (PD) courses for middle school teachers in the areas of science, as well as mathematics; the main goal of these courses was to familiarize the teachers with the content and pedagogy of the curriculum.

After the teachers completed the PD course, those who implemented the program participated in a Professional Learning Community (PLC) (Vescio and Adams, 2015). In this PLC, the teachers shared their questions and difficulties regarding the implementation of the "Speak to Me in Numbers" curriculum, as well as suggested solutions and successes. Meeting regularly in an atmosphere of mutual trust (Waldman and Blonder, 2020), the teachers were able to develop their practice and their visions of the relevant Pedagogical Content Knowledge (PCK), a concept initially understood as "the ways of representing and formulating the subject that make it comprehensible to others" (Shulman, 1986, p. 9).

In the next section, we will briefly describe two of the curriculum's units and discuss how these design features are expressed in each unit.

Expression of the design features in the program

Below we describe, from the point of view of the program's developers, how the four design features described above found expression in the program, in two of its units that relate to the Sustainable Development Goals (SDGs): (1) Good Health and Well-Being (SDG 3) and (2) Life Below Water (SDG 14).

Good health and well-being (SDG 3)

The goal of this SDG is "to ensure healthy lives and promote well-being for all at all ages" (United Nations [UN], 2015). The worldwide COVID-19 pandemic provided a real-world context to help students better understand the complex situation around them. For example, concepts common in news items, such as "flattening the curve" and "exponential growth," need to be explicated in order for students to understand them and act accordingly.

The unit of SDG3 begins with a news article describing an experts' prediction of the number of COVID-19 cases about a month into the future. At first glance, this prediction seems exaggerated. Students need to decide whether this is the case or not, based on their analysis of the data, using an Excel spreadsheet. As part of this assignment, students learn about how an epidemic spreads and the meaning of exponential growth. In this way, students develop their critical thinking and mathematical skills to develop evidence-based arguments.

Next, students learn about the concept of "orders of magnitude" while investigating the size of the Corona virus and how this size relates to more common objects. This activity is used to help students assess the relative protective effectiveness of different types of masks, to stop the spread of the virus. Students watch a news video that addresses the costs and benefits of different types of masks. Students observe Scanning Electron Microscope (SEM) images of different types of masks (see **Figure 1**) to estimate the different sizes of the spaces between the fibers and combine all the different sources of information in the activity to draw their conclusions about the preferred mask.

The students then analyze data from 10,000 people who were tested for COVID-19; these data include different symptoms and health outcomes associated with each person. Students use the "CODAP" application[1] to examine the large data sets from confirmed COVID-19 cases to evaluate different arguments about what symptoms predict COVID-19 infection. The unit concludes with an activism activity challenge: Students are asked to analyze data regarding different "activity centers" (restaurants, museums, businesses, etc.), leading to policy recommendations for opening up the economy, after a lockdown. They draft a letter to policymakers based on this analysis. Teachers can decide on another activism scenario depending on the class they teach, as happened in the cases presented below (see section "How the program promoted student activism").

Life below water (SDG 14)

The goal of this SDG is "to conserve and sustainably use the oceans, seas and marine resources for sustainable development" (United Nations [UN], 2015). The unit based on this SDG relates to the negative consequences of human activities that involve the oceans. At the beginning of the unit, students are asked if they think is it important for them to know what is happening in the oceans because, after all, most students don't live next to them. Why should they care?

Next, the students are exposed to graphs that connect carbon dioxide emissions with ocean acidification. They come to the conclusion that an increase in the concentration of carbon dioxide causes the pH level to decrease, thus increasing ocean acidity. Students also examine how different predictions of carbon dioxide levels may cause different ocean acidification levels, leading to negative consequences for marine life. (This activity about the effects of atmospheric carbon dioxide is connected to another unit in the curriculum, Climate Action, SDG 13).

In the activity that follows, the students learn about The Great Pacific Garbage Patch, a collection of plastic debris in the Pacific Ocean (Plastic Ethics, 2018). Based on real data, they estimate its size (about 1.6 million square kilometers) and learn about ways in which plastic waste at sea can be treated. They do so while learning about Boyne Slatt, a Dutch entrepreneur who was first exposed to the problem of ocean plastic waste as a teenager on a diving vacation, and decided to take action by setting up a company that uses boat interceptors to remove this plastic.[2] Next, students analyze graphs that help them understand the relationship between macro-plastics and micro-plastics in the ocean and how the forecast of a reduction in sea macro-plastic waste does not necessarily result in a similar decrease in micro-plastics.

What are the implications of micro-plastics on marine life? Students address this question by relating to data in a scientific paper (Mattsson et al., 2017); they analyze a graph showing that a high concentration of micro-plastics causes greater and faster mortality of *daphnia* (a small planktonic crustacean), causing harm to the marine food chains (**Figure 2**). They are asked to draw conclusions and contemplate what would have happened if the starting point of the experiment had been different (i.e., with a different concentration of micro-plastics and a different initial number of daphnia) based on their earlier

