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A model of curricular content for the educational reconstruction of Green Chemistry: the voice of Chilean science teachers and science education researchers

Pía José González-García, ^{*ab} Anna Marbà-Tallada ^a and Mariona Espinet ^a

The introduction of Green Chemistry (GC) into school science curriculum is considered an important step that encourages students to build connections between chemistry, other school subjects, and different aspects of their daily lives. The concepts associated with GC can be applied throughout the various levels of education with different degrees of complexity and provide a systematic approach to the teaching of science for sustainability. However, there is limited knowledge regarding the specific content that can be associated with the teaching of GC in primary and secondary schools in Chile. This study aims to provide a model of curricular science content for GC school education, utilizing the framework of Educational Reconstruction. The research question was "What links do in-service science teachers and science education researchers establish between GC and the school curriculum?" Specifically, we were interested in comparing science teachers' and science education researchers' perceptions of the links between GC and school science subject, school science contents, and crosscutting science concepts. A qualitative approach was employed for data collection and analysis, focusing on the written responses of 20 in-service science teachers and 20 science education researchers. We conclude the study by proposing an empirically based model of curricular content for GC school education (GCSE), comprising three dimensions: the multidisciplinary dimension of school science subjects represented here by chemistry, with the greatest presence, biology, physics, and geology; the intradisciplinary dimension of core disciplinary contents within each school subject; and the interdisciplinary dimension linked to a range of crosscutting concepts for GC.

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Introduction

In the current environmental context, education plays an essential role in building more sustainable and equitable future scenarios (OCDE, 2005; Eilks, 2015; UNESCO, 2016, 2017). This poses the challenge of restructuring the content of school science, the teaching and learning processes and settings, to steer the transition in school science towards sustainability. The 2030 Agenda for Sustainable Development (United Nations, 2015), proposes that through education for sustainable development (ESD) and the adoption of sustainable lifestyles, among other things, all students should develop theoretical and practical knowledge necessary to promote sustainable development.

According to Haack and Hutchison (2016), Green Chemistry (GC) has emerged as a powerful means of reducing the dangers associated with the production and use of chemical products. Along these lines, Zuin *et al.* (2021) identify different contributions of GC to the field of education, based on new concepts and strategies adopted in chemistry education programmes. Although, GC helps enrich the perspective of sustainability, especially at the undergraduate and postgraduate levels, there is still a need to incorporate GC into primary and secondary education with the same urgency (Savec and Mlinarec, 2021; Eilks and Linkwitz, 2022; Nahlik *et al.*, 2023).

Teachers are key players in the design and incorporation of educational innovations (Stavrou *et al.*, 2018). Their involvement and participation in the processes of reflection on and change of school curricular contents are vital. In the situation we are currently facing, this is particularly so in terms of science subjects and environmental studies, which are the central themes of this paper.

The research presented here is part of a wider study carried out within the framework of the Model of Educational Reconstruction

^a Department of Didactics of Mathematics and Experimental Sciences, Faculty of Educational Sciences, Autonomous University of Barcelona, Catalonia, Spain.
E-mail: piajo@uchile.cl

^b Centro Saberes Docentes ("Teaching Knowledge Centre"), Faculty of Philosophy and Humanities, University of Chile, Santiago, Chile

(MER) based on the *ex post facto* use of the model proposed by Duit *et al.* (2012). The empirical results we present in this paper are concerned with component 2 of the MER: the perceptions of science teachers and science education researchers of the subject matter of GC. The research question we address is: “What links do in-service science teachers and science education researchers establish between GC and the school curriculum?” More specifically, we are interested in comparing science teachers’ and science education researchers’ perceptions of the links between GC and school science subjects, school science contents, and crosscutting science concepts. Our goal is to contribute to establishing a robust model of the content of school science curriculum that is suitable for use as a means of teaching GC.

Theoretical framework

Green chemistry

The current climate emergency situation is pushing scientific subjects directly or indirectly to achieving sustainability (Kajikawa *et al.*, 2014). Fostering economic development, social welfare, and care for the environment requires the integration of different knowledge, skills, and tools that have their roots in many aspects of technology, society, and economics. In the case of chemistry, interest has focused on a specific object of study: matter and its transformations or as Manley *et al.* (2008) argue particularly: “Green Chemistry pursues the Webster’s definition of chemistry, ‘the study of matter and all of its transformations’”. Thus, the logic of knowledge production in this area has been altered to take into consideration broader links with society, the economy, politics, and education in the development of innovation and technology (Manley *et al.*, 2008) granting in this way the interdisciplinary nature of GC (Marques *et al.*, 2020). Marcelino *et al.* (2020) identify this as the context that led chemists in the 1990s to reflect on the influences of their practices and the lack of awareness that the scientific community in general had of the responsibilities associated with the effects of their research.

The emergence of GC has had a major impact on the traditional view of chemistry and its possible effects on society, environment, health and safety of all people potentially affected by the chemistry (Marques *et al.*, 2020; Etzkorn and Ferguson, 2023). This materialized in the 1998 book titled *Green Chemistry: Theory and Practice* (Anastas and Warner, 1998) which brings together different efforts to re-examine and redesign scientific tools to produce, transform and use chemical products that increase the efficiency and effectiveness of processes while at the same time minimising waste and harm to both humans and the environment.

GC is founded on 12 principles which act as criteria or guidelines and provide the general framework for the design and use of chemical products from a sustainable perspective. They also constitute a means for the development of safer chemical products and transformations. Working from within these principles forces practitioners of chemistry to look critically at the intrinsic properties of molecules and their transformations.

Zimmerman *et al.* (2020) maintain that the material basis of a sustainable society will depend on chemical products and processes that are designed following principles that are conducive to life. The 12 principles of GC are (Anastas and Warner, 1998): (1) prevent waste; (2) maximise atom economy; (3) design less hazardous chemical syntheses; (4) design safer chemicals and products; (5) use safer solvents and auxiliaries; (6) increase energy efficiency; (7) use renewable feedstocks; (8) avoid chemical derivatives; (9) use catalysis; (10) design chemicals and products to degrade after use; (11) analyse in real-time to prevent pollution; and (12) minimise the potential for accidents.

Today, GC has grown and diversified through a vast scientific output (Marques *et al.*, 2020) that transcends the 12 principles proposed by Anastas and Warner (1998) at the time of its formulation. The development of sustainable chemistry (Blum *et al.*, 2017; Anastas and Zimmerman, 2018; Eilks and Zuin, 2018; Horváth, 2018; Falcone and Hiete, 2019; Zuin *et al.*, 2021) is evidence of how the framework within which we understand GC has broadened: its formulation is based on the 12 principles of GC, but it embraces the need for a more holistic proposal including the political, economic, and sociocultural context, among other aspects. Similarly, principles linking GC to engineering have been developed in the so-called green engineering, with publications such as *The 24 Principles of Green Engineering and Green Chemistry: Improvements Productively* (Tang *et al.*, 2008). Principles of GC education (GCE) have even been developed (Saqueto, 2015; Zuin *et al.*, 2019; Andrade and Zuin, 2021), to promote the introduction of GC into chemistry education, offering a new framework for its development at the university level.

