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Teaching high school chemistry through education for sustainability: a collaborative case study from Chile

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ABSTRACT

Integrating education for sustainability into chemistry teaching is regarded as essential for preparing young people to respond to complex environmental and social challenges, including in post-colonial Chile. This research explores the experience of Maria, a Chilean high school chemistry teacher, as she worked collaboratively with a teacher educator to reframe her practice as chemistry for sustainability. Drawing on interviews and researcher fieldnotes collected during a four-month collaboration and follow-up interviews conducted one and five years later, the study traces how Maria reimagined chemistry education beyond curriculum constraints. Her approach became more interdisciplinary, promoting students' critical thinking, ethical reasoning, and engagement with real-world issues. She adopted pedagogies that were action-oriented and place-responsive, which are elements that remained central to her teaching years after the collaboration ended. The findings highlight the lasting impact of professional learning rooted in practice and supported through collaboration with external partners who combine subject expertise with broader educational insights. We argue that such sustained, context-aware collaborations are crucial for meaningful integration of sustainability into subject teaching and require investment and supported from policy makers to become more widely accessible.

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Introduction

The integration of sustainability into chemistry education is increasingly regarded as essential for preparing young people to live with and respond to complex societal and environmental challenges, including in Chile (Chilean Ministry of Environment, 2015). Traditional chemistry education often emphasises content transmission (Sevian & Bulte, 2015) rather than encouraging students to make connections between scientific knowledge and broader societal issues. In recent years, scholars have argued for the importance of adopting approaches that transcend conventional subject boundaries, promoting a holistic understanding of sustainability issues (e.g. Jensen, 2002; Orgill et al. 2019).

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Sustainable development (SD) and sustainability are multifaceted concepts with diverse meanings (Burmeister et al. 2012). The most common definition stems from the Brundtland Report (1987), which describes SD as meeting present societal needs without compromising future generations' ability to meet their own needs. Subsequently, the three-pillar model of sustainability was articulated, which balances the relationship between human needs and nature's capacity across economic, social and environmental dimensions (OECD, 2001). The three-pillar model is widely referenced in sustainability literature, although alternative models include cultural and institutional pillars (Purvis et al. 2019). Effective integration of sustainability in education requires operationalising these abstract concepts into concrete learning experiences (Purvis et al. 2019). Since the Brundtland Report (1987), sustainable development and sustainability have been embedded in the United Nations' Decade of Education for Sustainable Development and various national policies (Le Grange, 2017). However, as political slogans, these concepts often overlook the imbalance between present and future generations and fail to challenge neoliberalism while promoting global education for sustainability and citizenship (Le Grange, 2017). Critics argue that ESD is a meaningless concept promoting unsustainable economic growth (Jickling & Sterling, 2017) with instrumentalism prioritised, and a neglect of personal, cultural, and value aspects (Stevenson, 2014). Griffiths (2021) highlights the limitations and possibilities of ESD within the framework of Sustainable Development Goals (SDGs), arguing that while ESD can promote transformative learning, it often falls short in challenging the structural conditions underpinning unsustainable practices. However, other authors view ESD as inherently part of Environmental Education, using EfS and ESD interchangeably (e.g. Birdsall, 2014).

In the field of Environmental Education, some scholars prefer the term 'Education for Sustainability' (EfS) which is understood as an approach to teaching which aims to promote knowledge, skills, attitudes and values for living sustainably. EfS encompasses different aspects of sustainability, such as poverty, democracy, human rights and environmental care (Oe et al. 2022). Furthermore, EfS developing skills such as critical thinking, argumentation, and decision-making (Sjöström et al. 2015). Thus, it involves both understanding both knowledge and fostering skills necessary for creating a sustainable society (e.g. Griffiths, 2021; Oe et al. 2022). Kopnina & Cherniak (2016) underline that justice dimensions in education for sustainable development should enable inclusive pluralism, which challenges anthropocentric ideas of social justice that marginalise more-than-human communities and in so doing, achieve education for nature. Researchers underline that pedagogies for EfS should be interdisciplinary, experiential, and encourage critical reflection on current sustainability issues that connect with students' everyday lives (Birdsall, 2014; Sipos et al. 2008). However, insights as to how such pedagogies might be implemented in the setting of a high school chemistry remain lacking (Olude et al. 2024; Quiroz-Martinez, 2024). This research responds to that gap and is situated in the context of teaching chemistry to high school students in Chile, a post-colonial country still grappling with environmental injustices including exploitative practices wrought by colonisers over many centuries. Given this we consider the place of sustainability in high school chemistry education in Chile.

