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Integrating Sustainability Through Socio-Scientific Issues in Chile: Towards a Decolonial Chemistry Education

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ABSTRACT

This study examines how integrating sustainability through socio-scientific issue (SSI) in secondary chemistry teaching shapes epistemic openness and closure from a decolonial perspective, as mediated through classroom discourse. Drawing on a co-planned lesson on copper mining in Chile – a scientifically rich yet ethically and politically charged context – I analyse how pedagogical decisions positioned chemistry either as an apolitical framing (Gandolfi 2025b) or as a practice entangled with extractivism, environmental injustice, and responsibility. Using reflexive thematic analysis of lesson audio recordings, student artefacts, and researcher fieldnotes, and interpreting classroom interaction through Mortimer and Scott's (2003) communicative approaches and Gandolfi's (2025a) decolonial framework, I identify three key pedagogical moments across the lesson. Findings show that dialogic discourse initially opened space for students' ethical concerns but remained limited without follow-up that foregrounded structural causes of harm. A subsequent authoritative focus consolidated disciplinary understanding while producing epistemic closure. Epistemic openness was later re-activated when chemical evidence was reconnected to sustainability and enacted materially through waste-management deliberations. Findings suggest that decolonial perspectives in chemistry education can move teaching beyond content delivery toward pedagogies that centre justice, epistemic plurality, and critical engagement with real-world challenges, while remaining contingent on communicative shifts and deliberate pedagogical mediation.

Meanings of sustainability are “value-laden” (Fien and Tilbury 2002, p.p. 3) and diverse (Birdsall 2014; Salas-Zapata and Ortiz-Muñoz 2019; Ávila 2018). The current understanding of this concept is based on the economic, political and social priorities and interests of nations (Wals 2012) and promotes a balanced relationship between three main pillars: environmental, economic, and social (United Nations UN 2024). Nevertheless, current understandings of development have an anthropocentric perspective, which tends to overvalue the economic growth of nations over both social and environmental justice (Kopnina 2020) whilst at the same time, the pursuit of a more sustainable world is one of the hardest and important modern challenges (Van Poeck and Östman 2018).

Education for Sustainability (EfS) is an approach to teaching and learning that is rooted in sustainability and attempts to promote among students' values and skills for living sustainably (Iliško et al. 2017; Kioupi and Voulvoulis 2019). EfS typically encompasses themes such as environmental care, health, democracy, poverty, and human rights, alongside skills related to citizenship, including critical thinking, argumentation, and decision-making (Leal Filho et al. 2015; Misiaszek 2015; Sjöström et al. 2015). However, a growing body of critical scholarship cautions that EfS risks becoming normative or behaviourist when framed primarily as a tool for steering learners toward pre-determined “sustainable” behaviours (Jickling and Wals 2008; Dunlop et al. 2022). Such approaches may limit learners' autonomy and foreclose opportunities for critical interrogation of the structural roots of unsustainability.

In response, scholars have argued for a transformative and critical orientation to EfS, grounded in reflexivity, dialogue, and the examination of power relations (Tippins et al. 2015; Kioupi and Voulvoulis 2019). From this perspective, EfS should not merely promote sustainability as a set of desirable outcomes, but should foster critical consciousness about the historical, economic, and political conditions that produce socio-environmental crises (Feldman and Nation 2015; Rauch 2015; Niens et al. 2020; Oe et al. 2022). These arguments resonate strongly with traditions of critical pedagogy, which position education as an inherently political practice and emphasise dialogue, agency, and the questioning of dominant narratives (Freire 2021; Walsh 2012).

1 | Chemistry Education for Sustainability

Chemistry and the chemical industry are fundamental to the economic development of industrial countries, and hence play a core role in the sustainable development of modern societies (Rauch 2015). Chemistry education for sustainability can support students in understanding deeply how the social, economic and environmental systems are connected within a sustainable world, as well as in evaluating and thinking critically about these connections (Frank et al. 2011; Sjöström et al. 2015). For example, chemistry supports students to understand how industries work today, how industrial manufacturing affects or contributes to sustainable development (Hofstein and Kesner 2015; Zuin et al. 2021), and how to foster sustainable living and the appropriate use of natural resources (Rauch 2015).

Chemistry is essential for understanding contemporary sustainability-related challenges, including the principles underpinning renewable energy technologies and the implications of single-use plastics, among others (Shwartz et al. 2020). Embedding sustainability within chemistry education enables teachers to link the discipline to broader educational objectives, such as fostering intellectual and personal skills, cultivating social responsibility, and promoting holistic learning (Fisher 2012; Moura 2025). Such an approach helps students to appreciate the relevance of chemistry in addressing and interpreting issues that extend beyond the discipline, both in other areas of their education and in everyday life (Shwartz et al. 2020). For example, chemistry education can illuminate how chemical innovations intersect with and influence the environmental, social, and economic pillars of sustainability (Burmeister and Eilks 2012; Hofstein and Kesner 2015).

A growing body of literature in science education advocates for a shift from content-heavy, discipline-bound teaching towards more holistic, value-based approaches that foster students' engagement with real-world challenges (Morin et al. 2014; Orgill et al. 2019; Sjöström and Talanquer 2014; Morales-Doyle 2017; Gandolfi 2021). These calls align with the three pillars model of sustainability: environmental integrity, economic viability, and social equity (Jegstad and Sinnes 2015) since the lens of sustainability support students to relate their interests and priorities to societal challenges that humanity face (Fisher 2012; Shwartz et al. 2020). Hence, chemistry education for sustainability draws on a multi-dimensional and society-oriented approach (Burmeister and Eilks 2012).

Despite increasing curricular emphasis on sustainability, chemistry education remains particularly resistant to such integration (Gandolfi 2024). Commonly, chemistry teaching prioritises decontextualised facts, abstract representations, and isolated reactions, leaving little room for ethical or political considerations (Gandolfi 2025a; Miani et al. 2025). As such, sustainability is often treated as an add-on topic rather than an organising principle for the subject. Despite increasing curricular references to sustainability, chemistry education remains particularly resistant to sustainability integration, leaving ethical, political, and historical dimensions marginalised (Sjöström and Talanquer 2014; Gandolfi 2025a; Miani et al. 2025).

A growing and increasingly recent scholarship has called for approaches that move beyond this reductionism by embedding chemistry concepts within complex, interdisciplinary socio-environmental issues (Sjöström and Eilks 2018; Levinson 2018; Miani et al. 2025; Gandolfi 2024; Tytler et al. 2025). These calls align with sustainability-oriented and critical perspectives that position chemistry not only as a technical discipline, but as a socially embedded practice with uneven impacts and responsibilities. Such approaches argue for chemistry education that enables learners to examine how chemical knowledge and technologies contribute to – and are shaped by – systems of power, inequality, and environmental harm (Gandolfi 2025a).

1.1 | Socio-Scientific Issues and Decolonial Perspectives for Chemistry Education: The Copper Mining Industry in Chile

Socio-scientific issues (SSI) have been widely proposed as a pedagogical approach for integrating sustainability into science and chemistry education (Zeidler et al. 2005; Sadler 2011; Shwartz et al. 2020). It is rooted in methods of inquiry in which students interpret issues, make decisions based on moral judgments and problem-solving skills, while also developing different communication skills such as argumentation and negotiation (Zeidler 2014). Such skills are paramount for educating critical thinkers (Nussbaum 2008).