It is therefore not surprising that in recent years the presence of GC has increased considerably in undergraduate university study and postgraduate courses, in scientific journals, and at academic events some of which have a central theme of GC, its applications, projections and how to teach it (Green Chem, 2018; Aubrecht *et al.*, 2019a; Zuin *et al.*, 2019, 2021; Franco and Ordoñez, 2020). Meanwhile, some authors have claimed that it is necessary to broaden the focus of action; not to limit it to universities and academic circles, but also to include GC in primary and secondary school education (Anastas and Kirchhoff, 2002; Cannon and Warner, 2009; Savec and Mlinarec, 2021; Zuin *et al.*, 2021; Eilks and Linkwitz, 2022; Nahlik *et al.*, 2023)

Green chemistry and education

Programmes associated with ESD have been incorporated into school curriculum in most countries around the world, thanks to the efforts of different international associations (OCDE, 2005; UNESCO, 2016, 2017). Rauch (2015) states that over the last two decades, chemistry teaching has addressed topics that are in line with sustainable development, including the effects of acid rain, the consequences of the hole in the ozone layer, and renewable energy sources and raw materials. However, there are no signs within the current environmental context to show that this shift has brought about substantial changes in the behaviour of citizens, which are still considered limited (Zuin *et al.*, 2021). It is therefore necessary to continue the work

of restructuring the content of school science courses and introducing other innovations and modifications in the field of education that will have a significant impact on society.

The Green Chemistry has transformed and grown, incorporating other scientific fields, and posing new challenges for its epistemological construction (Marques *et al.*, 2020). In this sense, the educational field has made important efforts to build a solid foundation for the teaching of GC leading towards sustainability. Evidences of this move can be found in the following two special issues: *Reimagining Chemistry Education: System Thinking, and Green and Sustainable Chemistry* (J. Chem. Educ., 2018); and *Reuse and Recycling/UN SGDs [sic]: How can Sustainable Chemistry Contribute?* (Eilks and Zuin, 2018); and the book *Worldwide trends in Green Chemistry Education* (Zuin and Mammino, 2015). In these works, the focus has been placed on GCE, including the development of systems thinking and examining experiences from around the world that demonstrate its integration at all levels of education.

According to Eilks and Linkwitz (2022), integrating GC into the curriculum is a crucial step towards sustainability in chemistry education. The early introduction of GC concepts into the school science curriculum of primary and secondary education might be a useful pedagogical strategy to connect chemistry education with sustainability leading to more profound citizens' understanding and appreciation of sustainability issues in the future (Marques *et al.*, 2020; Savec and Mlinarec, 2021; Zuin *et al.*, 2021; Eilks and Linkwitz, 2022; Grieger *et al.*, 2022; Nahlik *et al.*, 2023).

The inclusion of GC in the school curriculum can have significant effects on students' content learning, argumentation skills, and motivation (Eilks and Linkwitz, 2022). According to the authors, this inclusion is essential for enabling students to make informed decisions as consumers and actively participate in social discussions concerning the applications of chemistry and its impact on life and the environment. Consequently, it implies the need to further develop competencies for sustainability and establish a stronger connection with GC.

The European Sustainability Competence Framework (GreenComp) (Bianchi *et al.*, 2022) was developed in response to the increasing demand for individuals to enhance their knowledge, skills, and attitudes in order to live, work, and act sustainably. This framework includes 12 competencies organised into 4 areas: (a) embodying sustainability values, including the competences: valuing sustainability; supporting fairness; and promoting nature; (b) embracing complexity in sustainability, including the competences: systems thinking; critical thinking; and problem framing; (c) envisioning sustainable futures, including the competences: futures literacy; adaptability; and exploratory thinking; and (d) acting for sustainability, including the competences: political agency; collective action; and individual initiative.

The GreenComp framework is aligned with the recent developments of GCE linking systems thinking and GC (Hurst *et al.*, 2019; Aubrecht *et al.*, 2019a; Aubrecht *et al.*, 2019b; Hurst, 2020; MacKellar *et al.*, 2020; Grieger *et al.*, 2022). It also encourages chemistry educators to consider the broader, systemic, and life cycle implications of the choices made when

enacting GCE (MacKellar *et al.*, 2020). The adoption of GreenComp would open the way for the development of competencies in GCE such as "exploratory thinking" (within "envisioning sustainable futures"), which calls for adopting a relational way of thinking, exploring, and linking different disciplines, using creativity and experimentation with new ideas or methods.

Other chemistry education researchers such as Stavrou *et al.* (2018) state that it is necessary to identify and include cutting-edge research topics in school curriculum, as is the case of GC. This need is based on a series of arguments, but two of them are highlighted. First, according to Kitchens *et al.* (2006), the concepts associated with GC are important and can be applied at all levels of education; moreover, they offer a systematic approach to ESD. Despite the force of this claim, there is little evidence regarding exactly which of these concepts can be included for GC teaching and learning at the school level, or how they have affected the selection and structuring of the science contents taught in schools. Secondly, Karpudewan *et al.* (2012) indicate that GC allows students to make connections between chemistry and other subjects, and even with different aspects of their lives (such as their economic, environmental, and social context). Through GC, students can gain an understanding of how different environments in which chemicals are used, or where pollutants and waste are dispersed, are affected by them. This necessarily requires the involvement of subjects such as biology, geology, and physics, in order to understand the complexity of the environmental implications and their relation to social justice problems, as well as to develop humanistic approaches to chemistry (Armstrong *et al.*, 2018). However, once again, research is severely lacking on the nature and scope of the interdisciplinary connections that can be made when teaching GC in the non-university education context.

Educational reconstruction of Green Chemistry

The selection of contents and topics to be taught at school is a complex process, and different approaches have been developed in the science education research community (Chevallard, 1989; Duit *et al.*, 1997; Duit *et al.*, 2012). Although GC is a cutting edge and well-defined scientific field of knowledge it cannot be introduced as such into school science curriculum. The Model of Educational Reconstruction (MER) (Duit *et al.*, 2012) constitutes a theoretical framework that can be applied to study the relevance of teaching GC in schools, considering international debates on the interdisciplinary nature of GC and its role in restructuring school science contents (Mahaffy *et al.*, 2019). It provides a frame for the identification of a coherent and beneficial body of content for students that reinforces the pedagogical justification for the inclusion of GC in science classrooms (Nahlik *et al.*, 2023).