The place of sustainability in high school chemistry education in Chile

In Chile, national policy, including teachers' professional standards, recognises the role of teachers in ensuring children and young people have both the knowledge and the skills which foster the necessary cultural transformation to achieve a sustainable society (MINEDUC, 2012). National policy focused on science teachers, outlines the crucial role which science education has in ensuring the formation of scientifically literate citizens, who are committed to sustainable development (MINEDUC, 2012). Science teachers (biology, chemistry and physics) are required to support children and young people to develop a commitment to sustainable development through developing their scientific knowledge, the use of models, the application of science and students' participation in practical work (MINEDUC, 2012). Science subjects including chemistry are compulsory for students until the age of 18, when they finish high school. In the context of our study, this means that classes of students aged 15-16 years include students with a range of abilities and levels of interest in chemistry. In Chile, sustainability concepts are part of the National Curriculum, including in chemistry. For example, chemical principles, which are essential for understanding sustainability issues, including renewable energy, resource extraction, and waste management. Teachers of chemistry in Chile are expected to 'motivate their learners to design and participate in collaborative projects…to promote learners' commitment to citizenship values necessary for sustainable development and environmental care' (MINEDUC, 2012, p.227). As has been previously noted, this framing of sustainability in the context of chemistry education has a narrow focus on the individual, with the teachers' role to enable students to become responsible citizens who question their personal consumption and the ecological and social implications through a singular pedagogical approach: collaborative projects (Quiroz-Martinez, 2024). Absent from this framing are conceptualisations of EfS which are action-oriented, enabling young people to understand sustainability as inherently complex and systemic socio-political issues, which require the development of young people's action competence (Howard-Jones et al. 2021; Van Poeck et al. 2024). Missing too are ideas of place-responsive pedagogies, where reciprocal learning exists between and across teachers, young people and the places in which they learn and teach (Lynch & Mannion, 2021). Place-responsive pedagogies are concerned with what teachers and students are able to notice and respond to, how this noticing and response-making is integrated into education and, how the agencies of places are incorporated into teaching and learning (Lynch & Mannion, 2021). Recent research has underlined the importance of professional learning opportunities for teachers in a range of contexts, including Chile, if they are to engage in EfS in their settings (Quiroz-Martinez, 2024; Rushton & Walshe, 2025). In what follows, we briefly outline collaborative educational innovative as both the framework for this research and as an approach to professional learning between teachers and colleagues who work in settings beyond schools, in this case a university.

Analytical framework: a case study of a collaborative educational innovation

As sustainability is included in the Chilean science curriculum through a singular pedagogical approach, integrating new approaches represents an education innovation.

Educational innovation involves introducing new practices to promote improvement within specific contexts, emphasising social activities aimed at changing practices (Marsh, 2009). Hence, it requires more than setting curricular goals or imposing top-down approaches; it demands recognising teachers' and schools' realities and needs, providing relevant resources, and encouraging collaboration (Priestley et al. 2015). Reasons for adopting an educational innovation vary according to each educational community's needs and context. A problem-solving approach to educational innovation addresses peoples' actual needs and contexts during planning and implementation (Morrish, 2012). Innovation begins when a community recognises a problem in their practice, prompting the need for change, which educational innovation aims to address (Morrish, 2012).

Marsh (2009) identifies three phases of educational change process. Firstly, *the orientation phase*, which involves recognising a need, prompting questions about the nature and importance of the problem and the willingness to act. Teachers strive for coherence by making sense of conflicting messages in their context, navigating ambiguity from competing goals, limited resources, and unclear roles (Allen & Penuel, 2015). Secondly, the *initiation phase*, individuals or groups promote new approaches by addressing what should be done, what it will look like and the implications. Sensemaking helps educators interpret changes and integrate new practices while managing ambiguity (Allen & Penuel, 2015). The initiation phase involves confronting and interpreting one's environment, recognising change, and potentially integrating new practices and actions (Allen & Penuel, 2015). Thirdly, in *the implementation phase*, educators put the innovation into practice, and reflect on questions concerning the implementation, the support needed and the impact on the students they teach. Robust dialogical structures within schools can significantly enhance sense-making and innovation processes related to, for instance, the implementation of new curricular policies (Allen & Penuel, 2015; Priestley et al. 2015). In the context of this study, the teacher, Maria, and the researcher created a dialogue-rich, critical collaboration (Drew et al. 2016; Farmer & Childs, 2022) which supported sense-making through each phase of the education innovation. This emphasis on collaboration builds on the educational innovation approach (Marsh, 2009) focusing on the pedagogical sensing-making which took place in the context of integrating sustainability into teaching chemistry.