SSI are real-world controversial and open-ended problems which are closely related to science and have multiple viable solutions (Shwartz et al. 2020; Sadler 2011; Zeidler et al. 2003; Zeidler et al. 2005; Högström et al. 2024). Such solutions cannot be addressed solely through scientific considerations; they also involve social factors such as political, ethical, and economic (Zuin et al. 2021; Shwartz et al. 2020; Levinson 2018).

In chemistry education, SSI approaches have been shown to increase student engagement and support reflection on the societal use of chemical knowledge (Marks and Eilks 2009; Burmeister et al. 2012). However, much of this work has focused on individualised and consumer-oriented framings of sustainability, such as personal choices related to plastics, fuels, or household chemicals (e.g., Feierabend and Eilks 2011;

Nida et al. 2021; Ambrogi and Eilks 2023). Critics argue that such framings risk obscuring the structural, industrial, and political dimensions of sustainability challenges (Morales-Doyle et al. 2019).

If chemistry education for sustainability is to support societal change, it must engage learners in examining sustainability issues at both micro (personal) and macro (industrial, economic, political) levels (Quiroz-Martinez 2024). Doing so requires pedagogical designs that explicitly foreground systemic causes, power relations, and the historical conditions that produce and sustain environmental problems, rather than reducing sustainability to individual responsibility or technical solutions (Jensen 2002; Simonneaux 2014). Despite the growing prominence of socio-scientific issues in chemistry education, critical engagement with SSIs grounded in local industrial activity and extractivism – particularly those that expose relations of power, inequality, and environmental injustice – remains markedly underexplored (Gandolfi 2025a).

Decolonial theory offers a powerful lens for examining this gap. Incorporating a decolonial perspective into chemistry education entails questioning the historical and epistemic legacies that position Western scientific knowledge as neutral, universal, and superior, while local, Indigenous, and experiential knowledges are marginalised. Quijano (2007) refers to this structure as the "colonial matrix of power," in which the control of knowledge is deeply entangled with political, economic, and cultural domination. Walsh (2012) argues that to decolonise education is not merely to diversify content but to engage in "epistemic disobedience"; that is, to unsettle the hegemony of Eurocentric thought and create space for epistemologies that emerge from lived experiences and social struggles.

Gandolfi (2025a) builds on this idea by proposing a decolonial approach to chemistry education that critically examines how scientific knowledge is produced, circulated, and legitimised in relation to power and justice. Drawing on the notion of political epistemology (Moura et al. 2021), Gandolfi (2025a) argues that chemical knowledge and practices cannot be disentangled from the industrial, institutional, and economic contexts in which they operate. This perspective is particularly salient in Latin America, where scientific development has historically been intertwined with extractivism and neoliberal governance (Solimano 2012).

Chile provides a critical context for operationalising these ideas. Visions of sustainable futures often promote 'clean' energy alternatives to fossil fuels, with electric cars cited as a key example due to their potential to reduce pollution and climate change. However, their production relies heavily on copper – for batteries, motors, and infrastructure (International Copper Association, n.d.). As the world's top copper producer, Chile depends on this metal as its main export (OECD 2021), making the copper industry central to its economy. Nevertheless, this economic reliance has significant costs. Chile ranks among the top eleven countries globally for environmental conflicts, most of which are linked to copper mining (Temper et al. 2018). This dependence has generated severe socio-environmental conflicts, particularly in zones such as Quintero-Puchuncaví (Cabello 2025; González-Urzúa et al. 2025). Copper extraction reveals the inequities embedded in so-called 'sustainable' transitions. While a privileged few profit from copper extraction or can afford electric vehicles and 'clean energy', local populations and ecosystems are affected by pollution and its consequences. Clearly, neither extractivism nor narrow definitions of sustainable futures ensure justice for all.

Chilean scholarship in science education has begun to engage with these realities. Research shows that while chemistry teachers recognise sustainability as important, teaching often remains focused on environmental protection and individual responsibility, with limited engagement with political and economic dimensions (Quiroz-Martinez 2024). Other authors highlight the importance of place-based, justice-oriented, and critically hopeful approaches to science education in communities affected by environmental harm (Cabello 2025; Salinas et al. 2023; Torres-Olave and Bravo González 2021; González-Urzúa et al. 2025).

Recent work on complexity in science education further highlights the limitations of traditional pedagogical frameworks for addressing contemporary sustainability challenges (Tytler et al. 2025). Miani et al. (2025) argue that contemporary sustainability challenges, such as those related to climate change, extractive economies, and systemic inequality, are inherently complex, characterised by uncertainty, non-linearity, and multiple, often conflicting perspectives. Yet dominant approaches to science teaching often struggle to engage with the ethical, political, and existential dimensions of such "wicked problems" (Bazzul 2020). This limitation can be conceptualised as a form of epistemic closure, which Gandolfi (2025a) argues as chemistry being foregrounded as a neutral, technical, and internally coherent discipline, while its entanglements with extractivism, coloniality, and social injustice are marginalised. Such an approach reinforces what Gandolfi (2025a) describes as a naïve neutrality, obscuring how chemical knowledge, practices, and industries are historically and contemporarily embedded within the colonial matrix of power (Quijano 2007). This epistemic closure is evident in the persistent emphasis on experimentation, modelling, and representational competence, with ethical and political questions treated as peripheral or external to chemistry itself.

From a decolonial perspective, epistemic closure is not merely a curricular omission but an active process through which certain ways of knowing are legitimised while others – particularly those emerging from communities most affected by chemical industries – are silenced. Traditional approaches for teaching chemistry have limited capacity to support decolonial perspectives, as they rarely interrogate chemistry's socio-historical role in extractive economies or its complicity in environmental injustices (Gandolfi 2025a; Morales-Doyle et al. 2019; González-Urzúa et al. 2025).

In contrast, epistemic openness emerges when chemistry education intentionally disrupts these dominant framings by foregrounding chemistry's socio-political, moral, and historical dimensions. Epistemic openness does not imply abandoning disciplinary rigour; rather, it involves expanding what counts as legitimate chemical knowledge to include ethical reasoning, historical accountability, and the voices of communities affected by chemical practices. This shift requires what Walsh (2012) terms epistemic disobedience: a deliberate refusal to treat chemistry knowledge as detached from power, justice, and lived experience.

Gandolfi's (2025a) proposal for a decolonial chemistry education reframes its practice as a potential site of epistemic openness when it supports learners in developing critical consciousness (conscientização, Freire 2021) through a reading of the world of chemistry in all its complexity. Such an approach positions chemistry not only as a means of explaining material transformations, but also as a social practice entangled with extractivist industries, unequal distributions of harm and benefit, and contested futures.

Copper mining thus emerges as a potent, place-based SSI for a decolonial perspective for chemistry education: scientifically rich, politically charged, and ethically complex (González-Urzúa et al. 2025; Cabello 2025). It exposes contradictions within dominant visions of sustainable futures, such as clean energy transitions that rely on environmentally destructive extraction (González-Urzúa et al. 2025; Quiroz-Martinez (2026)). Engaging with this context allows learners to interrogate sustainability not as a neutral or consensual goal, but as a contested terrain shaped by power, policy, and lived experience.