According to Stavrou *et al.* (2018), the MER has been developed as a theoretical-methodological framework to study the relevance of teaching specific scientific concepts, based on three interrelated components (Duit *et al.*, 1997; Duit *et al.*, 2012): (a) clarification and analysis of the science content; (b) research on teaching and learning, comprising investigations

of students' and teachers' perspectives with regard to the topic selected; and (c) design and evaluation of teaching and learning environments.

The clarification and analysis of the science content constitutes the first component of MER and involves hermeneutical-analytical research on subject matter clarification and analysis of particular science content. It aims at configuring a structure for the content from an educational perspective and transforming specific scientific concepts so that they can be taught. This process of transformation of scientific concepts can be carried out based on various reconstruction strategies. Duit *et al.* (1997) propose that continuous monitoring of the literature on the topic that is being reconstructed can be carried out, while Duit *et al.* (2012) suggest conducting a critical qualitative content analysis of textbooks and key publications on the subject being examined.

Research on teaching and learning. The study of students and teachers' perspectives on the topic selected has the purpose of identifying and incorporating pre-instructional conceptions, affective variables, interests, self-concepts, attitudes, and skills of students and teachers. According to Kattmann *et al.* (1996), this second component of MER consists of empirical research into students' and teachers' understanding of the basic ideas involved in the topic selected. This phase is important when it comes to projecting the design and assessment of learning environments, as it allows the objectives of the teaching material to be set.

Design and evaluation of teaching and learning environments that incorporate the topic to be studied and which are suitable for implementation in schools constitutes the third component of MER. This component comprises the design of instructional materials, learning activities, and teaching and learning sequences (TLS) (Stavrou *et al.*, 2018), taking into account the perspectives of students, teachers, and researchers (Duit *et al.* 2012).

Method

As mentioned in the introduction, research presented here is part of a wider study carried out within the framework of the Model of Educational Reconstruction (MER) based on the *ex post facto* use of the model.

We report the empirical results for component 2 of the MER, which is the perceptions of science teachers and science education researchers of GC content knowledge. Components 1 and 3 of the MER are not included in this paper, since both the construction of teaching and learning sequence (TLS) and the study of proposals deserve particular and extended attention. Fig. 1 shows the general design of our model for the educational reconstruction of GC, with the three components represented.

Due to the exploratory and descriptive nature of this study, we developed qualitative research methods for data collection and analysis (Bryman, 2016; Cohen *et al.*, 2018).

Context of the professional teacher development program

Data used in this study was partly collected in the professional teacher development program (PTD), specifically, a diploma named "Teaching and learning Green Chemistry for the teaching of chemistry and natural sciences". This program was developed by the Centro Interdisciplinario de Líquidos Iónicos ("Interdisciplinary Centre of Ionic Liquids") and the Centro Saberes Docentes ("Teaching Knowledge Centre"). The PTD included a total of 43 sessions organised into 15 teaching modules and aimed to promote the understanding and practice of GC in Chilean primary and secondary education.

In each session, teachers were familiarized with the 12 principles of GC (one principle per session) using the guiding questions and the implementation of experimental activities shown in Table 1.

After the PTD, a group of science education researchers was convened to supplement the research conducted with teachers. Likewise, they were acquainted with the 12 principles of GC, along with its definition, and the same guiding questions and experimental activities (Table 1) that were employed with the teachers' group.

The guiding questions and experimental activities were the result of the clarification and analysis of the GC content (MER component 1) undertaken by the research team.

Within this context, the aim of this research is to compare science teachers' and science education researchers' perceptions of the links between GC and school science subjects, school science contents, and cross-cutting science concepts.

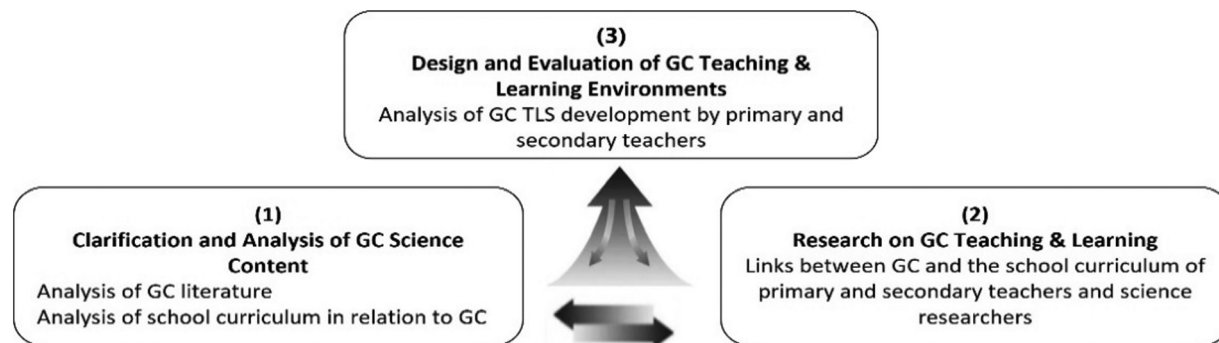


Fig. 1 Model of educational reconstruction for GC, adapted from Duit *et al.* (2012).

Table 1 The 12 principles of GC, associated with 12 guiding questions and 12 aims/practical activities