In this research, we draw on a case study of one teacher, Maria's, experiences of integrating sustainability into her teaching for the first time, through a collaborative educational innovation with Author one, a researcher (who was also teacher educator and former chemistry teacher. The research is guided by the following question: *Which pedagogies are identified and developed through a teacher-researcher collaboration which integrates EfS in the context of teaching chemistry?* In responding to this question, we draw on insights developed from fieldnotes and interviews which were collated as part of a four-month classroom-based collaboration between Author one and Maria. This collaboration culminated in the co-creation and implementation of a 90-minute chemistry lesson which integrated sustainability into a lesson focused on waste and resources in the context of the copper industry. Data was also drawn from two subsequent interviews held between the teacher and Author one, one which took place a year following the completion of the collaboration and the second interview held after five years. This study is novel as it seeks to develop an understanding of EfS

pedagogies in the context of teaching high school chemistry in a post-colonial context. Furthermore, through this collaborative approach between a classroom teacher and a researcher and teacher educator which extended over six years, this research expands our understanding of the types of professional learning which could better equip school teachers of a range of subjects who are seeking to integrate sustainability into their practice for the first time.

Materials and methods

Our research focused on a case study on one teacher's educational innovation. The participant profile, data collection, ethical considerations and limitations are described before outlining the analysis process.

Participant profile

Potential participants for this research were identified from Author one's professional networks developed through Author one's roles a chemistry teacher and teacher educator. Three factors were considered when inviting participants to engage in this research. Firstly, that potential participants had at least seven years experience of classroom-based teaching overall and at least two years in the school in which the research would take place. In this research, we understand an experienced teacher as one who has more than seven years of teaching experience and who are therefore likely to have encountered a range of teaching strategies and have been involved in curriculum development and design (Zhao et al. 2023). Having at least two years experience in the research setting ensured that the participant had sufficient understanding of their own professional context. Secondly, that the school context was supportive of the potential participants' engagement in the research and would provide them with the time to collaboratively plan lesson and reflective upon their practice. Thirdly, Author one considered their previous experience of engagement with potential participants to ensure that there was good foundation for collaborative work, given that this would take place over an extended period of time. Of the two participants who were invited to participate, only one, Maria, obtained the support and permission from their school setting. In this research, Maria is understood as a knowing and approving expert who has substantive experience which is relevant to the research (Rubin & Rubin, 2011).

At outset of the study, Maria was in her mid-30s who graduated with a degree in chemistry and natural sciences with a teaching qualification and whose parents did not attend higher education. Maria is an experienced teacher who at the beginning of the study beginning had ten years experience teaching chemistry in private and public schools in Chile. Author one met Maria when they previously worked together as science teachers in the school in which the study took place. This school was a small private school with 330 students aged 5-18 years located in the Metropolitan Region of Chile. In 2016, when Author one was a doctoral researcher and no longer a teacher at Maria's school, and with the permission of the school's Headteacher, Author one invited Maria to participate in collaborative work focused on teaching sustainability in the context of chemistry. The focus of this research was Maria's

teaching of chemistry to a class of 30 students aged 15-16 years, with one-third of students studying a pathway focused on science subjects and two-thirds studying a pathway focused on humanities subjects.

Data collection

The main phase of data collection took place over a period of 4 months during 2017, where Author one worked collaboratively with Maria during the four days per week she taught in school. At the outset of the research and as part of the orientation phase of the educational innovation, Author one observed lessons over a two-week period to better understand the teachers' practice, the context in which Maria worked and the student community she taught. Following this period of observation, Author one took on a more active role as a teaching assistant in Maria's classroom, responding to students' questions and marking homework and assessments. This more active involvement of Author one was part of the initiation phase of the educational innovation and, as with the orientation phase, this phase also included series of daily conversations and reflection between Maria and Author one. These phases of orientation and initiation over a period of nine weeks helped Author one understand the decisions Maria took when planning, teaching and evaluating her practice and supported Author one's nuanced interpretation of how Maria experienced integrating sustainability into her classroom teaching.