By situating chemistry content within the contemporary, place-based socio-scientific issue of copper mining in Chile, this study contributes to efforts to reimagine chemistry education as a space for ethical inquiry, political engagement, and decolonial critique. It investigates how integrating sustainability through SSI in chemistry teaching shapes epistemic openness and closure from a decolonial perspective, as mediated through classroom discourse. Drawing on the Gandolfi (2025a) proposal for a decolonial chemistry education, the study examines a co-planned lesson on copper mining implemented by a secondary school chemistry teacher in Chile. This study examines how pedagogical decisions enacted through discourse legitimise or constrain scientific, economic, political, social, and ethical forms of knowledge. In doing so, it illuminates how everyday chemistry teaching can either reproduce or unsettle colonial epistemic legacies.

2 | Methodology

2.1 | Materials and Methods

This investigation adhered to British Educational Research Association's (British Educational Research Association BERA 2024) ethical guidelines. Data were confidential and information was only used for investigation purpose. Judgements of knowledge, practice, and opinions were not categorised as correct or incorrect. This research is located within the qualitative, interpretative paradigm (Cohen et al. 2000) and is based on empirical work with a high school chemistry teacher, who had over 7 years of classroom experience in both public and private schools in Chile. The teacher, a woman in her thirties, taught both standard and advanced chemistry courses to students aged 13 to 18.

In Chile, chemistry teaching takes place within a policy context of hyper-accountability (Quiroz-Martinez and Rushton 2024), where exam preparation dominates teachers' practice. Standard chemistry, a compulsory subject, is assessed through national examinations that strongly shape students' career trajectories, including access to university (Quiroz-Martinez and Rushton 2024). At the same time, sustainability is not established as a distinct subject in the national curriculum. Rather, it appears unevenly across disciplines and is addressed most explicitly only in the final 2 years of schooling (ages 17-18; Salinas et al. 2022). This fragmented and unbalanced approach produces tensions for teachers, who are required to prioritise exam performance while simultaneously engaging learners in sustainability education that demands critical, interdisciplinary, and context-sensitive practices extending well beyond what examinations assess.

Within this research, the teacher was teaching standard chemistry to a class of 30 learners (aged 15-16). At the time of the study, all students followed the same compulsory chemistry curriculum and participated in the same classroom activities. However, students differed in their elective subject choices and anticipated post-secondary pathways. Ten students were enrolled in Higher Chemistry, indicating an interest in STEM-related university degrees, while twenty students were enrolled in Higher History, reflecting interests aligned with humanities or social sciences. These distinctions did not entail different chemistry curricula, assessments, or instructional expectations and were not used as analytic categories in this study.

The study took place over 3 months (March–May) in a Chilean secondary school, where I worked closely with the chemistry teacher to implement a co-planned lesson sequence on copper mining as a socio-scientific issue. This involved attending the school 4 days per week, engaging in lesson planning, participating in classroom activities, and conducting post-lesson reflections with the teacher. The data set includes audio-recorded classroom lesson (90 min); fieldnotes documenting observations, reflections, and contextual details; and student artefacts (written responses, lab reports). The focus of this article is the enacted classroom lesson as a discursive event, rather than the co-planning process or comparisons between planned and enacted instruction. Detailed analysis of the extended teacher-researcher collaboration and its role in supporting chemistry teaching for sustainability is reported elsewhere (Quiroz-Martinez and Rushton 2025). That longitudinal study highlighted how sustained collaboration supported the development of interdisciplinary, place-responsive, and critically oriented pedagogies over time. Building on this work, the present study shifts the analytical focus from the process of teacher learning to the moment-by-moment enactment of classroom practice, offering a fine-grained analysis of how pedagogical decisions and classroom interactions shaped epistemic openings and the emergence of diverse knowledge systems. In the present study, the lesson plan provides contextual orientation, but analytic claims are derived from classroom discourse and artefacts.

The teacher and I used a voice recording device while we moved around the classroom, in order to provide further evidence of what had happened in the lesson. Transcripts of these audio-records served as the primary source of data for interpreting how the planned lesson was enacted. Fieldnotes were interpretative and written immediately after observations or interactions. They captured both descriptive details (e.g., classroom dynamics, student engagement) and subjective interpretations of teacher decisions and classroom culture. These served as contextual data to support the interpretation of classroom discourse and pedagogical strategies, and were used as secondary data for supporting my interpretation of the teacher's experience in integrating sustainability to her practice.

Pedagogical materials were also relevant for generating data in this study. Students' responses provided information portraying their involvement and participation in the lesson (Herrenkohl and Guerra 1998). Students' lab reports and answers in the lesson were used as a primary source of data for interpreting the impacts of pedagogical actions within the planned lesson, since talk plays an important role in learning. I consider students' discourse practice in the lesson and their writing as a way to understand and analyse their understanding and contribution in the class (Herrenkohl and Guerra 1998). While the study analyses students' discourse and work artefacts, these are examined as indicators of epistemic conditions created through teaching practices, rather than as measures of individual learning outcomes.

2.2 | Data Analysis

This study adopted Reflexive Thematic Analysis (RTA) (Braun and Clarke 2019; 2023) as the overarching analytical approach, complemented by classroom discourse analysis (Mortimer and Scott 2003) and interpreted through a decolonial perspective on chemistry education (Gandolfi 2025a).

2.2.1 | *Stage 1: Identifying Key Pedagogical Moments*

Following an inductive and reflexive orientation (Azungah 2018; Braun and Clarke 2023), I analysed the lesson as a single, coherent pedagogical event, drawing on the complete dataset generated from its implementation, including lesson audio recordings, lesson artefacts, students' written work, and researcher field notes.

Rather than fragmenting the lesson into micro-codes or treating instructional phases as predefined analytic units, the analysis focused on identifying patterns of pedagogical intention, classroom interaction, and epistemic orientation as they unfolded over time.

Although the lesson was co-planned with a broad structure comprising a beginning, middle, and end (Quiroz-Martinez and Rushton 2025), these planned phases were not treated as a priori analytic categories. Instead, the analysis examined how the lesson was enacted in practice and whether these planned phases functioned as epistemically significant moments during classroom interaction. The identification of key pedagogical moments therefore, emerged from close, reflexive engagement with the data, grounded in how pedagogical intentions were taken up, negotiated, or transformed through classroom discourse and activity.

Through this process, I identified three specific key pedagogical moments, which correspond broadly to the beginning, middle, and end of the lesson, but are analytically defined by their epistemic function, rather than by their position in the lesson sequence: Focusing the lesson on students' knowledge; Focusing the lesson on chemistry; Focusing the lesson on chemistry and other knowledge. Figure 1 outlines the planned structure of the lesson and its relation to the co-planned pedagogical intentions.