GC principle	Guiding question	Aim/practical activity
1. Prevention	Why should oil be collected in a pot or jar and not thrown down the drain?	Understand that the costs of chemical waste are a serious economic, environmental, and social liability to foster prevention/experimentally verify the relationships that exist between temperature and concentration of solutions in relation to pollution of the oceans with oil as waste.
2. Atom economy	Can we use just one indicator to analyse how green a process is?	Calculate and analyse the E-factor, as a measure of greenness/compare CO ₂ formation from fruit and yeast to that from acetic acid and sodium bicarbonate, as a function of atom economy and the E-factor.
3. Synthetic methods	Should you be concerned about the origin of certain substances, such as sweeteners?	Understand the impact of products of different toxicity/compare different acid–base indicators and their usefulness (red cabbage and turmeric); qualitatively assess the toxicity of all the products.
4. Designing safer chemicals	Are all so-called chemicals toxic for people and for the environment?	Identify hazardous substances and replace them with less hazardous ones/compare the utility and toxicity of a biopolymer with those of a commonly used polymer and consider the environmental implications.
5. Safer solvents and auxiliaries	Can you use water to clean any stain off cloth?	Evaluate the use of water as a green solvent and the impact of traditional solvents/analyse the properties of different traditional solvents and green solvents, relating their characteristics to intermolecular interactions and the effects they have on the environment.
6. Design for energy efficiency	Is the microwave oven an efficient heating device?	Select the most efficient energy sources in a chemical reaction/analyse the empirical differences between electromagnetic and thermal energy; assess the advantages of using electromagnetic radiation (microwave oven) in a chemical reaction.
7. Use of renewable feedstocks	Can household waste be a renewable raw material?	Promote the use of waste as a raw material/analyse and replicate the process of the formation of biodiesel from a recycled compound (used oil).
8. Reduce the use of derivatives	In what daily activities can we reduce the number of stages in a process or the use of energy?	Evaluate the phases and the use of energy in daily actions, as an analogy of chemical synthesis/develop an understanding of the importance of avoiding the use and generation of derivatives; compare synthetic routes and evaluate them (reagents, products, stages, auxiliaries, derivatives, and waste).
9. Catalysis	Do you know of any catalysts other than those used in a car?	Understand the relevance and operation of catalysts/through simple laboratory experiments, demonstrate parameters that affect the speed of a reaction.
10. Design for degradation	What advantages and disadvantages would there be to banning the use of plastic bags in your town?	Differentiate the conception of degradability and biodegradability/predict and determine which materials are biodegradable and which are not, based on their behaviour over a given period.
11. Real-time analysis	Do you know of any things you do that reduce negative impacts on the environment?	Reflect on daily actions and their immediate impact on the environment/distinguish and come to understand alterations in biogeochemical cycles due to changes in the properties of some solutions.
12. Safer product synthesis	Why do we have, and should we follow, environmental safety rules and regulations?	Review safety protocols in the laboratory/propose protocols of how to act in the case of accidents during experimental work and gain an understanding of their importance.

Participants

Two different participant groups took part in the research: Group A (in-service primary and secondary school teachers) and Group B (science education researchers).

Group A. This group included 20 in-service teachers with between 1 and 20 years of teaching experience. They comprised: 11 primary school teachers, of whom 9 were specialised in teaching natural sciences and 2 in mathematics; and 9 secondary school chemistry teachers, of whom one had a doctorate in chemistry, 3 were specialised in technology, and 3 in the natural sciences. All 20 teachers took part in the professional teacher development program (PTD) “Teaching and learning Green Chemistry for the teaching of chemistry and natural sciences”.

Group B. This group consisted of 20 science education researchers with experience in the school system or in in-service and preservice science teacher training. They comprised: 5 researchers with first degrees in chemistry (1 with a doctorate in science education, 1 with a doctorate in chemistry, and 3 with master's degrees in science education researchers with first degrees in physics (2 with doctorates in science education and 3 with master's degrees in science education); 5 researchers with first degrees in biology (2 with doctorates in science education and 3 with master's degrees in science education); and 5 researchers with first degrees in geology (1 with a doctorate in science education, 2 with master's degrees in science education and 2 with master's degrees in geology).

At the beginning of the study, both groups of participants were informed about the content of the study, that participation in the study would be voluntary, and that they could leave the study at any time. Written consent was obtained from the participants before the study began. The 40 (20 teachers and 20 researchers) participants took part in the study voluntarily and pseudonyms were adopted for them to keep their identities confidential.

Data collection

Data were drawn from the responses provided by Group A and Group B participants to the guiding questions. These responses were enriched through the reflection on both the proposed experimental activities and the study of each GC principle.

Data collection for Group A. During the PTD process, the participating teachers worked in small groups answering each of the 12 guiding questions shown in Table 1. They then performed the 12 experimental activities proposed and attended 12 sessions of presentations, which involved reflection on the topic under consideration. The 12 questions were accompanied by a rubric to guide the writing of the answers. This rubric laid out the following 4 criteria: (1) links with GC; (2) links with the curriculum; (3) clarity and coherence; and (4) conclusions. Each criterion had 4 possible performance levels (Excellent, Satisfactory, Regular, and Needs Improvement), and the rubric provided details of the performance expected in each of them.

The data selected for this study were drawn from the answers to the 12 guiding questions that corresponded to criterion 2: "links with the curriculum". In total, we collected 72 responses since the 20 teachers worked in groups of 3 or 4, that is, 6 groups were formed and therefore 6 responses were collected for each principle. From these responses, we identified 114 units of analysis (UA) of links with the curriculum cited by the teachers; these are presented as our units of analysis in Table 2.

The following is an example from one of the responses written by one in-service primary school teachers' group, associated with GC principle 6, on the question: Is the microwave oven an efficient heating device?

"Concerning links with the curriculum, this principle allows for the development of activities related to types of energy and the transformations they undergo, offering options for examples that can connect with the daily activities of the students and at the same time suggesting work on the concept of energy efficiency. It is also a scenario in which work could be done on the atomic model, due to the functioning of the microwave oven, and in this way show that it is possible to contextualise this unit, which students find very complex". (Translated excerpt from session 13.)

Data collection for Group B. The 20 researchers participated online by completing a Google Form consisting of two parts.

One part of this instrument was purely informative and provided the 12 definitions of the GC principles, the 12 guiding questions and the 12 descriptions of a practical exercise related to each principle and question, as shown in Table 1. The other part of the instrument consisted of the following question for each of the 12 GC principles: What links can you establish between each GC principle and your science subject?

We obtained a total of 240 written responses from the completed forms. The answers were written individually, and we organised them according to the field in which each of the researchers had graduated, meaning the answers were separated into the areas of biology, chemistry, physics, and geology. From these responses, we identified a total of 528 units of analysis (UA) as links with the curriculum cited by the researchers (Table 2).

The following is an example of one of the responses written by a researcher with a biology degree, associated with GC principle 10, and its curricular links:

"In the 1st year of secondary education, the effects of human actions and natural phenomena must be explained and evaluated, where the idea of environmental safety seems very relevant to me. This same theme is also present in the curriculum of the subject Citizen Science, in the safety, prevention, and self-care module, about risks of natural origin or caused by human action in their local context (such as avalanches, fires, high-magnitude earthquakes, volcanic eruptions, tsunamis, and flood, among others) and concerning evaluating the existing capacities in the school and the community for prevention, mitigation, and adaptation when faced with their consequences". (Translated excerpt from answer 12.)

Data analysis

We selected a qualitative approach (Cohen *et al.*, 2018) for the analysis of the data collected, since all the MER processes were exploratory in nature. More specifically, we used qualitative content analysis (QCA) for the scrutiny of the textual data (Krippendorff, 2019). We performed this QCA on the 72 answers from the teachers and the 240 answers from the researchers at 3 distinct levels (Table 3).

(a) At the first level of analysis, we identified the degree of explicitness of the curricular links with GC. A curricular link was explicit, semi-explicit, or implicit when the presence of the principle and its links with educational cycles, educational levels, scientific subjects, learning objectives, and curricular content were directly observed in the textual response, partly observed, or interpretation was needed, respectively. Table 3 provides excerpts illustrating the degree of explicitness that participants' textual responses could have.