As part of the implementation phase, over the course of seven weeks, Author one and Maria collaboratively planned a chemistry lesson with a focus on sustainability. Planning took place over a series of daily meetings in the five weeks prior to the lesson and during this period Author one continued to observe/participate in the lessons to gain a good understanding of the students and their learning immediately prior to the planned lesson. The lesson lasted 90 min and was taught as part of a class for students aged 15-16 years (see Appendix). Following the lesson, Author one and Maria met to reflect on the lesson together. Across all these aspects of observation, participation and collaboration across the three phases of educational innovation, Author one took extensive fieldnotes and regularly complied written reflections consistent with a case study approach (Yin, 2012). These fieldnotes supported Author one's interpretation of Maria's experiences in integrating sustainability into her practice. These phases also included almost daily interactive or active interviews (Cohen et al. 2000) between Author one and Maria which were organic, dynamic and served to co-construct knowledge. Through these dynamic conversations which were audio-recorded, Author one and Maria explored topics such as the meaning of sustainability, chemistry education in Chile and connections with her practice as a teacher.

Following the end of this phase of engagement with Maria and her school as a research site, Author one interviewed Maria on two separate occasions, once in 2018 and once in 2023 to further reflect on Maria's experience teaching chemistry and to gather detailed and reflective insights regarding integrating sustainability into teaching chemistry over time. The schedule for the semi-structured interview in 2023 was co-developed by Author 1 and Author 2. Each online interview lasted approximately 60 mins and was audio-recorded for transcription purposes.

Research design limitations

The limitations of this research must be acknowledged. As this study focuses on a single teacher, working with one class as part of one school community in Chile, our focus is to understand the lived experience of a teacher as she integrates sustainability into her practice through a collaborative educational innovation. Consistent with previous research with small numbers of participants (e.g. Dawes & Wheeldon, 2022) this case study approach will elicit rich insights and detailed learning which helps researchers and practitioners broadly understand approaches to integration EfS into the teaching of sustainability in the context of high school chemistry. However, we make no claims that this research provides a generalisable experience across communities of chemistry teachers in Chile and beyond.

Ethical considerations

The research was approved by Author one's institutional ethics committee prior to the commencement of the data collection periods and voluntary, informed consent was obtained in writing from Maria, following permission for the school headteacher for the research collaboration to take place. During phases of research design, data collection and analysis our approach was consistent with the BERA (2024) guidelines for ethical research. For example, as part of the recruitment strategy, Author one drew on her own professional networks to identify potential participants. Therefore, it was important as part of the recruitment process to explicitly state that both the decision to consider participation and to participate (or not) and any responses provided would have no bearing on current or future professional relationships (BERA, 2024 paragraph 19). Given the nature of the study, dynamic ethical considerations were in place as throughout the focused 4-month period of the classroom-based collaboration to ensure that ideas of consent were revisited as the collaboration evolved. Data were managed consistent with the UK GDPR and DPA 2018. Data was pseudonymised by Author one before analysis.

Data analysis

Data from transcribed fieldnotes and interview transcripts were collated and reviewed by Author one in the first instance to determine the next steps in the data analysis process. The first phases of data analysis were undertaken by Author one, following the reflexive thematic analysis approach outlined by Braun et al. (2023). This involved a hybrid process of inductive and deductive coding focused on aspects of Maria's experience which provided insights as to the pedagogical sense-making and decision-taking. Following this first analysis phase, which produce findings and phases of written outputs, a second phase of analysis was undertaken with Author two. This involved an iterative process of individual reflection and joint discussions concerning the themes identified in the data set, including during the writing process. This second phase of analysis brought together deductive analysis informed by ideas, including those from published literature focused on school-based chemistry and/or sustainability education in Chile (e.g. Quiroz-Martinez, 2024), and collaborative professional learning

(e.g. Drew et al. 2016; Marsh, 2009). We also approached data analysis inductively. As part of this approach, we understood our roles as researchers as organising and interpreting the data points such that we can develop patters of information, or themes. Consistent with reflexive thematic analysis, we drew on our professional lives and experiences as secondary school teachers and university-based teacher educators and education researchers, and how these shaped our engagement with the data. The inclusion of Author two during the data analysis phase, who did not participate in phases of data collection and whose expertise is derived from different contexts (England, Scotland) to that of the study (Chile), provided a different perspective to data analysis.