These key pedagogical moments are described as critical because each marked a distinct pedagogical turning point that shaped the epistemic direction of the lesson and acted as a "causal push" (Miles et al. 2020) toward – or away from – epistemic openness. From a decolonial perspective, epistemic openness refers to moments in which chemistry teaching disrupts dominant, apolitical framing (Gandolfi 2025b) of the discipline by foregrounding its socio-political, moral, and/or

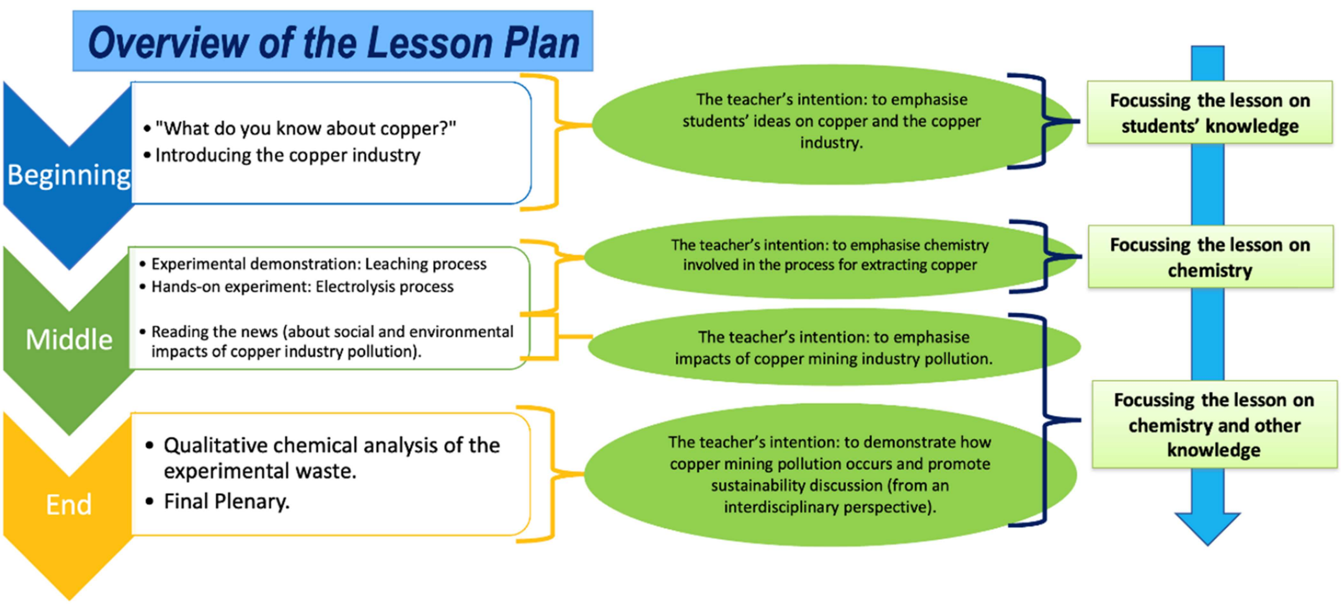

FIGURE 1 | An overview of the lesson and the co-planned pedagogical intentions.

historical dimensions. In the context of integrating sustainability into chemistry education, this entails intentionally engaging with the social, economic, and environmental implications of chemical practices in society – particularly, in this study, those associated with industrial copper mining. Importantly, the criticality of these moments was not assumed from the lesson design but established analytically, based on how each moment enabled or constrained epistemic openness in practice. Taken together, the three moments provide both a chronological and analytic account of how epistemic openness was progressively constrained, reconfigured, and re-opened within a co-planned chemistry lesson.

2.2.2 | Stage 2: Analysing Classroom Discourse Within Each Key Pedagogical Moment

Within each of the three key pedagogical moments, I examined how classroom discourse functioned by drawing on Mortimer and Scott's (2003) framework of communicative approaches. Importantly, these communicative categories were not used during the co-planning process as prescriptive strategies for lesson design. During co-planning, the teacher and I discussed broad pedagogical intentions and the sequencing of lesson phases (e.g., eliciting students' prior knowledge, engaging with disciplinary chemistry, and returning to sustainability and socio-political considerations (see Quiroz-Martinez and Rushton (2025) for more details about the co-planning experience)), but we did not explicitly plan when or how specific communicative approaches (such as authoritative-interactive or interactive-dialogic discourse) should be enacted.

Instead, this framework was applied retrospectively as an analytic lens to characterise how meanings were constructed through teacher-student interactions, rather than as a prescriptive model for instructional design. Attention was given to whether classroom talk opened space for the exploration of multiple viewpoints or, conversely, guided students toward convergence on specific, canonical interpretations of chemistry knowledge.

Through this analysis, I traced how the teacher's discursive moves alternated between interactive-dialogic approaches, in which students' ideas were invited, revoiced, and sustained without immediate closure, and authoritative-interactive approaches, in which the teacher steered discussion toward disciplinary norms and scientifically accepted explanations. Importantly, the analysis also attended to shifts between these approaches within and across lesson phases, as these shifts played a central role in shaping what kinds of knowledge were legitimised at different moments of the lesson.

2.2.3 | Stage 3: Decolonial Interpretation of Epistemic Openness

The final analytical stage involved interpreting each key pedagogical moment through Gandolfi's (2025a) proposal for a decolonial chemistry education, which foregrounds chemistry's entanglements with socio-political, historical, and moral dimensions. This perspective moves beyond treating chemistry as a discipline that is merely influenced by social contexts or that influences society, instead understanding chemistry knowledge, practices, and industries as intrinsically hybridised with socio-political relations and systems of power.

In this study, this decolonial lens is grounded in the Chilean context of copper mining, a historically and economically significant industry shaped by extractivist logics and socio-environmental inequalities. This context informed the analytical focus by directing attention to how classroom discourse engaged (or failed to engage) with issues of environmental injustice, governance, and the uneven distribution of risks and benefits associated with mining practices.

Drawing on this decolonial framing, the analysis examined whether and how each key pedagogical moment supported: (a) an understanding of chemistry as intertwined with socio-political and moral elements; (b) recognition of how historical and contemporary power relations shape who benefits from chemical knowledge and chemistry-related industries; and (c) engagement with voices, experiences, and contexts – particularly those of communities most affected by chemistry-related injustices – that are often marginalised in school chemistry education. Epistemic openness/closure and the inclusion or marginalisation of knowledge systems are used here as analytic constructs applied retrospectively to interpret classroom interaction, rather than as prescriptive aims explicitly adopted by the teacher during planning.

Moments characterised by authoritative discourse were examined for how they risked reinforcing an apolitical framing (Gandolfi 2025b) of chemistry, where disciplinary knowledge is positioned as objective, neutral, and self-contained, thereby limiting engagement with its ethical, environmental, and socio-political entanglements. Conversely, dialogic moments were analysed for their potential to open epistemic space by legitimising diverse perspectives, foregrounding socio-environmental concerns, and positioning chemistry as a contested field intrinsically entangled with sustainability, extractivism, and environmental injustice.

Across the three key pedagogical moments, this decolonial interpretation therefore focused on how the teacher's pedagogical decisions – e.g., revoicing, narrowing or expanding acceptable responses – mediated what kinds of knowledge were legitimised, whose experiences were rendered visible or marginalised, and how sustainability was framed within chemistry teaching. In doing so, the analysis sought to illuminate how classroom discourse can either reproduce dominant epistemic hierarchies associated with the colonial matrix of power (Quijano 2007) or create conditions for epistemic disobedience and critical engagement with chemistry's socio-political entanglements. Epistemic openness/closure, inclusion or marginalisation of knowledge systems, and decolonial perspectives are analytic constructs applied by the researcher, not pedagogical intentions explicitly adopted by the teacher during planning. Importantly, these concepts function as a critical interpretive lens rather than as indicators of pedagogical success or failure.

Tables 1,2 and 3 exemplifies the analytical process adopted in this research.

2.3 | Reflexivity

Consistent with Reflexive Thematic Analysis (Braun and Clarke 2023), this study understands knowledge production as inherently interpretative and theoretically situated. My role as a researcher was not neutral or procedural, but actively involved

TABLE 1 | Mapping classroom discourse to communicative approaches and decolonial interpretations for the key pedagogical moment "Focusing the lesson on students' knowledge".

Analytic dimension	Description
Communicative approach	Interactive-dialogic
Initial analytic code	Recognition of socio-environmental harm
Decolonial interpretation	Exposes socio-political dimensions of science; questions extractivist narratives
Indicative quotes	**Student 1:** A lot of people die
	The teacher: A lot of people die in the extraction process (Audio from the lesson).
Analytical notes	This moment illustrates an initial epistemic opening, where students' lived and ethical concerns are acknowledged without immediate evaluation, allowing socio-political dimensions of chemistry to surface.

TABLE 2 | Mapping classroom discourse to communicative approaches and decolonial interpretations for the key pedagogical moment "Focusing the lesson on chemistry".

Analytic dimension	Description
Communicative approach	Authoritative-interactive
Initial analytic code	Clarifying chemical concepts. Linking macro and micro levels of chemistry triplet (Talanquer 2018) with higher conceptual complexity.
Decolonial interpretation	It supports scientific understanding while maintaining epistemic closure by foregrounding technical accuracy and reinforcing chemistry as a canonical, and adopting an apolitical framing of chemistry knowledge, where disciplinary content is treated as objective, neutral, and disconnected from its socio-political and environmental entanglements (Gandolfi 2025b).
Indicative quotes	**Student 2:** CuH_2SO_4?
	The teacher: Could it be $CuSO_4$? (Audio from the lesson).
	The teacher: So, we had the malachite. The malachite has copper, right? What we're doing is making the copper react with the sulphuric acid. Right? What would we expect to have in that … What do you [students] think the blue liquid is? We are not seeing copper here; it is just a liquid.
	Student 3: But the blue liquid is copper
	The teacher: Yes, it contains copper. (Audio from the lesson).
Analytical notes	Across this moment, classroom discourse is oriented toward the accurate identification and explanation of chemical substances and processes, particularly through linking observable phenomena (e.g., the blue solution) to canonical chemical representations (e.g., $CuSO_4$). The teacher's questions and feedback guide students toward convergence on scientifically accepted answers, reinforcing chemistry as a discipline concerned with correct formulation, prediction, and explanation. Notably, within these exchanges, the chemical processes are treated as self-contained phenomena, without explicit reference to their environmental, ethical, or socio-political implications. This framing is also reflected in students' written work (Appendix A), where explanations predominantly focus on describing observable changes and chemical transformations (e.g., movement of Cu^{2+} ions, colour changes, and deposition of copper), with limited attention to the broader environmental or socio-political significance of these processes. Chemistry is framed as a self-contained and apolitical domain, where emphasis on technical accuracy and canonical explanations limits engagement with the socio-political and environmental dimensions of the copper mining context. In line with Gandolfi (2025b), this reflects an apolitical positioning of scientific knowledge as objective and neutral, thereby constraining opportunities for epistemic openness despite conceptual sophistication.

in shaping both the generation and interpretation of data. I therefore approach this analysis as a situated and reflexive process, in which meanings are constructed through engagement with the data, rather than discovered as fixed entities.

My positionality as a Chilean chemistry educator and researcher, with prior experience in science teaching and a strong commitment to sustainability and decolonial perspectives in education, informed the analytic lens adopted in this study. This background supported a nuanced engagement with both disciplinary content and pedagogical practice, while also requiring ongoing critical awareness of how my theoretical commitments shaped what I attended to in the data, particularly in identifying moments of epistemic openness and closure.

TABLE 3 | Mapping classroom discourse to communicative approaches and decolonial interpretations for the key pedagogical moment "Focusing the lesson on chemistry and other knowledge".

Analytic dimension	Description
Communicative approach	Interactive-dialogic
Initial analytic code	Tension between economic benefit and environmental harm
Decolonial interpretation	Challenges the colonial matrix of power by foregrounding socio-political critique, power asymmetries, and environmental injustice
Indicative quotes	**Student 14:** And, of course, it is super hard for them (people that live nearby the industry) to sue these industries because of their pollution. So, poor people generally do not complain about it. It is because powerful people do not listen to them. I mean, it should not be like that, but it happens (Audio from the lesson).
Analytical notes	This moment enacts a sustained epistemic opening, positioning chemistry as entangled with power, justice, and sustainability rather than as a neutral technical discipline.

Rather than attempting to eliminate this subjectivity, I engaged with it reflexively throughout the research process.

While the analysis presented in this article is based on classroom discourse and student artefacts, reflexivity was supported through my sustained collaboration with the teacher over the 3-month period of the study. This collaborative engagement enabled the development of trust and provided insight into the teacher's pedagogical reasoning. Although fieldnotes entries were not treated as primary data sources in this article, they played an important role in supporting reflexive awareness during the broader research process, helping me to critically examine my assumptions, interactions, and emerging interpretations. These reflections informed subsequent analytic decisions and supported a more nuanced interpretation of classroom discourse.

Importantly, the analytic constructs used in this study, such as epistemic openness/closure and apolitical framing, are not treated as inherent properties of the data but as theoretically informed interpretations shaped by my engagement with decolonial scholarship and science education research. In this sense, the findings presented should therefore be understood as one situated and interpretative account, grounded in a specific theoretical and methodological orientation. They should not be understood as a neutral or exhaustive representation of classroom practice.

3 | Findings

This section presents the three key pedagogical moments, which together constitute the full analytic focus of the study. Each subsection (see 3.1–3.3) examines one moment in depth, drawing on classroom discourse and students' artefacts to show how pedagogical decisions shaped epistemic openness or closure in relation to sustainability and chemistry teaching.

3.1 | Focusing the Lesson on Students' Knowledge: Opening a Partial Epistemic Space

The lesson opened with a whole-class dialogue exploring the question: "What does copper mean to Chile?". This phase aligned with the co-planned intention to elicit students' prior knowledge and everyday meanings before introducing disciplinary chemistry. The teacher adopted an interactive-dialogic communicative approach, inviting students to share their ideas without immediate evaluation.

Most initial responses framed copper in terms of national wealth, economic development, and technological progress, reflecting dominant extractivist narratives. For example, students referred to copper as "Chile's salary" and a source of national pride. This dialogic space became particularly visible when a student introduced a counter-narrative that disrupted the dominant framing of copper as national wealth:

Student 1: "A lot of people die."

The teacher: "A lot of people die in the extraction process." (pause)

Student 2: "Why?"

Student 1: "Because there are a lot of accidents during mining operation."

The teacher: "A lot of people die."

Rather than challenging, evaluating, or redirecting the statement, the teacher repeatedly revoiced the student's contribution verbatim, both immediately after it was introduced and again after the brief peer-to-peer clarification. This discursive move sustained the issue within the shared classroom space without closing it down or reframing it in technical or disciplinary terms. Importantly, the teacher did not introduce alternative explanations, correct the causal account offered by the student, or shift the discussion back toward economic benefits or chemical processes. This non-judgmental stance illustrates how students' ethical concerns – specifically, the human costs associated with mining – were legitimised within classroom discourse.

From a decolonial perspective, this exchange constitutes a partial epistemic opening. The recognition that "a lot of people die" during copper extraction disrupted extractivist narratives embedded in the colonial matrix of power (Quijano 2007), momentarily repositioning chemistry-related industries as sites of risk and harm rather than unproblematic progress. At the same time, the epistemic opening remained limited. The teacher did not pursue follow-up questions regarding the structural causes of mining accidents, labour conditions, environmental degradation, or regulatory responsibility, nor were alternative knowledge systems or affected community perspectives explicitly invited. As such, this moment illustrates both the potential and the fragility of dialogic pedagogy for unsettling dominant epistemologies when critical questioning is acknowledged but not yet pedagogically foregrounded (Gandolfi 2025a).

3.2 | Focusing the Lesson on Chemistry: Reinforcing Disciplinary Norms and Epistemic Closure

The second key pedagogical moment centred on a practical demonstration involving the leaching of copper from malachite using sulphuric acid. This phase aligned with the co-planned intention to consolidate students' understanding of the chemical processes underpinning copper extraction before returning to broader sustainability questions later in the lesson. In practice, this intention was enacted through a shift to an authoritative-interactive communicative approach, in which the teacher guided students toward canonical chemical explanations. This discursive orientation is illustrated in the following exchange:

The teacher: "So, we had the malachite. The malachite has copper, right? What we're doing is making the copper react with the sulphuric acid. What would we expect to have in that... What do you think the blue liquid is? We are not seeing copper here; it is just a liquid."

Student 3: "But the blue liquid is copper."

The teacher: "Yes, it contains copper. But it is liquid. So, what should it be?"

Student 2: "CuH_2SO_4?"

The teacher: "CuH_2SO_4? Or could it be $CuSO_4$, a ternary salt? It is copper sulphate."

Here, the teacher repeatedly narrowed the range of acceptable responses, steering students toward the chemically correct identification of copper sulphate. Student contributions were acknowledged only insofar as they could be refined into canonical disciplinary knowledge. This pattern exemplifies an authoritative-interactive approach in which conceptual accuracy and disciplinary norms were prioritised over exploratory or critical discussion. Notably, the chemical processes are treated as self-contained phenomena, with no explicit connection to the environmental or socio-political implications of copper extraction, despite the broader lesson context.

Students' lab reports further reflected this epistemic orientation (see Appendix A). While some students demonstrated higher levels of conceptual sophistication – such as recognising the reduction of Cu^{2+} to Cu^0 and the role of electron transfer – others focused primarily on macroscopic observations or employed imprecise concepts (e.g., referring to "particles" rather than ions or atoms). Across reports of varying complexity (see Appendix A), students largely confined their explanations to chemical transformations within the experimental system. Notably, none of the reports engaged with environmental toxicity, waste generation, or the broader socio-political implications of copper extraction.

From a decolonial perspective, this moment exemplifies epistemic closure, not because disciplinary rigour is foregrounded, but because the chemical processes are consistently treated as self-contained and context-independent. Although the lesson successfully supported scientific understanding, it foregrounded technical accuracy and reinforced an apolitical framing of chemistry as a canonical discipline, in which knowledge is presented as objective and neutral, with no explicit connection to the environmental, ethical, or socio-political dimensions of copper extraction. This absence is evident not only in classroom discourse but also in students' written work (Appendix A), where explanations remain focused on chemical transformations within the experimental system, without reference to toxicity, waste, or environmental impact. In line with Gandolfi (2025b), such framing leaves limited space for the relational and ethical dimensions of science education. Thus, epistemic closure here does not arise from the presence of canonical knowledge itself, but from the absence of opportunities to situate that knowledge within broader socio-political and environmental contexts.

Chemistry was positioned as a self-contained epistemic system, exemplifying what Gandolfi (2025a) critiques as naïve neutrality in chemistry education. Thus, while this moment achieved its disciplinary aims, it simultaneously constrained opportunities to connect chemical knowledge with sustainability, power relations, or environmental injustice.

As Miani et al. (2025) argue, reductionist framings in science education often ignore complexity, thereby limiting students' capacity to grapple with wicked problems like climate change or environmental injustice.

While this part of the lesson improved students' understanding of the scientific process, it failed to connect disciplinary learning with real-world socio-political contexts (Gandolfi 2025a).

3.3 | Focussing the Lesson on Chemistry and Other Knowledge: Enacting Sustained Epistemic Opening

The final key pedagogical moment returned explicitly to the opening question – "What does copper mean to Chile?" – but now reframed through the integration of chemical knowledge, sustainability principles (the 3 pillars model), and socio-political considerations. This phase expanded on the co-planned intention to reconnect disciplinary chemistry with broader societal concerns and was enacted through a deliberate shift from authoritative-interactive explanation to interactive-dialogic discourse. The transition is evident in the following exchange:

The teacher: So, when we started the lesson, I asked you 'What does copper mean to Chile?', and you said [...]

Student 1: [interrupting the teacher] our economy depends on it.

The teacher: yes, you said the economy of our country depends on it. So, now I ask you again: 'What does copper mean to Chile?'. What can you say?

All Students: pollution.

The teacher: pollution.

Student 2: it is responsible for the destruction of the environment.

Student 3: death.

Student 4: but, it is important for our economy [students started to talk together].

Unlike in the earlier chemistry-focused phase (see 3.2), the teacher here sustained students' critical contributions and explicitly invited tension between economic and environmental perspectives:

The teacher: so, if the copper industry is so bad, let's stop it. What would happen with economy of our country?

Student 4: our economy dies.

Student 15: it would decrease.

The teacher: and what would it happen with us?

Student 6: employment would reduce.

Student 17: it would produce an economic crisis.

The teacher: it would be an economic crisis.

This questioning foregrounded the structural complexity of sustainability rather than resolving it prematurely. As the dialogue progressed, students began to draw on media articles analysed earlier in the lesson (see Appendix B), referencing discrepancies between Chilean regulations and World Health Organisation standards for heavy metal pollution. As students stated:

Student 10: [the copper mining industry] is avoiding its responsibility. They are evading everything [the law; environmental regulations]

Student 11: They don't care about [pollution].

The teacher: They don't care. Some of you said that councils do not have enough power. Maybe, a council is doing a lot, but it does not have enough power to control [industrial activity].

Student 12: Yes, because some industries do not care if the government fines them. Sometimes, industry prefers to pay the fine. In some cases, it is cheaper to pay the fine than to treat its waste properly.

Student 13: Yes. Fines should be higher.

The epistemic opening deepened further when a student articulated how power and inequality shape environmental harm:

Student 14: Yes. But, [economically disadvantaged people] who are affected by this pollution do not have enough money to move to other areas. And, of course, it is super hard for them to sue these industries because of their pollution. So, poor people generally do not complain about it. It is because powerful people do not listen to them. I mean, it should not be like that, but it happens.

From a communicative perspective (Mortimer and Scott 2003), this episode was characterised by an interactive–dialogic approach, in which the teacher actively invited and sustained multiple student contributions without narrowing discussion toward a single authoritative conclusion. When students described the copper mining industry as "not sustainable," the teacher repeatedly prompted elaboration through open questions such as "Why?" and "So, why is [the copper industry] not sustainable?", encouraging students to build on one another's ideas. Through this dialogic scaffolding, students collectively mobilised the three pillars of sustainability, arguing that the industry "only supports the economy pillar," that "there is not a balance," and that economic interests are "overvalued."

Importantly, the teacher revoiced and validated these contributions rather than evaluating them, for example reiterating that sustainability involves "balancing economy, the environment, and people's wellness." This revoicing functioned to legitimate ethical, social, and environmental perspectives as relevant to chemistry-related reasoning. As the dialogue unfolded, students extended the critique to human health, linking heavy metal pollution to drinking water and illness ("when all that pollution is in water resources and people drink it, it is harmful for them"), and explicitly situating these harms within a local context by referencing Puchuncaví (Cabello 2025). One student's reflection – "before this lesson, I had another perspective on the copper mining industry... I did not know what they actually do with their waste" – signals an epistemic shift, indicating how dialogic engagement enabled students to question previously taken-for-granted assumptions about industrial responsibility.

Taken together, this episode illustrates how interactive-dialogic discourse supported sustainability to be constructed as a contested socio-scientific issue rather than a fixed definition, and positioning chemistry-related industries within broader ethical and socio-political debates.

From a decolonial perspective, this key pedagogical moment directly challenged the colonial matrix of power by foregrounding how chemistry-related industries disproportionately affect economically disadvantaged communities and whose voices are marginalised in environmental decision-making.

Moreover, the epistemic opening in this key pedagogical moment was materially enacted during the subsequent waste management activity. Unlike earlier moments of this lesson, where chemical processes were treated as self-contained phenomena (see Section 3.2), this exchange explicitly connects chemical knowledge to environmental and ethical considerations through students' reasoning about waste disposal:

The teacher: "So, when you wash all the materials you used in the experimental activity, what are you going to do with the residue? Can you dispose of it down the drain?

All students: No

Student 1: No, because fish are going to get poisoned.

The teacher: Ok, you are worried about fish. That is good. Yes, water from the drain ends up in the sea. Drain water treatment does not remove lead. And we know our waste contains heavy metals. Any other ideas?

Student 12: No, because it pollutes.

Student 3: Underwater is going to get polluted.

The teacher: Underwater will be polluted. Polluted with what?

Student 14: With the liquid that all the copper releases?

The teacher: We saw what was in the liquid. What will the pollution be? What do these chemicals contain?

Student 5: Lead.

All students: Lead and mercury.

The teacher: Lead, mercury, and arsenic. Right. And this is going to go underwater, which is where we get drinking water from, and obviously our drinking water is contaminated with these metals. Ok. So, we will keep this experimental waste in a bottle.

As students identified lead, mercury, and arsenic in the solution (see Quiroz-Martinez (2026) for more details on this qualitative chemical analysis), they connected chemical composition to environmental consequences, such as water contamination and harm to living organisms, demonstrating how disciplinary knowledge was mobilised within an ethical and socio-environmental frame. The teacher invited them to propose solutions, sustaining dialogic engagement rather than providing a single correct answer. While further technical treatment of waste was discussed in subsequent activities (see Quiroz-Martinez 2026), the analysis here focuses specifically on how these ideas emerged through classroom discourse in this moment.

This moment—represented in Figure 2—constitutes the specific pedagogical enactment of epistemic opening. Chemistry was no longer framed solely as a technical discipline, but as a field entangled with environmental responsibility, ethical decision-making, and care for human and non-human life. From a

FIGURE 2 | Students collecting experimental waste in a bottle for proper disposal.

decolonial perspective, this sustained dialogic engagement positioned chemistry as a contested practice implicated in power, justice, and sustainability, fostering emerging critical consciousness (Sadler 2004) and decolonial empathy (Zembylas 2018).

4 | Discussion

This study examined how integrating sustainability through a socio-scientific issue (SSI) in secondary chemistry teaching shaped epistemic openness and closure from a decolonial perspective, as mediated through classroom discourse. Drawing on reflexive thematic analysis of a single co-planned lesson, interpreted through communicative approaches (Mortimer and Scott 2003) and Gandolfi's (2025a) decolonial framing of chemistry education, the analysis focused on three specific key pedagogical moments. Together, these moments illuminate how epistemic possibilities – openness and closure – were not inherent to the SSI itself, but were actively produced through teacher pedagogical decisions enacted in discourse.

The first pedagogical moment illustrates how dialogic pedagogy can create initial epistemic openings by legitimising students' lived experiences and ethical concerns. The teacher's decision to revoice – rather than evaluate or redirect – a student's reference to mining fatalities temporarily unsettled dominant extractivist narratives. This finding aligns with decolonial scholarship that emphasises the importance of recognising voices historically marginalised in science education as a starting point for epistemic justice (Gandolfi 2025a; Walsh 2012).

However, the analysis also shows that epistemic openness is fragile and contingent. In the absence of pedagogical moves that explicitly foreground structural causes of harm – for example, labour exploitation, environmental degradation, or regulatory failure – the dialogic space remained limited. Epistemic openness requires intentional questioning and curricular framing that make power relations and historical injustices explicit, particularly in contexts shaped by extractivism. Epistemic disobedience (Walsh 2012) requires intentional pedagogical moves that foreground power, history, and injustice, rather than relying on spontaneous student contributions.

The second pedagogical moment demonstrates how authoritative-interactive discourse can consolidate disciplinary understanding while simultaneously producing epistemic closure. The teacher's sustained focus on chemical explanation – evident in the narrowing of acceptable responses toward canonical formulations – supported students' understanding of copper sulphate formation and copper (II) ion behaviour. This aligns with longstanding research emphasising the pedagogical value of authoritative discourse for conceptual development in science classrooms (e.g., Mortimer and Scott 2003).

From a decolonial perspective, however, this moment exemplifies what Gandolfi (2025a) critiques as naïve neutrality in chemistry education. Chemistry was framed as technically sophisticated yet socially detached, and students' lab reports –regardless of conceptual complexity (see Appendix A) – remained confined to chemical transformations within the experimental system. This approach reinforced a reductionist view of chemistry (Orgill et al. 2019; Miani et al. 2025). The framing was technical and value-neutral, failing to reveal the broader entanglements between scientific processes and systemic injustice. Ethical, environmental, and political dimensions of copper extraction were absent, indicating that disciplinary knowledge was not yet mobilised for socio-scientific reasoning. Importantly, this interpretation does not position the teacher's practice as deficient. Instead, it reveals a structural tension within chemistry education between maintaining disciplinary rigour and advancing epistemic justice.

At the same time, the analysis suggests that this moment of epistemic closure was pedagogically consequential. By establishing a shared chemical understanding – to present scientific evidence essential for understanding the causes of the sustainability issue under consideration (see Quiroz-Martinez (2026) for more details) –, the lesson created a form of evidentiary grounding that later enabled students to engage more substantively with socio-political critiques. Heavy metals do not emerge spontaneously; rather, they are a by-product of the industrial process. As such, heavy metal contamination constitutes a socio-scientific issue, and in contexts shaped by legacies of industry, housing segregation, and post-industrial disinvestment, it becomes a socio-justice science issue (SJSI), understood within the broader dynamics of environmental racism (Morales-Doyle et al. 2019). The chemistry perspective thus underpinned students' understanding of the causal mechanisms associated with the sustainability challenges of the copper mining industry – particularly, the causes associated with heavy metals pollution. In this sense, epistemic closure and openness should not be understood as binary opposites, but as dynamically related moments within the pedagogical flow of the lesson.

The third pedagogical moment illustrates how epistemic openness can be re-activated and sustained when disciplinary knowledge is deliberately reconnected to socio-political contexts. By returning to the opening question and introducing the three pillars of sustainability, the teacher created conditions for students to integrate chemical evidence, media sources, and ethical reasoning. Dialogic discourse supported students in articulating critiques of environmental injustice, regulatory failure, and power asymmetries, echoing findings from SSI research that highlight the role of structured controversy in promoting socio-scientific reasoning (Morin et al. 2014) and moral sensitivity (Sadler 2004). These insights reflect what Zembylas (2018) terms decolonial empathy, a relational understanding grounded in solidarity and the recognition of systemic harm.

Crucially, epistemic openness was not only discursive but materially enacted during the waste management activity. From a decolonial perspective, when students were prompted to consider the composition and disposal of experimental waste, chemistry practices themselves – rather than abstract discussions alone – can became sites of ethical and political engagement (Moura 2025). Chemistry was no longer positioned as an insulated epistemic canon, but as a practice entangled with responsibility, emotional responses (Zembylas 2018), and care for ecosystems and human health. This pedagogical moment exemplifies how chemistry education can make visible the discipline's entanglement with the colonial matrix of power and environmental injustice (Gandolfi 2025a).

However, this moment also exposes the limits of epistemic openness when it is not extended toward collective, community-oriented praxis. While students demonstrated critical awareness by proposing technical and regulatory responses – for example, improved waste treatment and stricter sanctions – these responses remained largely hypothetical, laboratory-bound, and detached from the lived realities of communities affected by extractivist harm. As justice-centred science pedagogy argues, understanding the harms and benefits of scientific practices is necessary but insufficient if learners are not supported to mobilise scientific and other forms of knowledge in ways that address socio-environmental impacts beyond the classroom (Morales-Doyle et al. 2019).

From a decolonial perspective, this limitation resonates with Gandolfi's (2025a) argument that epistemic critique must be coupled with praxis: a movement from recognising chemistry's entanglements with environmental injustice toward acting upon those realities in solidarity with affected communities. While this study does not document sustained collective or civic action within the analysed lesson sequence, such praxis often requires extended pedagogical engagement beyond a single instructional episode. Without pedagogical designs that foreground community voices and create pathways for sustained, socially grounded action, epistemic openness risks remaining at the level of awareness rather than enabling epistemic disobedience (Walsh 2012).

Although this study focuses on a single lesson, related longitudinal work with the same teacher (Quiroz-Martinez 2026) suggests that sustained attention to these issues may support students in developing more concrete responses to environmental challenges. However, a detailed analysis of these developments is beyond the scope of the present paper. In this sense, the absence of collective action in the present study should not be read as a failure of SSI pedagogy, but as an indicator of the temporal, institutional, and curricular constraints that shape how far epistemic openness can be enacted within formal schooling.

Across the three pedagogical moments, teacher decision-making and pedagogical decisions – for example, revoicing student contributions, narrowing or expanding acceptable responses, and shifting between authoritative and dialogic discourse – functioned as mechanisms through which epistemic openness or closure was enacted. This analytic approach responds to calls in science education to move beyond binary evaluations of teaching quality and instead examine how teachers navigate epistemic tensions in situ (Mortimer and Scott 2003; Gandolfi 2025a).

5 | Conclusions and Implications

This study examined how integrating sustainability through a socio-scientific issue (SSI) in secondary chemistry teaching shaped epistemic openness and closure from a decolonial perspective, as mediated through classroom discourse. Focusing on co-planned lessons on copper mining in Chile, the analysis identified three specific key pedagogical moments through which epistemic possibilities were actively produced rather than predetermined by lesson design. By tracing how communicative approaches and pedagogical decisions unfolded across these moments, the study offers an empirically grounded account of how chemistry teaching can alternately constrain or enable decolonial engagements with sustainability.

Findings demonstrate that epistemic openness in chemistry education is neither automatic nor linear. Initial dialogic engagement created a partial epistemic opening by legitimising students' ethical concerns and lived experiences, yet this openness remained fragile in the absence of pedagogical moves that explicitly foregrounded structural power relations. A subsequent focus on disciplinary chemistry produced epistemic closure, reinforcing chemistry as a technically rigorous but socially detached domain. Crucially, this closure was not merely restrictive; it provided the evidentiary grounding that later enabled students to mobilise chemical knowledge for socio-political critique. Epistemic openness was ultimately re-activated and sustained when disciplinary knowledge was deliberately reconnected to sustainability, environmental injustice, and questions of responsibility – most notably through dialogic discussion and the material practice of waste management.

Together, these findings show that epistemic openness and closure should not be understood as oppositional states, but as dynamically related pedagogical conditions that emerge through shifts in discourse, content, and classroom activity. From a decolonial perspective, the study illustrates how chemistry education can make visible the discipline's entanglement with the colonial matrix of power, particularly in contexts shaped by extractivism and environmental injustice (Gandolfi 2025a).

This study contributes to ongoing debates about how chemistry education can support sustainability and social justice without abandoning disciplinary integrity (e.g., Morales-Doyle et al. 2019). The findings suggest that integrating SSIs through a decolonial lens requires more than the inclusion of socially relevant topics. Epistemic openness depends on deliberate pedagogical decision-making, including when and how teachers shift between authoritative and dialogic communicative approaches, how disciplinary knowledge is positioned in relation to ethical and political concerns, and whose experiences and voices are legitimised in classroom discourse.

Importantly, the study highlights the pedagogical potential of treating chemistry practices themselves – for example laboratory work and waste disposal – as sites of ethical and political engagement. When students were invited to reason about the composition and treatment of experimental waste, chemistry moved beyond abstract discussion to become a practice of care, responsibility, and accountability. This suggests that decolonial chemistry education can be supported not only through discussion-based SSIs, but also through material engagements that foreground the consequences of chemical practices for human and non-human life.

At the same time, the analysis reveals persistent limitations. Indigenous and community-based knowledge systems were not explicitly incorporated, and students' critiques did not extend to concrete civic or political action. These absences point to the need for curriculum designs and teacher education programmes that more explicitly scaffold epistemic plurality, critical media literacy, and pathways from socio-scientific reasoning to collective action.

For teachers, this study underscores the importance of communicative flexibility and reflexive pedagogical judgement. Supporting decolonial perspectives in chemistry teaching does not require abandoning authoritative instruction, but rather using it strategically within a broader pedagogical arc that opens space for critique, dialogue, and ethical engagement. Teacher education should therefore support teachers in recognising epistemic tensions and navigating them productively in situ.

Author Contributions

Denise Quiroz-Martínez conceptualisation, methodology, investigation, formal analysis, data curation, project administration, writing – original draft, writing – review and editing.

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Ethics Statement

Institutional ethical approvals were obtained prior to the commencement of this study (Ethical Approval Number Z6364106/2018/05/170).

Conflicts of Interest

The author declares no conflicts of interest.

Data Availability Statement

Research data are not shared. The data that has been used is confidential.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.
Supporting File 1: sce70083-sup-0001-Appendix_A.docx.
Supporting File 2: sce70083-sup-0002-Appendix_B.docx.