1 https://codap.concord.org/

2 https://theoceancleanup.com/about/

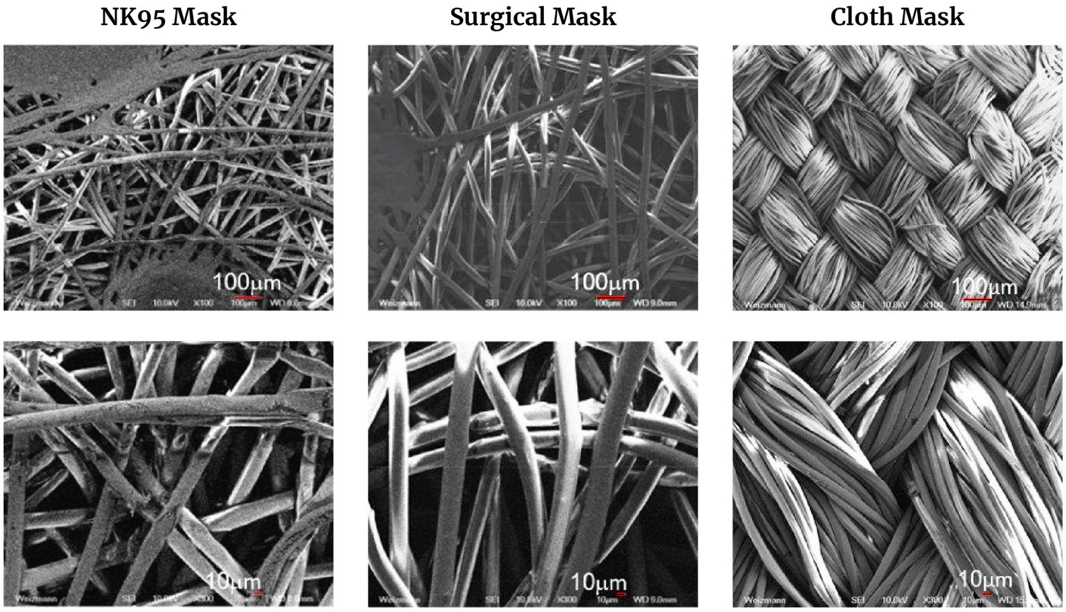

FIGURE 1
Example of question from unit on "Good health and well-being" (SDG 3). Question and accompanying illustrations of three main types of masks on the market for public use, taken from a Scanning Electron Microscope (SEM) and depicting the surface of the masks on the micrometer scale.

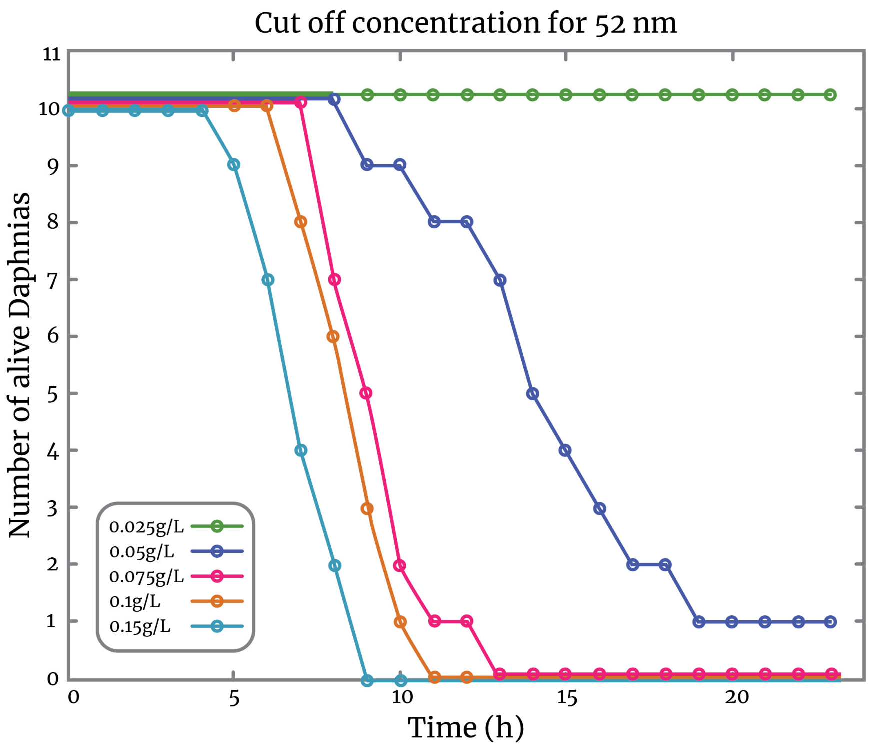

FIGURE 2
Example of question from unit on "Life below water" (SDG 14). Based on research presented in a scientific paper (Mattsson et al., 2017), students learn about the effect of micro-plastics on the marine food chains.

data analysis. Subsequently, students are asked to think about "real life" consequences of micro-plastics in the oceans.

In the following activity, students are exposed to the concept of "the tragedy of the commons" (Hardin, 1968) by working through a simulation of overfishing. In a playful game-playing atmosphere, the simulation challenges students to examine various goals related to the survival of the fish population, the survival of the families dependent on this food source, and their respective economic gains. Students link their conclusions from the simulation to the real-world of commercial-scale marine fishing.

The activism challenge for this unit deals with the issue of plastic packaging for various consumer products. Students analyze data diagrams and conclude that most plastic waste comes from packaging. They use mathematical skills to calculate the different surface areas that can enclose the same volume and conclude that some packaging shapes use less plastic than others, for the same volume. Based on this knowledge, they are asked to examine the plastic packaging of products at their local supermarket and make recommendations for how to change the packaging, in order to reduce the amount of plastic used.

In summary, the above presentation of the two units illustrates how the curriculum's design features were expressed in these units in the "Speak to Me in Numbers" curriculum. Specifically, the SDGs provide a broad and productive context in which students (a) are exposed a given sustainable issue and to data-based challenges which require the use of mathematical thinking to address them, (b) construct evidence-based scientific arguments, and (c) use the knowledge and skills from them in addressing a concluding activism activity challenge that involves their local environment.