Findings and discussion

We present findings across two themes (see Table 1.) Firstly, the theme of *reframing the purpose of chemistry education to 'chemistry for sustainability'*. This first theme included the sub-themes (1) moving beyond existing system and curriculum constraints and linking chemistry with other subjects, and (2) enabling students' critical thinking and ethical reasoning with environmental issues which includes different dimensions of sustainability. The second theme focused on action-oriented and place-responsive pedagogies, including sub-themes (1) embed experimental and practical activities to enhance students' understanding of sustainability, (2) situate the teaching of sustainability in students' everyday, local and national contexts and, (3) teachers integrate and facilitate discussion and dialogue when teaching about sustainability.

Reframing the purpose of chemistry education to 'chemistry for sustainability'

Through our process of analysis, we identified two distinct themes which captured the experience of the teacher and research EfS collaboration. Firstly, that this collaborative process resulted in the teacher reframing the purpose of chemistry education such that it became 'chemistry for sustainability' (Table 1). This reframing had two broad features. Firstly, the teacher identified the need to move beyond the existing system and curriculum constraints, so that chemistry could be linked to other subjects. As part of an interview during the planning phase, Maria shared:

> There [when talking about resources exploitation] is when we start to link the lesson to history. In fact, it is related to geography too. I would like to link to history more, but the teacher never has time for collaborative work.
>
> (Teacher interview, lesson planning, 2017).

Reflecting in 2023 on the value of teaching chemistry for sustainability through links to other subjects, Maria said, 'I think that, among the opportunities, I'm now starting to see working together with other subjects as a key one' (Teacher interview, October 2023). This reflection, more than five years after the collaboration began, that Maria is only 'starting to see' the clear value of teaching chemistry through connects with other subjects perhaps speaks to the constraining nature of the curriculum and school system in which Maria is working, including the dearth of opportunities to work with other subject specialists to co-create lessons. For example, during

Table 1. Themes, Sub-themes which were identified through a process of reflexive thematic analysis, alongside indicative quotes.

Theme	Sub-theme	Indicative quotes
Reframing the purpose of chemistry education to 'chemistry for sustainability'.	Moving beyond existing system and curriculum constraints and linking chemistry with other subjects.	When we worked together, we worked collaboratively…it opened up my perspective on teaching chemistry, bringing it more towards sustainability…I've been using it ever since… I was very academic and very lecture-based, so I didn't connect the teaching of chemistry to environmental issues. The topics I was covering– like, for example, I could teach redox reactions and go through all of them–in a very academic way, but I didn't relate them to what was actually happening in Chile, for instance… (Interview, October 2023).
	Enabling students' critical thinking and ethical reasoning with environmental issues which includes different dimensions of sustainability.	Through this approach to chemistry lessons you are educating aware citizens… because you are making them think not only about themselves. You are making them think about the Other. For example, that idea that [sustainable issues related to the copper industry] always affect poor and vulnerable people… after…the…lesson, students changed their perspective on the copper industry…They talked about economy, economic power of industries. (Teacher interview, post lesson implementation, 2017).
Action-oriented and place-responsive pedagogies.	Embed experimental and practical activities to enhance students' understanding of sustainability.	Now, I'm giving them the opportunity to do more practical and experimental work for the school science fair…I gave them that focus of chemical waste so that makes it clear and easier for them to define the problem and formulate hypotheses. But I also gave them the freedom to investigate things that they find interesting…It opened up a whole new…spectrum of ideas…creating projects. I started running a research workshop at the school. After participating in the school workshop some students participated in Explora CONICYT (A national scientific fair for schools in Chile, developed by the Ministry of Science). (Teacher interview, October 2023).
	Situate the teaching of sustainability in students' everyday, local and national contexts.	Reading the news articles lands them in the reality of the country…about issues that are happening today and related closely to chemistry in our lives. (Interview, planning our lesson, 2017). Students always greet you with that question: "What's the point of learning chemistry?". Before, I used to answer with, "Your body is a laboratory," and give the classic explanation about oxygen, the blood… the typical response. But now, if a student asked me that, I'd be able to respond differently. I could challenge them a bit more – talk about what they eat, about industrial processes… that's where I could bring in sustainability. I could connect it to the country's economy and everything they themselves have told me in our lesson. I think bringing it down to earth, making it more real, is what's going to help students truly understand. (Interview, after the implementation of our lesson, 2017).
	Teachers integrate and facilitate discussion and dialogue when teaching about sustainability.	To enable students to talk [in the lesson] about different ways water sources are polluted, and how Chile is losing its natural resources due to wrong management of the copper mining industry, and how this is a modern and historic problem which impacts water quality and health. (Interview, planning our lesson, 2017).