Table 2 Summary of data collection instruments and the units of analysis (UA) extracted from the links with GC expressed in the responses of teachers and researchers. The number of UA indicates the total number of mentions made by each group A and group B

Groups of participants	Data collection instrument	Data	Total units of analysis
A: 20 teachers	12 guiding questions, within the framework of the PTD	72 answers	114
B: 20 researchers	12 definitions of principles/guiding question/experiment objective	240 answers	528

Table 3 Excerpts from answers, exactly as they were collected in the questions, showing the 3 levels of explicitness (explicit, semi-explicit, and implied). Three responses associated with principle 10 (Pr10) are shown. LO = learning objective

Level of explicitness	Excerpt from responses
Explicit	The conceptual content associated with this principle, I believe, can be related mainly to the aspects of ecology that the school curriculum addresses, in terms of the explanation and evaluation of the effects of human actions concerning the different equilibriums within ecosystems, the availability of natural resources and raw material and possible measures for sustainable development (1st year of secondary education). This same theme is also present in the curriculum of the subject Citizen Science (3rd and 4th years of secondary education) with the LO "Investigate the life cycle of everyday products and propose, based on evidence, sustainable consumption strategies to prevent and mitigate environmental impacts", which brings into consideration energy efficiency, emissions reduction, how to manage water resources, conservation of ecosystems and waste management, among others. (Translated excerpt from answer Pr10, researcher)
Semi-explicit	Plastic is an abundant material (1st year of primary education), its use is indiscriminate and without measuring the consequences, it is easily discarded. The seas and oceans around the world bear witness to these discarded and abandoned polymers, which furthermore need more than 400 years to biodegrade. This leads to effects on marine ecosystems (5th year of primary education), damaging flora and fauna; and they have even grouped together in a new continent. (Translated excerpt from answer Pr10, primary school teacher)
Implicit	The curricular link would be through the manufacture of a polymer. This is linked to GC developing a biopolymer, which could be compared to a synthetic polymer in its temporary degradation process until biodegradability in the soil is demonstrated by measuring physical characteristics such as its mass and size. (Translated excerpt from answer Pr10, secondary school teacher)

(b) At the second level of analysis, we identified the type of curricular links with GC (links with school science subjects and with school curriculum content). A comparison between school-teachers and science education researchers were conducted.

(c) At the third level of analysis, we identified curricular components linked to GC that were present in 2 or more science subjects, thus acting as crosscutting concepts. A comparison between schoolteachers and science education researchers were also conducted.

Results and discussion

Which school science subjects are linked to Green Chemistry?

There was a high level of agreement between the teachers and researchers' answers concerning the degree of association between school science subjects and GC (Table 4). While chemistry was seen as the subject most closely linked to GC, geology was seen as the least closely linked by both teachers and researcher's answers. While the order of the degree of association was the same for both groups, we did observe differences in the percentages obtained for each subject, although these are not significant for our current research.

These links reinforce arguments in favour of continuing to work with GC as a cutting-edge research topic (Stavrou *et al.*, 2018) which generates a space for dialogue related to the different subjects that make up the school science curriculum. Next, we considered whether this degree of agreement is maintained when the teachers and researchers specified the contents that link each

of the school science subjects with GC. In this way, we aimed to identify the core disciplinary content that is necessary to teach GC and link it to each school science subject.

What school science contents are linked to Green Chemistry?

In what follows, we report the links between science content and GC that both teachers and researchers identified for each school science subject (chemistry [C], biology [B], physics [F], and geology [G]). We consider that the links between a specific school science content and GC are strong when more than 10% of the units of analysis refer to it; in contrast, they are considered weak when this percentage is less than 10%.

Moreover, we will consider that a specific school science content is a core disciplinary content when there is an agreement between the two groups that it has a strong link with GC.

School chemistry

From the 321 units of analysis linked to chemistry, 16 different curricular contents of school chemistry are associated with GC (Table 5), 15 of them stem from researchers' group, and only 6 from teachers' group.

We observed that the two groups showed a high degree of agreement in relation to the school chemistry contents most strongly linked to GC such as *physical and chemical changes of matter, chemical reactions, and stoichiometry* (C₁₆); *pure substances, mixtures, and solutions* (C₁₄); *organic chemistry* (C₁₅); and *the atomic-molecular model* (C₁₂).

Table 4 GC links with school science subjects, according to teachers and science education researchers' answers. (UA = 642 units of analysis including schoolteachers and researchers)

Group	Chemistry	Biology	Physics	Geology	Total UA
Teachers	40 (35.1%)	30 (26.3%)	29 (25.4%)	15 (13.2%)	114 (100%)
Researchers	281 (53.2%)	134 (25.4%)	57 (10.8%)	56 (10.6%)	528 (100%)
Total	321	164	86	71	642

Table 5 Contents of school chemistry linked to GC from teacher's and science education researchers' responses (UA = 321). The content that has links with other disciplines are declared in parentheses

Content of school chemistry linked to GC	Researchers (%)	Teachers (%)
C ₁ Properties of the states of matter and changes of state	0 (0)	5 (12.5)
C ₂ Biogeochemical cycles (B3 & G2)	2 (0.7)	0 (0)
C ₃ Renewable and non-renewable: natural resources and raw materials	2 (0.7)	0 (0)
C ₄ Properties and types of matter	3 (1.1)	4 (10)
C ₅ Nuclear energy and reactivity	4 (1.4)	1 (2.5)
C ₆ Chemical catalysis	4 (1.4)	0 (0)
C ₇ Safety during experimental work (B1 & P3)	4 (1.4)	0 (0)
C ₈ Chemical kinetics	7 (2.5)	3 (7.5)
C ₉ Energy model, responsible use of energy and energy efficiency (B4 & P7)	9 (3.2)	0 (0)
C ₁₀ Thermodynamics of chemical processes	10 (3.6)	0 (0)
C ₁₁ Chemistry of biological processes	10 (3.6)	0 (0)
C ₁₂ Atomic-molecular model, chemical bonds, and intermolecular forces	24 (8.5)	4 (10)
C ₁₃ Chemical industry: process and effects on society and the environment	27 (9.6)	0 (0)
C ₁₄ Properties and characteristics of pure substances, mixtures, and chemical solutions	30 (10.7)	9 (22.5)
C ₁₅ Organic chemistry and reactivity; properties and formation of polymers	65 (23.1)	6 (15)
C ₁₆ Physical and chemical changes of matter, chemical reactions, and stoichiometry: properties and characteristics	80 (28.5)	8 (20)
Total	281 (100)	40 (100)

In Particular, it was observed that the teachers' responses had fewer links compared to those of the researchers, they only linked 8 of the 16 curricular contents identified in total for GC. It should be noted that the only content that the researchers did not link to GC was *changes in the state of matter* (C₁), while for the teachers this was one of the contents strongly linked to GC.