Methodology

The two guiding research questions of the exploratory study were:

(1) How were the design features of the curriculum perceived by the teachers?
(2) What were the preliminary outcomes of the curriculum in terms of student and teacher argumentation skills and student activism?

In order to answer this question, we will present the perspectives of teachers who went through the PD and implemented the program in their classrooms. **Figure 3** presents how this article is organized, in terms of the agents of the curriculum: curriculum developers, teachers, and students.

We presented the design features that guided the curriculum developers, in building the program's units, and we provide examples of two different units that were presented as part of the teachers' PD. In the results section, we will present the reflections of the teachers relating to the curriculum's design features. In addition, teacher argumentation skills before and after the PD will be analyzed along with development of the students' argumentation skills before and after the program. Finally, interviews conducted with two teachers concerning their students' activism will be presented and analyzed.

Population

In 2020, the program was implemented as part of a 30-h professional development (PD) course. About 80 9th grade teachers of science and mathematics participated in the course. In this study, which was an exploratory study, we chose the appropriate population for each aspect we wanted to investigate. We present evidence from reflections of one PLC comprising 18 teachers who implemented the program in their classes. In addition, we selected representative arguments of these teachers and their students. We also interviewed two teachers who implemented the program in their classrooms and reported to us about the activism activities that were raised at the initiative of their students.

Limitations

The main limitation of the current research is that most of data rely on teachers, as windows into their students' learning. In future studies, we plan to collect more data from the curriculum's participating students, in order to further test and refine the resulting model. Another limitation is that the data collection on student agency occurred soon after the students completed the program. In the future in order to determine to what extent student agency is maintained, we suggest investigating this outcome also at a later date.

Research tools and data analysis

Teacher reflections about the program's design features

After completing the PD course and implementing the program in their classrooms, the teachers in the PLC provided their reflections on the program, how they understood the program's design features and how the program was received by their students.

The teachers were asked to answer the following questions:

- What are the differences between the teaching of the program "Speak to Me in Numbers" and the regular science teaching in your class? For each difference you point out please give an example.

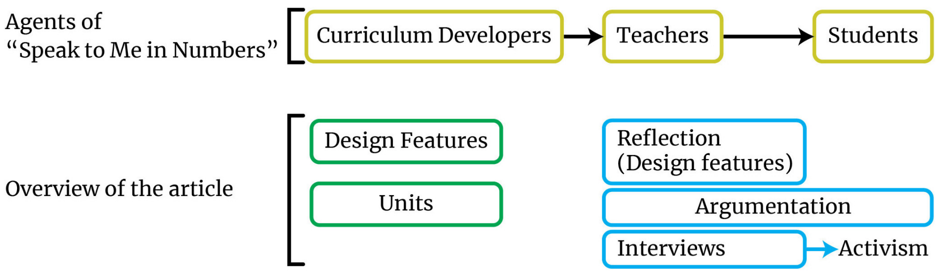

FIGURE 3
Agents of the program and article overview.

- How did the course make you think differently about issues you already knew?
- What do you think about the use of arguments during science lessons? And to what extent did the tasks you performed during the training promote the use of argumentation in your teaching?

The reflections were analyzed by applying a top-down approach according the design features of the program (similar to Dorfman and Fortus, 2019). After grouping the teacher statements according to the design features we looked for emergent categories for each feature. The first author conducted the described qualitative analysis and received feedback from the co-authors. The discussion continued until the authors reached a consensus. In the results, we describe the categories and provide examples of each.

Students and teacher data-based argumentation skills

Before beginning the PD course, teachers were asked to answer this question: "There is a claim that the human use of plastic products affects marine organisms. Do you agree or disagree? Provide an explanation for your answer." Teachers were also asked to answer this question after the PD course.

In addition, students were asked before and after the program the following question: "There is a claim that masks don't help to protect against the COVID-19 virus. Do you agree or disagree? Provide an explanation for your answer."

In both cases, by comparing these two answers, we were able to analyze the change in students' and teachers' argumentation skills. The arguments were examined using the Toulmin model (Toulmin, 1958; Osborne et al., 2004; Katchevich et al., 2013). Each of the arguments was analyzed in terms of the presence or absence of key components in this model, i.e., claim, evidence (or data), warrant, backing, and scientific explanation, defined as follows:

A claim is a conclusion whose merits are being established by the argument.

Evidence (or data) is facts that are presented as grounds for the claim.

A warrant is a principle, provision or chain of reasoning that connects data to the claim.

Backing is additional support, justification, and reasons to back up the warrant.

A scientific explanation is an explanation of a phenomenon based on principles of science.

The task of making a data-based argument required the students and the teachers to make connections between claims, supporting evidence, warrants, backing, and scientific explanations.

It is important to note that we chose our examples about changes in argumentation skills, in order to support what we found to be representative of teachers and their students. However, given our small sample size, we did not conduct a rigorous study regarding these changes.

Teacher interviews about student activism

Semi-structured interviews were conducted by Zoom with two teachers (Fontana and Frey, 1998). The interviews took place 6 months after teachers completed the PD course and after they implemented the curriculum in their classrooms. The goal of these interviews was to collect their perspectives regarding their students' activism and to understand how they felt the curriculum's design features were expressed, specifically in regard to the transformation process students underwent to become change agents.

The teacher interview included the following questions:

1. Can you describe the activism activity your students performed?
2. Who initiated the activism activity? Who led the activity?
3. How were the content and skills of the unit expressed in the students' activism activity?
4. Did your students add content or skills beyond what was included in the unit?

The interviews were analyzed in a top-down perspective according the design features of the program (Dorfman and Fortus, 2019).

Results

Below we first present data relating to how the design features of the curriculum were perceived by the teachers after they implemented the program. Afterward, we present data about the outcomes of the implemented curriculum and discuss to what extent student agency was part of these outcomes.

How did the teachers perceive the design features of the curriculum?

For each design feature we identified different categories that shed light on teachers' perceptions. Table 1 shows the teachers' perceptions about the four design features: (1) the context of the SDGs, (2) using data and developing high-level mathematical skills (3) developing argumentation skills, and (4) a concluding student activism activity.

The teachers' reflections provide some important insights. First, the teachers felt that the SDGs topics were relevant and important to learners as well as to themselves. The program integrates environmental topics and associated values. Second, the teachers appreciated the program's integration of mathematics and science, as well as the importance of mathematics in understanding and solving authentic problems. They noticed the effect that this approach had with their students, i.e., students were more convinced by working with the data and were not likely to forget the results. Third, teachers thought that the development of evidence-based scientific arguments is important not only for scientific thinking but also in everyday life and that it also leads to the development of critical thinking. Lastly, in regard to the design feature of concluding each unit with a student activism activity, teachers felt that this activity promotes student initiative on many levels (the classroom, school, community, and society). Another perspective on this design element, *via* teacher stories of student activism, is presented later in this paper.

What were the outcomes of the implemented curriculum and to what extent was student agency part of these outcomes?

How students and teachers develop their data-based argumentation skills

As described above, students were asked before and after the learning the program to respond to the claim that deal with Good Health and Well-Being (SDG3) "There is a claim that masks don't help to protect against the COVID-19 virus. Do you agree or disagree? Provide an explanation for your answer." Before learning the program, it was noticeable that most of the students did not substantiate their claims:

> *"No, I disagree [claim]. The masks reduce the option of contagion if people continue to wear them [claim]"*

> *"No, I disagree [claim], because the masks help by preventing the spread of air of the COVID-19 patient [claim]"*

After learning the program, students responses to the claim were more evidence-based, as illustrated by the following examples:

> *"No, I disagree [claim], the Centers for Disease Control and Prevention highlighted the need to wear the mask continuously. The masks provide maximum protection when they are snugly fitting around the face. It is known to us. During a single sneeze, as many as 3,000 droplets can be spread from the infected person's mouth. Some people are concerned that the virus will spread through droplets that are spread while talking, therefore it is recommended to wear a mask to reduce the spread of the contagion." [data + warrant]*

We can see that the structure of the argument written by the student changed. It is now based not only on an opinion but rather on new data and information obtained during the study of the unit. In this example, the student brought forth evidence and figures from the material taught in the unit, and based her claim on them. Below is another example.

> *I do not agree [claim]; I base my claim on what I discovered during the course when we learned about different types of masks. For example, "N95" masks cover the nose and mouth and prevent the transmission of the coronavirus, which is about 0.1 microns in diameter [data]. This way the masks contribute to the protection against viruses and infections, as these masks consist of several layers that prevent the entry of small particles like the coronavirus. There are other types of masks, such as woven cloth masks, which are considered among the least effective masks in protecting against Corona. This is because of gaps between the fibers of the cloth masks that are about 44 microns wide and about 22 microns long, which allow the coronavirus to enter easily through them. Therefore, I prefer to use the N95 mask, and I encourage my family and friends to wear it to protect them from infection." [Backing + warrant]*

This example illustrates how the student's argument improved. The student does not base his knowledge only on what is "learned in class" but puts the data into use, and bases his argument on the analysis he performed as part of the tasks. Finally, the student even indicates what is his preferred choice in light of the findings he came across during the course of the unit.

Similarly, we found out that the teachers also learned to substantiate their claims. In the context of SDG14, teachers were asked before and after the PD program to respond to the claim that "Human use of plastic products affects marine organisms". Teachers were asked if they agreed or disagreed with the claim; they were also asked to provide an explanation for their answers.

At the beginning of the PD, it was noticeable that most of the teachers did not substantiate their claims, and when they did, their reasoning was poor and not based on concrete data:

> *"Yes, I agree that (plastic) waste causes the death of marine organisms.[claim]"*

> *"I agree. [claim] The use of plastic products increases the amount of waste and toxic substances that harm life in the water."*

> *"Plastic waste in the oceans causes pollution and affects the organisms that ingest poisoned water. Moreover, fish and other marine organisms often feed on the plastic products and suffocate."*

It can be seen that the teachers' responses to the claim made after the PD were more evidence-based than were their responses before it. More specifically, after the PD the teachers used more arguments based on data processing to justify their claims, as can be seen in the following examples:

> *"The claim that the use of plastic products negatively affects marine organisms can be examined on two levels: (a) Laboratory studies, such as an experiment that examined the effect of different concentrations of microplastic on the survival of Daphnia placed in these solutions. In these experiments, the big advantage is isolating variables. In this case, it can be seen that microplastics have a great impact on the survival of Daphnia.* [claim + data + warrant] *(b) Measurements and testing of phenomena that exist in nature (in vivo). These studies have a great advantage because one can actually see the effect of the plastic (macro or micro) on the number of marine organisms that survive in different regions. There are certain locations around the globe where plastic pollution is particularly high. Immediate improvement at these locations can lead to a global change in ocean life. We must pay attention to everyone's plastic waste. Paying attention also means limiting the use of consumable plastics, and dealing properly with existing waste sites. Scientific and technological thinking, as well as encouragement and education for such thinking, can bring about a variety of solutions. Producing many ideas about how to improve the way we live will make an impact on everyone and on all the interrelated links that make up the ecological balance."* [data + warrant + conditional argument]

In this example, it can be seen that the teacher used data analysis which he had performed during the PD. He noted the data that were presented to him, which he analyzed in the context of the effect of the microplastic concentration on the Daphnia, and also their effect on the whole food chain. In addition, the teacher indicated the conditions under which there may be a change in this trend and what it requires of us in this context [conditional argument]. Below is another example.

> *"I agree with the claim that the use of plastic products affects aquatic organisms* [claim]. *We saw in an experiment that they examined the effect of the concentration of microplastics in water on the Daphnia population. As the microplastic concentration increased the Daphnia died earlier and at a faster rate. The size of the Daphnia population affects the entire food web, as Daphnia is part of the microplankton and many animals feed on it. Consequently, the effect travels up the entire food chain. There are also other marine organisms affected by microplastic."* [warrant + backing]

In this example as well, it can be seen how the teacher uses the data and its analysis in order to substantiate her claim. In addition, she explains the context and how it harms not only the Daphnia themselves but the entire food network.

From these teachers' answers we can see that their experience of data analysis in the PD was significant for them, since they addressed the same question more in depth, while using more argumentation components and moving away from the intuitive answers they had before the PD. They based their answers on the data they had analyzed in the PD course. In addition, some teachers added terms and conditions in order to strengthen their claims. So apart from the scientific knowledge they gained, they also improved their skill of argumentation.

To sum-up the program's influence on the development of argumentation skills, a pre-post study showed that the teachers' arguments regarding sustainability issues after the Professional Development course were stronger and more evidence-based than before it. We have presented examples of how both teachers and students have improved their argumentation skills, given Toulmin's model. From what we have seen, this change is representative for all teachers, but not for all students; however, as mentioned in the methods section, we cannot make a rigorous claim to this effect, given our small sample size.

How the program promoted student activism

Two teachers who participated in the PD and taught the program in their classes were interviewed in order to provide their insights regarding the student activism activity. We first present a summary of their descriptions of the activity, as conducted by their students, and then analyze these stories in terms of their common components (Table 2).

Annie, a ninth-grade science teacher taught the SDG-3 unit (Good Health and Well-Being, in the context of the COVID-19 pandemic) in a class of gifted science students. Annie's students initiated their own activism activity after they conducted the original activism activity that was part of the program (i.e., to draft a letter to policymakers, based on data-based arguments from the unit, regarding how the economy should be opened after lockdown. See the description of the unit above.). Her students said that they learned a lot and gained a new understanding of how the pandemic spread and how they can act responsibly. They said there is no reason the other students in school should not learn what they did and told her that they wanted to do something, in this regard. They asked Annie to present what they had learned to all the students in their grade level in order to promote their good health in the context of the COVID-19 virus. After consulting with the school science and mathematics coordinator, Annie suggested that she prepare a PowerPoint presentation for this purpose. However, her students asked that they prepare their

TABLE 1 Analysis of the teachers' perception regarding the design features.

Design feature	Perception	Example quote
1. The context of the SDG	a. The topics of SDGs are relevant to learners.	"It connects the learner to previous experience and knowledge, the learner's needs, her emotional world, skills, hobbies and occupations, and needs as an individual and part of society. For example, students usually will not acquire the information provided in the unit on COVID-19."
	b. The program integrates environmental topics and associated values.	"The program summons challenging, intriguing, and interesting content, messages and ideas tailored to the learner."
	c. The SDG topics were important to the teachers as well as to the students.	"The course made me think differently about the importance of integrating environmental topics and values into teaching... to understand how important sustainability and its long-term effects are."
2. Using data and high-level mathematical skills	a. Teachers appreciated the program's integration of mathematics and science.	"In this program for the first time I saw a real integration of mathematics and science. It is a new field to me, and I think it is very interesting and needed."
	b. Teachers felt encouraged to integrate mathematics skills into their science classes.	"The course certainly encouraged me to think differently about how I incorporate math into my science classes. Before, I would shy away from math and just mention it as a side note, but now I am more confident in discussing the mathematical elements that underlie scientific ideas. For example, when I teach about bacterial culture and the growth curve... I would usually call the steep part of the curve "exponential growth" and move on. Now I can discuss what an exponential curve is, what are its properties and so on."
	c. Teachers commented on the effect that this approach had on the students.	"Dealing with numbers and high-level mathematical skills creates an effective student, as the student can be involved using numbers as opposed to being provided with the information as "ready-made.""
	d. Students are more convinced by working with the data and are not likely to forget the results.	" I think it is worthwhile to let students calculate and deal with numbers, rather than just talk about trends, because when we analyze data we will help students understand the issue or curve better, more deeply and in a well-established manner. When the student has data in the form of numbers, it convinces them of the answer.... Without numbers, the student is not one hundred percent convinced, and then the information is not assimilated well and may quickly be forgotten."
	e. Mathematics is important in understanding and solving authentic problems.	"The course highlighted the important role of mathematics in understanding and solving authentic problems (e.g., how to deal with global warming), using mathematical skills and tools."
3. Developing argumentation skills	a. Development of argumentation skills is important.	"This is an important skill that students must acquire, to learn how to provide their arguments with opinions based on data-based explanations. This ability gives students the skill to present a reasoned position. I instruct many students to accompany their hypothesis, conclusion or argument with a scientific explanation and reasoning. Although I encourage students to use this skill, there is no doubt that the various discussions and activities during the course made me pay more attention to this point in order for students to have the ability to have a scientific discussion."
	b. Developing argumentation skills is important not only for scientific thinking but also in everyday life.	"The program is built in part on developing argument-building skills. I think this is an essential skill to develop in students... I think it is an important skill to teach as it helps in many aspects of life. If you know how to build an argument that is logically based and relies on objective data, then you can reach a higher level of thinking in each area... It is very important that students know how to build arguments and know how to provide answers to issues that they do not always agree to or accept."
	c. Argumentation skills lead to the development of critical thinking.	"Students often tend to approach different topics intuitively and do not exercise critical thinking. I find it difficult for students to reason or substantiate their position... I remember a lesson where something was said in the media, and the PD coordinators told us that what the media is saying is not always true. Suddenly I had to change my perception and formulate an argument that goes against what was told in the media. That was really significant and important for me."
4. Developing student activism	a. Activism promotes student initiative on many levels.	"The program encourages learners to be involved in the classroom, school, community and society and promote an exemplary society."
	b. The activism has crossed the boundaries of the classroom and affects the behavior in daily lives	"Today in our private home, our children are careful not to throw any plastic waste (or cardboard) in the trash but to collect and recycle. We also make sure to turn off unnecessary lights in the house and so on."

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TABLE 2 Analysis of the components of the student activism activities.

	Annie (SDG-3)	Jasmin (SDG-14)
Summary of the student activism activity	Students presented lessons to other students in the school, in order to develop their awareness about the importance of wearing masks to prevent COVID-19 infection.	Students wrote letters to stakeholders, requesting that they address the problem of plastic waste in their town. They also calculated the weight of disposable plastic used during the month of Ramadan.
Components of the activity		
Initiation of the activity	Students initiated the activity and developed the activity content independently.	The teacher initiated the activity. However, students chose the recipients of the letter and developed its content to support their request.
SDG knowledge	Students applied knowledge, skills and resources from the unit.	Students applied knowledge, skills and resources from the unit and added additional resources.
Data-based argumentation skills	Students adjusted the level of the SDG knowledge and the level of argumentation to the level of the students they taught.	Students conducted additional calculations, relating to the amount of plastics used by city residents during the Ramadan celebrations, in order to better support their arguments.

own presentation, claiming that they had a better understanding of the background of the other students. In their presentation, the students presented data and resources from the unit. In addition, they selected material in science and mathematic according to the different grade levels of each class. For example, the probability questions regarding the protection provided by mask-wearing were presented only to ninth graders and not to younger students. In addition to the unit's content and skills, they emphasized critical thinking skills in regard to being critical while watching news on TV or while reading newspapers, even when the person being interviewed is famous or an expert. The activity was conducted *via* Zoom to all the classes in the school. Each of the lessons was conducted to one class by two students, in the presence of the class homeroom teacher. The school's principal and vice-principal visited all the classes and were exposed to the activism activity. Annie received positive feedback from the school teachers and the school's management staff, who wrote about the activity in the school magazine. Annie also received positive responses from the parents of her students.

Jasmin taught the SDG-14 unit (Life Below Water). The students modified the activism activity as suggested in the original unit (i.e., to make recommendations for changing the packaging of products in order to reduce the weight of the plastic used, by applying mathematical skill and the knowledge students learned in the unit). They decided to address the problem of plastic waste in their town by writing letters to a variety of stakeholders: the city's mayor, the head of the sanitation department of the municipality, the school principal and a local kindergarten teacher. In their letters, the students described how each of these people could contribute locally in their town to the solution of a global problem. In order to convince these stakeholders to lead efforts to reduce and recycle disposable plastics, the students decided to connect the challenge to the everyday lives of the people living in their town. The activity was conducted during the month of Ramadan, when every evening Muslims celebrate the end of the Ramadan fast with a family feast. In this feast, many families use as great deal of disposable plastic cups, plates, and cutlery. The students also decided to calculate the weight of disposable plastics used in each house, in the school, in the city, and in the whole Muslim population around the word, during the month of Ramadan. In their letters to the above influential people, the students suggested what they should do in their roles to make a change. For example, the head of city's sanitation department should place collection cans for recycling in different locations in the town and the school principal should prohibit the use of non-recyclable plastics in the school cafeteria. Jasmin described how the unit and the student activism activity influenced her students. She said that she has taught the topic of polymers more than 10 years. In the past, her students usually knew how to solve related problems and received high grades but they tended to forget what they learned after the exam. In contrast, her students this year kept talking about the topic even at the end of the year; they discussed the influence of their letters and compared their respective contributions to influence their families and friends. Jasmin summarized that this time her students will not forget what they learned about polymers.

To sum-up the teacher interviews and the student activism activities, the students integrated their SDG knowledge and data-based argumentation skills to initiate projects that demonstrated their agency in making sustainability-related changes in their immediate environment. More specifically, students in Annie's classroom decided to teach other students in their school about what they had learned about how the COVID-19 virus spreads and what can be done about it. Students in Jasmine's classroom engaged in the unit's activism activity relating to plastic and added their own initiative: to write letters to influential people in their town, asking them to use their influence to limit the use of non-recyclable plastic there. Students also calculated the weight of disposable plastic used by residents of their city during the month of Ramadan, to better support their arguments.

Discussion

Given the many sustainability issues facing the world, one of the pressing challenges of education today is how to develop the responsible pro-environmental behavior of students to act and participate in society as agents of change (Dobson, 2010; Lidstone et al., 2015). This imperative is underlined by the finding that many students around the world are worried and pessimistic about the state of the environment and about their ability to make productive changes regarding these issues (Pihkala, 2020). For example, a recently survey of 10,000 children and young people in 10 countries showed that 59% were very or extremely worried and 84% at least moderately worried about climate change and government responses to climate change (Hickman et al., 2021).

The purpose of our study is to explore how a specific pedagogical approach, organized around four design principles, can help students develop and practice their agency about sustainability issues. The study's guiding questions are (1) *How were the design features of the curriculum perceived by the teachers?* and (2) *What were the preliminary outcomes of the curriculum in terms of student and teacher argumentation skills and student activism?*

In the following paragraphs, we address these questions in light of the study's findings and suggest several implications.

The curriculum's design features, according to the teachers, had several student outcomes. First, the SDG topics were relevant and important to the students. Second, the data-based challenges and the need to use mathematical thinking to address them, led students to be more convinced about their conclusions and less likely to forget them. In addition, the emphasis on developing evidence-based scientific arguments developed the students' critical thinking skills; a related finding was that the teachers' argumentation skills were stronger and more evidence-based, as a result of their Professional Development course. Finally, the student activism activities promoted student initiative; this finding was reinforced by the teacher interviews about two concluding student activism activities.

Based on these findings, we suggest that the structure of the program's units contributes to the development of student agency in two stages, each of which relates to the program's design features. In the first stage, students develop their self-efficacy (an aspect of student agency) by successfully (a) solving challenging problems that relate to a sustainability issue (*via* the SDGs), using mathematical skills to analyze the data, and (b) developing data-based scientific arguments. These mastery experiences (Britner and Pajares, 2006) promote the students' self-efficacy belief about their ability to address environmental challenges. In the second stage, when engaged in the concluding student activism activity, students apply their knowledge and skills, developed in the first stage, to make a sustainability-related change in their immediate environment. We suggest that in this two-stage process, students develop their agency about sustainability issues.

As demonstrated by the teacher interviews on student activism, each unit's concluding student activism activity has two possible forms: guided activism and open activism. In guided activism, the teacher initiates and guides the activism activity, as presented in the program; the students can make their own choices within this context. In open activism, students create their own initiative in their immediate environment. We have chosen these terms in parallel to similar terms relating to inquiry in science learning, i.e., guided inquiry and open inquiry (Domin, 1999; Sadeh and Zion, 2009). These two forms of student activism are not mutually exclusive. In fact, in the classrooms of both Annie and Jasmine, the students engaged in both guided activism as well as open activism.

In both forms of student activism, argumentation plays a central role. It is interesting to note that there are two basic approaches for argumentation: scientific and social (Osborne et al., 2004; Simon et al., 2006). Scientific arguments have the goal of understanding a phenomenon, based on supportive scientific data. Social argumentation, in contrast, has the goal of convincing others to accept a particular position and can use other types of support, such as an appeal to authority. It is interesting to note that in both student activism initiatives presented in this paper, the students' scientific arguments were used as a basis for their social arguments. In the case of Annie's classroom, her students tried to convince other students in the school about how the COVID-19 virus spreads and how to behave in response, based on the data-based scientific arguments they developed while learning the SDG 3 unit. In the case of Jasmine's classroom, the students tried to convince influential people in their town to limit the use of non-recyclable plastics, based on the data-based scientific arguments they developed while learning the SDG 14 unit. Thus, we can see how the development of data-based argumentation skills can support the development of student activism and agency.

We can also observe how developing mathematical literacy, within the context of addressing sustainability challenges, also can contribute to the development of student activism and agency. This is not only because these skills are necessary in order to develop scientific arguments. Another reason appears to be connected to the concept of "productive struggle" in mathematics; such struggle occurs when teachers include opportunities for students to attempt solving problems that target concepts that are new to them, rather than limiting those opportunities to tasks with familiar skills (Hattie and Zierer, 2017). When this happens, by trying to solve difficult problems, by making mistakes and learning from them, and at the same time being supported by their teachers to endure and to debate possible ideas and solutions, student agency is developed (Warshauer, 2015; Boaler and Dweck, 2016). In this way, we suggest that students developed agency also by engaging in "productive struggle" with mathematical problems in the Speak to Me in Numbers curriculum.

Nevertheless, the concept of agency is complex. According to the authors of *Children as Agents in Their World*:

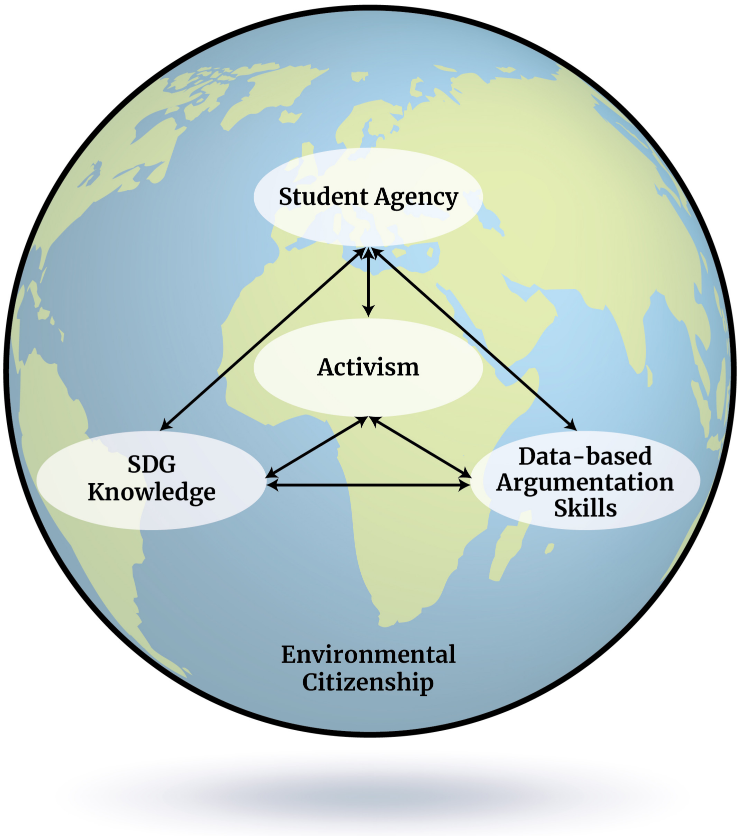

FIGURE 4
A model to develop data-based student agency on sustainability issues.

"...agency can mean different things to different researchers. The term agency is used to label a range of phenomena or processes, a fact which confounds drawing conclusions about how agency manifests itself, by whom and in what context. However, it seems clear that agency is expressed in very different ways by different children in different settings... It also varies according to their own attitudes and expectations about their position in the world, their understanding of their immediate context and their anticipations of their future" (Greene and Nixon, 2020).

The authors also point out that there are many individual differences in dealing with agency, such as age, gender, genetic inheritance and contextual sources of difference, such as social class and geographical location.

Given this complex view of agency, along with the results from our study, we suggest that the development of student agency was promoted by the teachers. In other words, both the students and their teachers engaged in "co-agency." This was an unexpected result, but we feel that the study's results necessitate this conclusion. The students did not develop their agency alone, but in tandem with their teachers. This is how the concept of "co-agency" is understood, i.e., as the "interactive, mutually supportive relationships–with ... teachers, the community and with each other–that help students progress toward their shared goals" (OECD, 2019). As a result of the "Speak to Me in Numbers" curriculum, both the teachers and the students developed their argumentation skills and their abilities to justify claims based on mathematical data and skills. Below, we will continue to discuss "student agency" by using these words, though we understand this concept to be closer to the concept of "co-agency" between students and teachers.

The research literature shows that the development of student agency regarding sustainability issues can vary among students, based on similar individual differences regarding their pessimism about the environment. Within this context, it is interesting to note a significant difference between two types of environmental pessimism: (1) pessimism about the general state of the environment; and (2) pessimism about being able to do anything about this problem (Sheppard, 2006). It is quite possible, and perhaps desirable, for students to have a realistic view about the general state of the environment, (that may involve some pessimism) while developing their agency regarding their ability to act to improve the situation, starting in their immediate environment. In this way, their agency will be a vehicle for offsetting their ecological anxiety by propogating hope, understood as "the belief in the possibility of a better future" (Kelsey, 2016).

Based on the findings of this exploratory study, along with the related literature discussed above, how might student agency on sustainability issues be developed? We address this question by first recalling that student agency, according to social cognitive theory (Bandura, 1986, 1997), is the ability of students "to regulate and control their cognition, motivation, and behavior through the influence of existing self-beliefs (i.e., self-efficacy)" and that it is composed of intentionality, forethought, self-regulation and self-efficacy (Code, 2020). The findings suggest that teachers of the "Speak to Me in Numbers" curriculum connected its four design principles to aspects of student agency, as related to sustainability issues: (1) The focus of the curriculum on the UN's Sustainable Development Goals (SDGs) was relevant to students, hence supported their motivation for learning about these issues; (2) The data-based challenges requiring the use of mathematical literacy to address them developed student efficacy in making data-based arguments regarding sustainability; (3) Student construction of evidence-based scientific arguments led to their critical thinking about sustainability issues; and (4) the concluding activism activity promoted student initiative-taking about sustainability on many levels: the classroom, school, community, and society. In addition, looking at the related literature, we suggest that student "productive struggle" with difficult math problems, the development of teachers' co-agency, and the students' experience of "doing something" about the sustainability issues they studied (despite possible environmental pessimism), *via* both their guided and open activism activities, also contributed to the development of student agency regarding sustainability issues.

In order to further develop student agency relating to sustainability issues, we suggest the following model (see **Figure 4**). The foundation of this model is the concept of Environmental Citizenship and its goal to promote "the responsible pro-environmental behavior of citizens who act and participate in society as agents of change" (Hadjichambis and Reis, 2020).

In this model, we suggest that a mutual and dynamic relationship exists between three pedagogical processes: developing SDG knowledge, developing data-based argumentation skills and developing student activism. Each of these processes (that constitute the model's inner triangle) contributes to and reinforces the others. In addition, each process contributes to the development of student agency on sustainability issues (located at the apex of the model's outer triangle).

Two other variables that reflect this type of agency are the development of a pro-environmental set of values and environmental hope. Studies have shown that if people do not have a pro-environmental set of values, they will choose not to engage in pro-environmental action. For example, in a 3-year controlled study, subjects were given feedback devices designed to help them monitor and modify their home energy use. The results showed that only those with environmental values used and derived tangible benefits from these devices, while people without these values did not (Puntiroli and Bezençon, 2020). Another variable that predicts pro-environmental action is environmental hope. People with environmental hope (1) believe in their own capacity to generate different pathways leading to the goal of protecting the environment ("pathway thinking") and (2) have the motivation to use these pathways to achieve that goal ("agency thinking") (Kerret et al., 2020).

In conclusion, our study suggests a promising pedagogy to strengthen student agency on sustainability issues *via* a data-driven pedagogy that focuses on the development of scientific argumentation, mathematical literacy, and activism. We call for future studies to investigate to what extent this proposed model can develop student agency on sustainability issues as well as pro-environmental values and environmental hope with students and teachers alike.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by IRB-Weizmann Institute of Science. The patients/participants provided their written informed consent to participate in this study.

Author contributions

SRa, RB, and SRo contributed to conception and design of the study and wrote sections of the manuscript. AS-B, SRa, and RB contributed to the data collection and analysis. All authors contributed to manuscript revision, read, and approved the submitted version.

Funding

The research was supported by the Trump Foundation, Grant 361.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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