the reflective interview in 2023, five years following the implementation of the lesson, the teacher described the existing school system and curriculum as 'very rigid'. In the context of this inflexible system, Maria reported that her colleagues' perception of her innovation to open out chemistry to become chemistry for sustainability, and include experiments, collaborations with other subjects and field trips, was 'wasting time' because these hours could have been used to 'cover the content the curriculum requires'. However, when encountering this response Maria reflected: 'it's a paradigm that we teachers often have; that we must cover all the content. But at what quality? Maybe we know the content inside and out…but does the student actually learn it?' (teacher interview, October 2023). These types of constraints to innovation, including lack of time to collaborate with colleagues beyond traditional subject specialisms and the content heavy nature of the curriculum are consistent with teachers' experiences of sustainability focused curriculum making in contexts beyond Chile, such as England (Rushton & Walshe, 2025). We also note the ways in which the opportunity for Maria to engage in professional learning which was focused on a collaborative educational innovation with a researcher provided a space where these constraints could be overcome (Marsh, 2009; Rushton et al. 2025). We also note that through the interviews, Maria shared that these experiences across the three phases of educational innovation led to a reframing of 'chemistry for sustainability', with an intention to teach across different subjects, which was still present in Maria's orientation to practice more than five years after the collaboration finished.

The second aspect of reframing chemistry education to 'chemistry for sustainability' focused on enabling students' critical thinking and ethical reasoning with environmental issues which includes the social, economic, and political dimensions of sustainability (Table 1). During the orientation phase of the educational innovation, Maria explored the ways in which the choice of topic, in this case the copper industry in Chile, provided opportunities to explore different dimensions of sustainability:

> Why did we choose the copper industry? Because…the Chilean economy depends on the copper industry… The copper industry is about sustainability…our lesson will be about different ways industry pollutes water sources…how Chile is losing its natural resources because of wrong management… our country is not worried about how to protect our natural resources.
>
> (Teacher interview, lesson planning, 2017).

Bringing in these different dimensions of sustainability supported the development of a lesson during the implementation phase which supported students to engage with critical thinking, by connecting different perspectives and ensuring that perspectives, such as economic and political perspectives were foregrounded in students' discussions. Moreover, Maria recognised her role as one which ensured that students looked across these different dimensions and shared their opinions, as this enabled them to develop critical thinking:

> I was coming at it from the idea of sustainability, focusing on investment and power–planning to approach it from an economic perspective. But the students started going toward the issue of pollution. So, I found it really interesting to think about how I could bring them back to the economic angle. Because, to me, pollution is already concerning, of course – but the link between economic investment and power is even more

> troubling…we're dealing with a topic where we have to cultivate critical thinking…where the teacher isn't giving them all the answers, as in a traditional chemistry class…So, what's my goal? That students come out with opinions.
>
> (Teacher interview, post lesson implementation, 2017).

Reflecting on this approach in 2023 following the three phases of educational innovation, Maria shared how this had shaped her thinking of the role of the teacher in the context of chemistry for sustainability, that her role moved beyond teaching to 'raise awareness' and became one which enabled the development of 'respect'. Maria reflected that that her idea of sustainability being grounded on respect was different to that of the majority of the Chilean population's focus on sustainability as economic stability:

> I believe it all forms a chain of respect: respect for the environment, respect for oneself, and respect for others – without harming one or the other – in order to achieve an economy that, for Chileans, I would say, is seen as sustainable. For many Chileans, sustainable means being economically stable. I think that's the concept most Chileans have.
>
> (Teacher interview, October 2023).

These broader ideas of values of respect move beyond the frequently economic framings of education for sustainable development (Jickling & Sterling, 2017) and towards education for sustainability which foregrounds values such as care for the planet and for each other (Dunlop et al. 2022). Approaching the topic of copper mining, which is authentic to the post-colonial context of Chile, also supported students to comprehend these issues from a holistic perspective (Orgill et al. 2019). Such an approach also required Maria to consider ideas and values which contrasted with national norms and placed her teaching of chemistry across domains (politics, economics) of which she was not an expert, requiring her to deal with uncertainty and complexity (Zeidler et al. 2003).

Action-oriented and place-responsive pedagogies

The second distinct themes which captured the experience of the teacher and research EfS collaboration was the development and implementation of action-oriented and place-responsive pedagogies (Table 1). One facet, included embedding experimental and practical activities, which Maria identified during the orientation and initiation phases would enhance her explanation of sustainability and therefore her students' understanding of sustainability:

> It is very important to relate practical work to sustainability… because that helps me to explain sustainability, I think it is much better than just to use theory.
>
> (Teacher interview, lesson planning, 2017).