Another important point is that curricular contents related to the concept of energy were linked to GC in the responses of both groups, but with different perspectives. Teachers and researchers agreed on considering *nuclear energy and radioactivity* (C₅) to be linked to GC, while only the researchers linked the other content related to *thermodynamics and energy* (C₁₀, C₉) to GC. The contents with a more transversal nature and sustainability links, such as *biogeochemical cycles* (C₂), *safety during experimental work* (C₇), *energy and its responsible use* (C₉), *renewable and non-renewable natural resources and raw materials* (C₃), or the *chemical industry and its social and environmental impact* (C₁₃), were considered only by the researchers.

School biology

Based on the responses from teachers and researchers, a total of 164 units of analysis were identified, enabling the identification of 9 curricular contents of school biology associated with

GC. In this case, all 9 contents were observed in the researchers' responses, whereas only 4 were mentioned in the teachers' responses (Table 6).

We observed agreement between the two groups over the content that is most strongly linked to GC, that is, *the effects of human activity on ecosystems and measures for protecting them* (B₉), followed by *energy and ecosystems* (B₇). Regarding *the organisation of living beings* (B₆) and *the human body: health and nutrition* (B₅), we observed partial agreement as these contents were strongly linked to GC in the teachers' responses, but only weakly linked in the researchers' responses. These four specific curricular contents of school biology can be considered part of the core disciplinary content for GC, necessary to teach GC, as there was agreement on the links.

As occurred with the links between the school chemistry contents and GC, the teachers' responses indicated no link for a set of 5 specific contents of a transversal nature that were linked to GC in the researchers' responses. The researchers strongly linked, *the sustainable use and consumption of chemical substances and resources* (B₈) with GC, while they linked the remaining 4 weakly (*safety during experimental work* [B₁]; *scientific-technological controversy* [B₂]; *biogeochemical cycles* [B₃]; and *the energy model* [B₄]).

Table 6 Contents of biology linked to GC from teacher's and science education researchers' responses (UA = 164). The content that has links with other disciplines are declared in parentheses

Content of school biology linked to GC	Researchers (%)	Teachers (%)
B ₁ Scientific-technological controversies (P4)	3 (2.2)	0 (0)
B ₂ Safety during experimental work (C ₇ & P ₃)	4 (3.0)	0 (0)
B ₃ Biogeochemical cycles (C ₂ & G ₂)	10 (7.5)	0 (0)
B ₄ Energy model, responsible use of energy and energy efficiency (C ₁₂ & P ₇)	11 (8.2)	0 (0)
B ₅ Human body: health and nutrition	12 (8.9)	6 (23.3)
B ₆ Organisation of living beings	12 (8.9)	7 (20.0)
B ₇ Energy and ecosystems	16 (11.9)	8 (26.7)
B ₈ Sustainable use and consumption of chemical substances and resources (P ₆)	23 (17.2)	0 (0)
B ₉ Effects of human activity on ecosystems and measures for protecting them	43 (32.1)	9 (30.0)
Total	134 (100)	30 (100)

School physics

From the 86 units of analysis linked to physics, the responses from the teachers and researchers allowed for the identification of 7 curricular contents of school physics that are associated with GC.

In this case, 4 contents were identified in the researchers' responses, 2 were mentioned only in the teachers' responses, and 1 content was linked by both groups (Table 7). There was an agreement between the two groups concerning only one item: *the energy model, responsible use of energy, and energy efficiency* (P₇). This content represented 50.9% for the researchers and 31% for the teachers, which is why it is the only core disciplinary content of school physics linked to GC. There was a significant disagreement regarding the other 6 contents, shown by the absence of links identified in either the teachers' or researchers' responses. However, it is worth noting that all the links identified from the teachers were somehow related to energy. On the other hand, the links identified from the group of researchers were more diverse encompassing contents with a transversal nature that were also present in the links identified in the other subjects considered in this study.

As observed for school chemistry, a different perspective on the concept of energy was adopted by the two groups. The 3 specific science contents of school physics linked to GC from the teachers' responses are all related to energy (*natural energy resources* (P₁); *types and transformations of energy* (P₂); and *the energy model, responsible use of energy and energy efficiency* (P₇).

In the case of the researchers, of the 5 curricular contents for which they identified links with GC, 2 were related to the concept of energy (*the energy model, responsible use of energy and energy efficiency* (P₇); and *thermodynamics* [P₅]) and represented 66.7% of all the links identified by this group. This means that regardless of the perspective adopted towards these

contents, the concept of energy is central to school physics for work on GC in school.

School geology

Finally, 71 units of analysis were identified from teachers' and researchers' responses, which allowed for the identification of 4 curricular contents of school geology associated with GC. These contents are strongly linked to GC and include 2 contents that emerge from the responses of the group of teachers and 3 from the responses of the researchers (Table 8).

The data indicated that the two groups showed agreement on one content (*the effects of human activity and protective actions in Earth's layers* [G₃]). This item was the specific content of school geology most strongly linked to GC in the case of the teachers (80% of the identified links). In the case of researchers, it was the second most strongly linked to GC (40% of the identified links). This constitutes the only core disciplinary content for school geology and its link with GC.

There was significant disagreement over the other three specific contents of the school geology curriculum. The analysis of the link absences points at a different perspective on the role of geology in GC. As it happened in other school subjects, teachers did not make connections with the crosscutting concept: *biogeochemical cycles* (G₂) as well as *environmental management and sustainable development* (G₄), which appeared linked to GC for the first time here. The item for which links to GC were not identified from the researchers' responses refer to a single content related to *the structure of Earth and the development of life*, which is clearly very subject-specific.

Based on the agreement observed between the teachers and researchers on the contents of school science linked to GC, we were able to identify the core disciplinary contents necessary for teaching and learning GC. While for biology, physics, and

Table 7 Contents of physics linked to GC from teacher's and science education researchers' responses (UA = 86). The content that has links with other disciplines are declared in parentheses

Content of school physics linked to GC		Researchers (%)	Teachers (%)
P1	Natural energy resources	0 (0)	7 (24.1)
P2	Types and transformations of energy	0 (0)	13 (44.8)
P3	Safety during experimental work (C ₇ & B ₁)	3 (5.3)	0 (0)
P4	Scientific-technological controversies (B ₂)	5 (8.8)	0 (0)
P5	Thermodynamics	9 (15.8)	0 (0)
P6	Sustainable use and consumption of chemical substances and resources (B ₈)	11 (19.3)	0 (0)
P7	Energy model, responsible use of energy and energy efficiency (C ₁₂ & B ₄)	29 (50.9)	9 (31.0)
Total		57 (100)	29 (100)

Table 8 Contents of geology linked to GC from teacher's and science education researchers' responses (UA = 71). The content that has links with other disciplines are declared in parentheses

Content of school geology linked to GC		Researchers (%)	Teachers (%)
G1	Characteristics of Earth's layers and the development of life	0 (0)	3 (20)
G2	Biogeochemical cycles (C ₂ & B ₃)	10 (18)	0 (0)
G3	Effects of human activity and protective actions in Earth's layers	22 (39.3)	12 (80)
G4	Environmental management and sustainable development	24 (43)	0 (0)
Total		56 (100)	15 (100)

geology education these contents refer to issues associated with environmental care and prevention or sustainability, in the case of chemistry education they constitute specific conceptual content related to the subject. In this way, a particular functional dynamic of school science subjects can be traced for the teaching of GC as a space for interdisciplinary dialogue, thanks to the identification of the core disciplinary contents.

Which crosscutting concepts are linked to Green Chemistry?

From the links identified, we can see that there are 5 specific curricular contents of the school science curriculum that are found in more than one subject (Table 9). These contents represent 19.3% (124) of all the connections made by the teachers and researchers together ($n = 642$, 528 from researcher's responses, and 114 by teacher's responses). We assert, in the context of this study, that these contents constitute what is known as crosscutting concepts. According to the US science curriculum framework from the National Research Council (NRC, 2012), a crosscutting concept is one that crosses disciplinary boundaries and can provide students with an organisational framework through which to connect different fields of knowledge within various subjects. Other researchers such as Izquierdo (2005) understand this type of content as a 'structuring idea'.

The first thing to notice in Table 9 is that biology is the only subject to contain all 5 crosscutting concepts, while geology includes the least: only 1. Meanwhile, the crosscutting concept with the greatest presence is the *energy model, responsible use of energy and energy efficiency*. It is particularly striking that *sustainable use and consumption of chemical substances and resources* is absent from both chemistry and geology. This is, however, consistent with our results for the links identified, which indicate that the only one of the 4 subjects that presents weak or almost non-existent connections with issues associated with caring for the environment is chemistry. Table 9 provides information on the 5 specific crosscutting concepts we have identified, and the subjects associated with them.

Recently, academics have debated the practical suitability of crosscutting concepts and the difficulties teachers encounter when teaching them (Osborne *et al.*, 2018). Here, we align with the position defended by Cooper (2020) in that the use of crosscutting concepts fosters an appropriate approach that respects disciplinary differences, while at the same time connects the different subjects. Crosscutting concepts are necessary to understand the complexity of the issues they are used to address, so we defend their importance and viability for the teaching of a cutting-edge research topic such as GC. At the

same time, we recognise that the principal difficulty in using this kind of content lies in the fact that it is necessary to generate conditions in which this type of proposal is widely known and used by teachers, as propounded by the researchers who participated in this study.

Limitations

All participating teachers and researchers reported their perceptions of the links of the Chilean school science curriculum with GC. We understand that science curriculum might vary across different countries, and thus it becomes impossible to extrapolate the data of this study precisely to other countries. However, the study provides the conceptual and methodological tools necessary to include the voices of in-service science teachers and science education researchers in the identification of the most appropriate school science contents to support the introduction of GC into primary and secondary education wherever possible.

In future studies, groups of teachers and researchers from different parts of the world could participate, to contrast the results obtained in this research.

Conclusions

The Model of Educational Reconstruction (MER) provides a perspective from which to approach the selection of Green Chemistry School Education (GCSE) content as an analytical and participatory process. Based on the voices of Chilean teachers and science education researchers, we have been able to identify curricular links with GC in the Chilean education system and propose a model of science curriculum content that represents an educational reconstruction of GC. Previous studies have highlighted the importance of considering teachers' views on the GC curriculum for GCSE to be successfully implemented within compulsory science education (Karpudewan and Kulandaisamy, 2018; Nahlik *et al.*, 2023). The present study adds to previous work in that it demands from teachers and researchers a higher level of specificity so that their contributions can be used in the development of a GC curriculum.

The responses of the teachers and researchers revealed their perceptions of the specific contents of the school science curriculum linked to the teaching of GC, in relation to different science subjects. From this, we have been able to identify core disciplinary contents and crosscutting concepts for GCSE. We propose that these three aspects be considered dimensions of a model of the content of the Chilean school science curriculum

Table 9 Crosscutting concepts from school science linked to GC by the researchers

Crosscutting concept	Chemistry (%)	Biology (%)	Physics (%)	Geology (%)
Energy model, responsible use of energy and energy efficiency	9 (60.0)	11 (21.6)	29 (60.4)	0 (0)
Sustainable use and consumption of chemical substances and resources	0 (0)	23 (45.1)	11 (23.0)	0 (0)
Biogeochemical cycles	2 (13.3)	10 (19.6)	0 (0)	10 (100)
Safety during experimental work	4 (26.7)	4 (7.8)	3 (6.3)	0 (0)
Scientific-technological controversies	0 (0)	3 (5.9)	5 (10.4)	0 (0)
Total	15 (100)	51 (100)	48 (100)	10 (100)

Table 10 Proposal for a model of the content of school science curriculum for GC school education

A model of curricular content for Green Chemistry school education		
Multidisciplinary dimension: School science subject	Intradisciplinary dimension: core disciplinary contents	Interdisciplinary dimension: crosscutting concepts
Chemistry (C)	Properties and characteristics of pure substances, mixtures, and chemical solutions Organic chemistry and reactivity; properties and formation of polymers Physical and chemical changes of matter, chemical reactions, and stoichiometry: properties and characteristics Atomic-molecular model, chemical bonds, and intermolecular forces	Energy model, responsible use of energy and energy efficiency (C & B & P) Sustainable use and consumption of chemical substances and resources (B & P)
Biology (B)	Effects of human activity on ecosystems and measures for protecting them Human body: health and nutrition Organisation of living beings Energy and ecosystems	Biogeochemical cycles (C & B & G) Safety during experimental work (C & B & P)
Physics (P)	Energy model, responsible use of energy and energy efficiency	Scientific-technological controversies
Geology (G)	Effects of human activity and protective actions in Earth's layers	(B & P)

for GCSE (Table 10). This model complements the proposal of GC principles for education (Saqueto, 2015; Zuin *et al.*, 2019) with a body of content defined for primary and secondary education and identifies the opportunities offered by the content of the school curriculum to work on GC at school. According to Nahlik *et al.* (2023), this responds to one of the main criticism or doubt about ecological or sustainable approaches to chemistry, which is the sacrifice of traditional content knowledge.

In addition, our model contributes to one specific category of the framework proposed by Jegstad and Sinnes, (2015), based on the research by Burmeister *et al.* (2012). This framework outlines five categories for a chemical education and ESD model. These categories include: (1) chemical content knowledge, (2) chemistry in context, (3) the distinctive and methodological nature of chemistry, (4) ESD competences, and (5) lived ESD. Specifically, our model contributes to the first category, which focuses on chemical content knowledge. This is significant because it is typically the starting point for educational planning, where schoolteachers decide on the specific chemical topic for their lessons and the first step towards the development of the other categories proposed by the model, such as the ESD competences.

The proposed model of curricular content for the educational reconstruction of GC has the following three dimensions: (a) multidisciplinary dimension (science curriculum subjects associated to GCSE); (b) intradisciplinary dimension (core disciplinary contents associated to GCSE); and (c) interdisciplinary dimensions (crosscutting concepts associated to GCSE). We will briefly consider each of these dimensions separately.

Multidisciplinary dimension of the curricular content for GCSE

This dimension emerges as a response to the question: Which school science subjects are relevant for GCSE in primary and secondary education? The results of this study suggest that there are four. Although chemistry continues to be the central subject, other school science subjects such as biology, physics,

or geology also have their place in GC teaching and learning. The challenge remains as to how science teachers can orchestrate the contribution of multiple school science subjects when they attempt to teach GC in real classrooms.

Intradisciplinary dimension of the curricular content for GCSE

This dimension emerges as a response to the question: What core disciplinary knowledge is relevant for the teaching of GC in primary and secondary education? The results of this study indicate that teachers and researchers see specific core disciplinary knowledge belonging to different scientific disciplines strongly associated to the teaching of GC. Although our work highlights the construction of interdisciplinary dialogues, at the same time it acknowledges the specific contribution of each subject and has allowed us to identify the core disciplinary contents necessary for teaching and learning GC in the Chilean context.

However, it is particularly important to reflect on the links with chemistry based on the results of this study. Although it is the school subject with the most links to GC in general, it is also the one that was found to have the fewest links to environmental issues, by both teachers and researchers. In fact, specific content associated with protection and care of the environment or themes associated with sustainability have strong links across all the subjects except chemistry. This can be explained through the analysis carried out of the Chilean curriculum which reveals that the curriculum contemplates few learning objectives linked to the sustainable perspectives of chemistry, thereby highlighting the need to contextualise and reformulate the learning objectives. This is in line with what Aubrecht *et al.* (2019a) recommended by proposing that science learning objectives should encompass a more holistic understanding of the interconnections between chemistry and human and environmental systems.

Interdisciplinary dimension of the curricular content for GCSE

This dimension emerges as a response to the question: What crosscutting concepts are relevant for the teaching of GC in primary

and secondary education? The perceptions of teachers and researchers participating in this study clearly point to several curricular contents that can be approached through the teaching of different disciplines when introducing GC into primary and secondary education. This reinforces the interdisciplinary positioning of GC in the educational field (Zuin and Mammino, 2015; Eilks and Zuin, 2018; J. Chem. Educ., 2018). This dimension offers us the possibility of interrelating the content of each individual science subject from a transversal perspective, thereby contributing to an interwoven framework that represents the educational reconstruction of GC or some other topic with a similar nature.

We wish to highlight that energy is the only crosscutting concept that is at the same time a core disciplinary content for GC. The results of this study support the importance of the concept of energy, not only as a crosscutting concept but as a key idea connecting the model of educational reconstruction of GC and the principles of GC for education (Saqueto, 2015; Zuin *et al.*, 2019; Andrade and Zuin, 2021).

The results of this study are bounded to the context of Chile, but we believe that they provide a methodological and conceptual organizer that could be applied to the selection of relevant content for the teaching of any cutting-edge research topic in primary and secondary education. In Summary, the curricular model for GCSE has three dimensions that are complementary. The multidisciplinary dimension is the first step towards understanding the complexity of the issues that can be addressed by considering any other cutting edge research topic. It becomes a tool that allows us to establish which science subjects are involved and whether there are differences in terms of their presence for the work to be undertaken in the classroom. The intradisciplinary dimension allows us to recognise the specific contribution of each science subject when reflecting on a cutting-edge research topic. At the same time, it leads us to acknowledge that the different nature of the subjects contributes with different content that is all necessary for working on such topics in the primary and secondary classroom.

The interdisciplinary dimension leads us to suggest a set of curricular contents that allow connections to be made between the subjects identified across a cutting-edge research topic, functioning as a bridge between them. This dimension is in line with the proposal of Cooper (2020), who support that these curricular contents can lead to a more significant understanding of a cutting-edge research topic.

The teaching and learning of GC require contributions from the different school science subjects, which will also require collaborative work between teachers. In agreement with Evagorou *et al.* (2020), teachers must feel comfortable when teaching in the midst of the uncertainty and complexity that emerge from embracing perspectives that involve more than one subject.

Even though 20 in-service teachers participated in this study, increased participation of other in-service teachers and preservice training that explicitly proposes curricular integration is required. Both the shortfall of relevant links identified by in-service Chilean teachers and the current context of environmental emergency require a perspective from which school science subjects enter dialogue with each other: where the boundaries between

school subjects are perforated by the different approaches to the issues that are to be grasped. Our results show that school chemistry is perceived to be less connected to current environmental problems than other science subjects. This reinforces the need to introduce GC (Zuin *et al.*, 2021) as a cutting-edge research topic that questions the traditional logic of the production and use of chemical products, and as a response to the need, expressed by young people (Royal Society of Chemistry [RCS], 2021), to be educated about climate change and sustainability at school in chemistry lessons.

To date, GC has evolved since the formulation of the 12 principles and considerable work has emerged that develops GC within and through education. However, it has still not found a formal place in all school curriculum, particularly not in the case of Chile. This is so despite the evidence regarding the promotion of interaction between subjects and the contribution of GC to better integrating learning about the impacts of chemistry and the use of up-to-date examples of critical issues such as sustainability and climate change (RSC, 2021), or the development of system thinking, among others. Therefore, it is necessary that primary and secondary school teachers acquire knowledge and understanding of GC at all stages of their development as teachers.

Finally, our analysis and clarification of GC as a science content and the subsequent research into teachers' perceptions, within the framework of the educational reconstruction of GC, has been the result of an inclusive process made possible thanks to the contributions of in-service science teachers and science education researchers. This represents a strengthening of the study of cutting-edge research topic since all the voices need to be heard, with equal levels of participation, to build meaningful bodies of content for the teaching and learning of school science.

Conflicts of interest

The authors declare no conflicts of interest.

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