When planning this approach, Maria reflected that the context of her school, where practical and experimental work was very much part of the 'culture' of teaching science was essential to enable her to take forward this approach to teaching chemistry for sustainability. However, reflecting on the educational innovation more than five years on, Maria's orientation increased towards ensuring her students have opportunities to

engage in practical work which seeks to solve problems and is action-oriented. Here, the integration of practical and experimental work provided students with the essential disciplinary knowledge and skills which provided the tools for action, in this case making decisions about the disposal of chemical waste. For example, Maria recounted that following engaging in practical lessons which resulted in waste residue, students held a discussion how this should be safely disposed of rather than tipping it down the drain, such that the lead and mercury waste did not damage the water quality of their local area. In these ways, Maria is seeking to develop her students' action competence (Jensen, 2002) with practical work and scientific inquiry as an essential foundation.

Central to this idea of creating educational experiences which include problem-solving, project-based learning and experimental activities was to stimulate students' 'curiosity', and provide a teacher-facilitated scaffold so that students were able to identify the next steps and actions which are authentically connected to their everyday lives:

> Maybe the curiosity should start from the students. We could present the problem…a current issue, something from their everyday life, and let them investigate starting from an idea…give them different brainstorming prompts, like saying, "We're going to explore this topic. How do you think we could find a solution to this issue?"
>
> (Teacher interview, October 2023).

Visible in this approach to embedding experimental and practical activities Maria recognised and valued students' 'everyday' lives as a starting point on which to pose questions and present problems or challenges. This idea, of situating the teaching of sustainability in students' everyday, local and national contexts is a further aspect of implementing action-oriented and place-responsive pedagogies. In these ways, Maria sought to create an educational innovation which, consistent with Souza et al. (2019) facilitated transformative interactions between people and places, which are fostered through a relation and collective learning process. For example, when planning the lesson, Maria reflected on ways to teach chemistry for sustainability in ways which were place-responsive, where the lesson 'landed' in the country context and students' everyday lives:

> Reading the news makes them land on the reality of the country…because one of our aims is to 'land' the lesson…the idea is to bring students to talk about local issues…and copper mining is 100% related to the reality of our country…it's about weaving it [sustainability] in little by little – helping the kids connect more with their everyday lives. And getting them to think a bit…To help them think beyond – like, "Hey, think about the quality of the water you're drinking."
>
> (Teacher interview, post lesson implementation, 2017)

Simply making connections to students' lives (e.g. quality of drinking water) and local and/or national issues (e.g. copper mining) was not sufficient, Maria also recognised the need to implement pedagogies which integrated and facilitated discussion and dialogue so to enable students' sense making focused on sustainability. This is consistent with the idea of reciprocal learning between and across teachers, young people and the places in which they are learning and teaching which is integral to place-responsive pedagogies (Lynch & Mannion, 2021). Maria's place-responsive pedagogy is to prompt noticing in her students and to provide spaces where she can

elicit response-making, through discussion and dialogue (Lynch & Mannion, 2021). For example, when planning the lesson, Maria reflected the need to 'organise the lesson properly' and to anticipate that students will 'ask a lot of questions' which would require time within the lesson and where her role was to support students to draw their own conclusions. Maria anticipated that providing opportunities for discussion and dialogue would support the sense making of those students who specialised in humanities subjects as well as those who sought to specialise in chemistry in further phases of school study and beyond:

> So, we have to organise the lesson properly…anticipate that they are going to ask a lot of questions…time for students to participate a lot. Yes, humanities students will participate as much as the science students…in that class, you have a lot of students who are going to overrun you with ideas and opinions…I want students to draw conclusions without me imposing ideas.
>
> (Teacher interview, lesson planning, 2017)

Immediately following the lesson, and more than five years after the implementation of the collaborative educational innovation, Maria reflected on the ways in which dialogue and discussion, where students were able to express their opinions and where students' ideas shaped the direction of the learning were essential aspects of pedagogies which support chemistry for sustainability:

> To start using more of that pedagogical approach where students express their opinions. That way, by the time they reach the last year of secondary school I'll have a class where everyone has something to say…today I leave with the idea of playing a bit with that whole notion of "we want to be heard," "I'm a teenager against the system," "I want to change the system" – and really diving deep into that. That's the idea I'm taking with me today. I didn't have it before.
>
> (Teacher interview, post lesson implementation, 2017)
>
> There are things I've been gradually learning such as letting the ideas come from the students, and me taking more of a guiding role rather than always being the main figure. Always aiming for the students to take the lead, to be the protagonists of their own learning. And those are things I've learned over time through this collaboration
>
> (Teacher interview, October 2023).

These features of action-oriented and place-responsive pedagogies are consistent with some of the principles which Souza et al. (2019) have outlined when considering relational approaches in the context of collective learning process. For example, through action-oriented and place-responsive pedagogies, Maria was able to facilitate learning for her students which incorporated transformative interactions between people and places (Souza et al. 2019) – in this case her students and the local and national context of the copper mining industry. Secondly, through incorporating discussion and dialogue across the different dimensions of sustainability which enabled students to undertake sense-making, Maria was able to ensure students engaged in learning within a climate of mutual acceptance (Souza et al. 2019). Finally, by creating opportunities for students with different subject-orientations and specialisms to general ideas, opinions and create projects which are action-oriented, Maria created spaces for multi-disciplinary learning, which may, in the future develop into ontological pluralism (Souza et al. 2019).

Conclusion

This research provides a new understanding of how, through a collaborative educational innovation, a high school chemistry teacher was able to implement EfS pedagogies which move beyond the existing constraints of the curriculum and are both action-oriented and place responsive. The orientation phase involved Maria grappling with questions about the nature and purpose of teaching chemistry in Chile today, and working with the researcher, making sense of the ways in which EfS can enhance the teaching of chemistry for all students. The initiation phase took place over a series of activities (e.g. lesson planning, discussion with the researcher) and collaboratively Maria engaged in a process of sense making, moving from teaching chemistry as a series of academic ideas rather than those which are socially and temporally grounded. Finally, during the implementation phase which, in this study took place over a number of years, Maria realised the integration of EfS in her practice, reflecting with her students and the researcher, through phases of dialogue to achieve further sense making as to the fuller purpose of teaching chemistry for sustainability and the pedagogical approaches which are required to achieve this. Given the lack of previous research, particularly that which is situated in a post-colonial context and where a collaborative extends over a period of six years, these findings provide detailed insights as to how relational approaches in the context of collective learning process (Souza et al. 2019) can enable a teacher of chemistry to realise chemistry for sustainability in a context (Chile) where there is perhaps a narrow understanding of relevant and appropriate pedagogical approaches.

Furthermore, by developing a clear insight into the types of pedagogical innovations which Maria developed, this case study research has furthered our understanding of pedagogical shifts which can support the implementation of EfS. In this way, this research has the potential to enhance teachers' practice across Chile and in other national contexts concerned with the implementation of EfS in formal education, both those contending with the impacts of environmental injustice in their roles as (former) colonisers and colonised nations. As Gandolfi (2025, p.71) argues, this requires us not only to approach education from, 'future-related' and/or purely scientific perspectives, but also from the socioeconomic, political and historical perspectives of communities that have been severely impacted by environmental issues for centuries'.

Future research could helpfully explore the ways in which these pedagogies support EfS across other school subjects, including physics and biology as well as those beyond science and also interdisciplinary approaches. Given the sustainability issues inherent in teaching chemistry as a practical subject (e.g. issues of resource use and waste) this case study provides an important starting point for teachers and teacher educators to consider the subject-specific sustainability issues which exist within their own subjects and disciplines.

We also reflect on the affordances of small-scale case-study research which accompany teachers during key periods of their professional lives and over multi-year periods of time. Such studies require little in terms of financial resources when compared to large-scale randomised controlled trial studies and yet, provide detailed and rich insights into the nature of teacher professional learning in the

context collaborative educational innovation. If these case studies can extend to include further engagement with participants' reflections one year and five years after the initial collaboration, this affords important insights into the nature and extent of changes to teachers' practice. As we look to the future, we note the ways in which teacher professional learning flourishes and supports long-lasting changes to practice when it is critical, collaborative and includes iterative phases of sensing-making and interrupting existing thinking and practices. Future research could further consider the necessary facets of teacher professional learning in the context of curriculum making and EfS, including the linkages and tensions between school subjects, curriculum orientations and teacher agency. Such research is essential if we are to authentically equip teachers, school leaders and policy makers to realise the potential of formal education to respond to environmental challenges now and in the future.

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Ethics statement

Institutional ethical approval was granted prior to all phases of this research.

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Appendix

The lesson structure: