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Green and Sustainable Chemistry Teacher Education: Experiences from a Brazilian University

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Abstract: Green and sustainable chemistry education provides opportunities to comprehend and base chemistry knowledge on relevant social and historical contexts, reflecting on fairer and sustainable realities. For this purpose, this work discusses the possibilities and challenges observed during a chemistry teacher training course at a Brazilian university, analyzing how the undergraduates utilized the formative experiences provided by the discipline and how they reinterpreted them when developing didactic sequences based on socio-scientific issues. Using discursive textual analysis, we studied the self-assessments and the didactic sequences produced. The activities developed were positively evaluated by the students and provided the opportunity to create didactic sequences with potential application in schools, founded on cooperative and democratic dynamics and topics that were locally important. On the other hand, the students had some difficulties including chemistry content, mainly considering their relationship with the topics addressed. However, the process proved to be fundamental for the students to perceive themselves as teachers, in addition to provoking them toward (re)constructions and other possibilities.

Keywords: green and sustainable chemistry education; teacher education; case studies; socio-scientific issues

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1. Introduction

Sustainable development is a growing concern and has been discussed in recent decades by various people from different initiatives around the world, aiming toward the safety and conservation of physical and human environments and the attainment of fundamental rights in an equitable manner [1].

As a result of some of these actions, green chemistry (GC) and sustainable chemistry (SC) became well known in the 1990s, in the United States and Europe. Generally associated with more benign practices, these terms can be found separately or combined in the literature—when they refer to a broader perspective that transcends the meaning expressed in just one of the approaches [2–5].

This perception is shared in this work, comprehending green and sustainable chemistry (GSC) as a philosophy that permeates (and goes beyond) the specificities of each approach. It is about using chemical knowledge to propose possible solutions that consider (with equal relevance) economic, political, historical, social, and ethical issues [3–5]. Just as greening alone does not guarantee the construction of more sustainable realities, SC also needs the epistemological premises of GC to achieve this goal, as a science concerned only with technological development and damage repair is inconsistent with the transformations required by the planet [2,5,6]. In philosophical terms (and therefore the understanding of green and sustainable chemistry as a philosophy as well), being greener or more sustainable presupposes the choice of values and propositions that are socially and historically constructed [4,5].

Documents by the United Nations or UNESCO also emphasize education as an important part for sustainable development [1,7,8]. Scientific literacy is essential for individuals to be aware of impacts and, above all, to have the necessary conditions (both material and immaterial) to plan and execute measures [6].

Even with the consolidation of green and/or sustainable chemistry in the literature, the incorporation of their premises into the curricula is still scarce because the formation of professionals and leaders engaged with contemporary challenges requires a critical and emancipatory education that enables problematizing and acting (individually and collectively) in the planet [4,5]. The integration of chemical knowledge with the 2030 Agenda for Sustainable Development is a pathway toward incorporating GSC into the curricula of primary, secondary, and tertiary education, as well as vocational schools, and courses related to science and engineering [2,9]. Despite the initiatives being carried out in different parts of the world to expand the materials available in the literature and inspire more actions, one of the challenges that remains is the strengthening of innovative curricula [2].

Specifically in Brazil, in recent decades, this philosophy has been incorporated into the undergraduate and graduate programs in chemistry at the Federal University of São Carlos (UFSCar), São Carlos [4,5]. Classes are conducted through case studies of socio-scientific issues, based on innovative contents and methods that can improve learning, understanding of the nature of science, and student motivation [4,5,10]. It is important to mention that the Open Courses Portal of UFSCar (PoCA) also offers the course Introduction to Green and Sustainable Chemistry, available online and free of charge in both Portuguese and English [11].

Thus, this work describes the possibilities and challenges of a chemistry teacher training discipline at UFSCar, investigating how undergraduates took advantage of the formative experiences offered by the course, and subsequently, how they reinterpreted and integrated them into developing didactic sequences. Thus, the text begins with a brief contextualization of the discipline's premises, followed by the methodological development to analyze the didactic sequences produced and self-assessments, as well as the observed results, and finally, some additional considerations about this study.

Introduction to Green Chemistry at UFSCar: A Brief Contextualization

In accordance with contemporary challenges, initiatives have been carried out at the Federal University of São Carlos (UFSCar). Among them, the implementation of a new curriculum in chemistry teacher training in 2017 [12].

The chemistry teacher training course at UFSCar is five years long (or ten semesters) and qualifies students to work as chemistry teachers, especially at high schools. One of the disciplines in the new curriculum, Introduction to Green Chemistry, is offered in the third year (or sixth semester) and the objectives are as follows: (i) understanding and analyzing the chemical processes in the production system, considering their technological, social, and environmental relationships; (ii) presenting the historical context and development of green chemistry, its principles and applications; and (iii) planning a pedagogical project based on the content studied [12].

The classes are developed based on case studies of socio-scientific issues and are structured initially with the reading and discussion of texts and other materials (documentaries, videos, etc.) that provide an understanding of the Principles of Green Chemistry from a systemic and interdisciplinary perspective. Additionally, the course includes practical activities that relate to and complement theoretical knowledge, as well as develop different skills using innovative tools and methodologies. An example of this is the explanation of one (or more) principle(s) of GC in a three-minute video, where undergraduates use their creative and didactic potential to develop scripts and learn video shooting and editing tools.

As a final product and result of previous constructions, students prepare a pedagogical case study on relevant issues to the Brazilian context, describing the sequence and resources necessary to apply it in schools. The development is mediated by the professor (at specific

times during some classes or with feedback via email). To conclude, students present it to their classmates as a seminar and submit a written version. The curriculum structure of the course is designed so that theoretical and practical knowledge is built interdependently throughout the classes. In addition to the contents related to green chemistry, before the development of the didactic sequence, students also have access to discussions on case studies in the educational context based on examples from the literature.

The activities throughout the semester (including two written assessments) are considered evaluation tools and provide a broader and coherent monitoring of the formative experiences offered to the students, based on the development (individual and collective) of content, procedures, and values.

2. Methodology

This study investigated the possibilities and challenges provided by the Introduction to Green Chemistry course, focusing on how undergraduates utilize and reinterpret their formative experiences. It consists of qualitative research conducted during 2019, monitoring classes throughout the semester to understand their dynamics and the subjectivities [13,14]. The course "Introduction to Green Chemistry" had thirteen enrolled students, who divided themselves into pairs (and one trio) according to their own preferences to develop the case studies, resulting in six didactic sequences. The analyses were based solely on the written version of these works, which followed a pattern of elements/formatting instructed by the professor beforehand.

The initial reading of the material helped to understand its context and main characteristics (theme, contents, target audience, socio-scientific issue, etc.). This overview also facilitated the delimitation of which information would be studied through discursive textual analysis, a qualitative research method that has become increasingly common in educational research, especially in the field of science education [10,15]. It breaks down the analyzed material into small phrases or words that have a meaning within the context of analysis in order to then find the relationship between these units in a categorization process—which moves from specific to general (Figure 1).

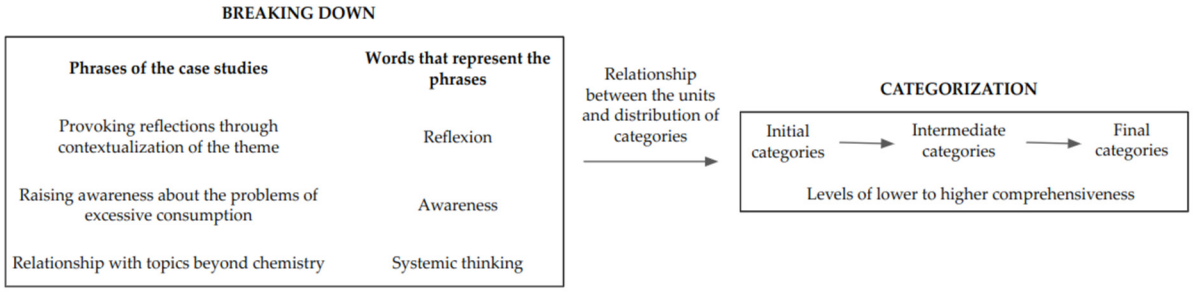

Figure 1. Breaking down and categorization process based on Discursive Textual Analysis [10,15].

Among the elements presented in the case studies, the methodological characteristics of the activities (how they would be worked on in the classroom) and the proposed objectives were categorized. It should be mentioned that all information was studied, but the analyses were made from two perspectives: a descriptive one, which made it possible to understand the didactic sequences in a broad way, and another—which involved categorization—to comprehend the intentions of the students and how they were manifested in the writing [10].

Categorization led to developing a text—which was different from the material but was formed from it. Several perspectives can be used in this construction, but we chose to look at the final categories and, as they were described (together with the interpretations of the authors of this text), the intermediate and initial categories were also represented—in a process that moved from general to specific [10,15]. When relevant, some notes taken during the class observations were also added to the text [10].

Regarding self-assessment, the undergraduates completed this during the final class, aimed at determining whether their expectations regarding the course were met or not. They assigned a grade to represent their individual performance in specific topics (see Table 1). The analysis of the responses was also conducted using discursive textual analysis, considering the same analysis carried out in the case studies [10,15].

3. How Did the Students Assess Their Formative Experiences and Their Own Development?

Before presenting the case studies, in which it was observed how the undergraduates resignified the formative experiences, it is worth discussing the results expressed in the self-assessments. The study using discursive textual analysis allowed for the emergence of four categories: **prior perception**, **instrumental rationality**, **formation**, and **difficulty**.

The **prior perception** category emerged from the students' expectations regarding the course, enabling us to discern their intentions and evaluate whether those expectations were fulfilled or not by the end of the semester. Overall, the analyses revealed that the expectations were surpassed in a positive manner. While some students mentioned having some knowledge of the topics that could be addressed, most of them were previously unfamiliar with the concepts of green chemistry and/or sustainable chemistry.

The philosophy of green and sustainable chemistry should permeate research, curricula, and pedagogical practices in scientific education [3–5,9,10]. In their research, Borreda and Peña demonstrated that teachers' understanding (both practicing and in training) of this topic is quite superficial and based solely on the etymology of the words. Additionally, the field of GSC is rarely addressed in textbooks and journals in the field of science education, further contributing to the vague comprehension of the topic [16].

The analysis indicates a lack of alignment between the philosophy of GSC and the practical laboratory classes in the chemistry teacher training course at UFSCar. One undergraduate commented: "Our main focus is solely on ensuring the success of the experiment and concluding the report. The proper disposal of generated waste is never a concern for us".

Considering the proportion of laboratory classes, particularly because chemistry is an experimental science, it is necessary to build sustainable and context-based references which need to be generated by using more benign reagents and procedures. It is crucial to engage in reflection to ensure that experiments are not conducted as mere "recipes", lacking pedagogical and social objectives [4].

This also reinforces a superficial comprehension of concepts, prioritizing the memorization of theories, formulas, and procedures that will be of little (or no) use in students' lives, thus distancing chemical knowledge from historical and social reality [3]. It is an instrumental rationality that only allows for ready-made schemes with no meaning and, consequently, fails to stimulate reflection, critical thinking, and the emancipation of individuals [4,17,18].

This **instrumental rationality** also observed the perception regarding the schedule provided by the professor on the first day of class (which included a description of the activities to be carried out throughout the semester and the references used). Although in fewer instances, statements in the self-assessments such as "the professor followed the schedule" were encountered, demonstrating an adaptation and conformity to what is predetermined, and disregarding the dynamics and active participation in the teaching and learning process [17].

Regarding the category of **formation**, the students pointed out that the methodologies used facilitated collaborative and dialogic construction of knowledge, even encouraging shy individuals who are not used to expressing their ideas during class. The tools were consistent with contemporary educational demands and possibilities beyond the approaches and assessments traditionally used.

Along similar lines, the students highlighted that the topics transcended the confines of the classroom, enabling the integration of GSC with real-world challenges, from a

perspective that integrated scientific, technological, and social knowledge. There were suggestions to include more industrial practices as examples during the classes.

The experiences provided by the course enabled a critical perspective on the construction of more just and sustainable realities, problematizing daily habits, values, and pedagogical practices. According to the undergraduates, the theoretical and methodological concerns in a teacher training course reflect self-confidence and professional appreciation. During one of the classes, a student questioned, "We feel unqualified when we come here, and the professor doesn't seem to care about how the content is addressed".

Self-criticisms regarding commitment exhibited variations, with a particular emphasis on the effort exerted in the proposed activities. A smaller number of self-criticisms were related to little involvement in specific situations, particularly when it came to reading texts. In line with this analysis, it was noticed that the students expressed discomfort regarding the length of the texts, which impeded their ability to keep up with the readings and complete the assigned tasks. However, this discomfort was not observed in other activities, such as case studies, which also demanded equal or even greater time and dedication.

This perception was also noted in the **difficulties** category, where undergraduates described how their lack of personal organization impacted their written assessments, particularly because they had not read or devoted themselves to the texts. Another challenge mentioned in this category was shyness in expressing ideas in public, which only occurred when prompted by the professor.

Regarding the lack of dedication to reading (in contrast to other activities), the interpretation of the results suggests that it may be associated with the concentrated distraction phenomenon [19]. In a digital culture that offers constant, instant audiovisual stimuli at a rapid pace, the ability to focus on activities that require pause and attention, such as reading, becomes increasingly challenging for individuals [10,19].

Self-criticism and awareness of one's training was reflected in the attribution of grades. In relation to the question requiring students to assess their own performance in various moments provided by the discipline (Table 1), it was noticed that reading texts and participating in discussions had the highest percentage of students receiving grades below 7.0. This observation suggests that these factors may have influenced the responses regarding their commitment to their own learning (see Table 1).

Table 1. Grades assigned by the undergraduates.

Formative Experiences	**<7.0**	**7.0**	**8.0**	**9.0**	**10.0**
Participation in discussions and other activities	6.6%	26.7%	33.3%	26.7%	6.6%
Participation in case studies	-	-	13.3%	33.3%	53.3%
Presentation of their activities to classmates (seminar)	-	13.3%	40.0%	20.0%	26.6%
Reading of texts	6.6%	20.0%	20.0%	20.0%	33.3%
Commitment to one's own learning	13.3%	6.6%	20.0%	40.0%	20.0%
Commitment to collective learning	-	-	60.0%	20.0%	20.0%
Overall performance in the discipline	-	-	26.7%	60.0%	13.3%

The rating bands (<7.0; 7.0; 8.0; 9.0; and 10.0) were determined by the course professor and incorporated into the self-assessments in this manner. The grades represent approximate values.

It is interesting to highlight that participation in discussions is also related to reading texts, as the class dynamics involved prior reading and writing a summary (based on problematizing the subject covered in the text), followed by a discussion and sharing ideas. Thus, shyness—mentioned by some students—may not have been the sole factor. Furthermore, the percentage of grades 10.0 (33.3%) indicates that the activity was productive.

Another relevant factor was the active participation in the case studies, with grades ranging from 8.0 to 10.0, and an impressive majority of students (53.3%) giving themselves a grade of 10.0. This indicates a high level of engagement during the activity. Overall, the

high performance across all activities was also well evaluated, prompting a discussion as to how these formative experiences were reinterpreted in the didactic sequences developed by the students.

4. Theoretical and Methodological Foundations of Case Studies

The analysis of the case studies enabled us to understand their main characteristics, according to Table 2.

Table 2. Case studies.

Case Study	Socio-Scientific Issue	Case Characteristics	Principles of GC and SDGs
Nightmare at landfill	Soil and groundwater contamination	Improper waste disposal in landfills. Relationship between landfill location and the poorest places in the city. Diseases caused by water contamination (symptoms, treatment, and prevention of giardiasis). Recycling.	GC: 1, 6, 11, and 12. SDGs: 3, 4, 6, 11, and 12.
The evil that's on your plate	Pesticides	Application of pesticides in soybean crops. Health of farm workers due to direct contact with pesticides. Social and environmental problems caused by exposure to pesticides. More sustainable agricultural techniques.	It was not informed.
Inactive future	Sedentary lifestyle caused by excessive use of technologies	Diseases associated with a sedentary lifestyle. Social and environmental consequences of excessive technology consumption. Healthier and more sustainable habits.	GC: 1, 6, and 11. SDGs: 3, 4, 11, and 12.
Little workers	Pesticides	Importance of bees in the ecosystem. More sustainable and/or organic agriculture. Other factors contributing to the death/disappearance of these insects (global warming, for example).	GC: 1, 7, 8, and 11. SDGs: 4, 11, 12, 13, and 15.
Oily holiday	Oil spill in the sea	Social and environmental consequences of seawater contamination by oil. Political issues involved in oils spills (such as misinformation). Solutions to mitigate the problem, considering social, economic, and environmental aspects.	GC: 1, 6, 7, 11, and 12. SDGs: 3, 4, 7, 9, 11, 12, 13, 14, and 15.
Reuse it or lose it	Water reuse	Waste and alternatives for water reuse in daily life. Social participation in public decisions.	GC: 1. SDGs: 6, 11, 12, and 13.

Principles of GC: 1. Prevention; 2. Atom economy; 3. Less hazardous chemical syntheses; 4. Designing safer chemicals; 5. Safer solvents and auxiliaries; 6. Energy efficiency; 7. Use of renewable feedstocks; 8. Reduce derivatives; 9. Catalysis; 10. Development of degradable substances; 11. Real-time analysis for pollution prevention, and 12. Security chemistry to prevent accidents [20]. Sustainable Development Goals (SDGs): 1. No poverty; 2. Zero hunger; 3. Good health and well-being; 4. Quality education; 5. Gender Equality; 6. Clean water and sanitation; 7. Affordable and clean energy; 8. Decent work and economic growth; 9. Industry innovation and infrastructure; 10. Reduced inequalities; 11. Sustainable cities and communities; 12. Responsible consumption and production; 13. Climate action; 14. Life below water; 15. Life on land; 16. Peace, justice, and strong institutions, and 17. Partnerships for the goals [1].

The case studies were based on relevant and current socio-scientific themes, and, above all, considering the Brazilian context, such as the problems involving the use of pesticides in soybean crops and oil spills at sea—which contaminated a large portion of the northeastern Brazilian coast at the time [21–23]. Resolutions of the cases were also founded on the Principles of Green Chemistry and Sustainable Development Goals and, although one of the groups did not mention them (see Table 2), it can be interpreted that they were implicit in the developed ideas.

In another perspective, the categorization using discursive textual analysis made it possible for two categories to emerge: **contents and methodologies**, which express how the activities were planned; and **formative experiences**, where it enunciates the experiences that could be provided based on what was being proposed.

Regarding the **contents and methodologies**, it was observed that the development of the activities would enable autonomy in the construction of knowledge, so that the learning objectives and the dynamics and intention of the classes were clear to the students—always mediated by the teacher.

Knowledge addressed in the cases was related to environmental, political, economic, social, ethical, and other issues, but a difficulty in incorporating chemical concepts into the classes was noticed. Even though the activities were proposed for chemistry classes, in only three cases was a specific content of chemistry observed—organic functions (in the cases *The evil that's on your plate* and *Oily holiday*) and solutions (in *Reuse it or lose it*).

This characteristic aligns with the instrumental rationality observed in some self-assessments and, above all, in the account of how activities in the laboratory are conducted. The instrumental approach to the content poses great challenges for knowledge to be planned in a systemic and contextualized perspective, and this hinders the approach because when the content is merely reproduced through pre-existing schemes and memorization, its reinterpretation is likely to be associated with the same technical and uncritical perception [10,17].

The proposals also considered the relationship between theory and practice, especially with activities outside the school environment that complemented the discussions. These activities included, for instance, visiting a landfill, a water treatment plant, and a recycling cooperative—all localized within the city of São Carlos, Brazil.

According to the students, the approach of the case studies would enable autonomy and a central and active role in the construction of knowledge, mediated by the teacher's actions. The suggested activities included group work and reflected respect for collectivity, dialogue involving diverse social communities, as well as encouragement for public participation in decisions (mainly at the municipal level).

The methodologies described were varied, including using texts, scientific papers, documentary screenings, role-playing [24,25], and theoretical classes, especially for explaining content. In addition, some of the suggested materials were developed by the undergraduates themselves, which provided an opportunity for using (and learning) various tools, such as recording and editing podcasts and videos.

In relation to the **formative experiences**, the didactic sequences could promote the learning of content from a systemic, interdisciplinary perspective, in line with critical action in society. Other highlighted experiences included: public speaking, interpreting different forms of texts (e.g., graphics and tables), argumentation, knowing how to listen, showing respect and empathy, paying attention to others, and having an awareness that decisions (individually and collectively) involve subjective aspects. Problem solving, searching based on different sources, and possible changes in habits were also listed as opportunities to be developed through the activities.

Among the six pedagogical case studies, the next subtopic will present two of them in greater detail to exemplify the nature of these constructions.

4.1. Case Study: Inactive Future

Inactive future addresses broader issues (and not just local) related to the excess of technology in daily life, problematizing sedentary habits as well as the consumption of these devices, which are often discarded without concern for the toxicity of their components. The case was inspired by news reported in the media, linking illnesses and even premature death to sedentary behavior [26]. Additionally, the undergraduates suggested that it be worked on in collaboration with the sociology, chemistry, biology, and physical education disciplines.

The controversial socio-scientific discussion was introduced into the didactic sequence through a curious fictional story about a teenager called Martin, who has very sedentary habits. One day, Martin encounters a scientist from the future who traveled in a time machine to warn the population about the risks caused by a sedentary life. Thus, the question addressed at the end of the story is: "*Imagine that you are Martin. What changes can be made to improve your quality of life?*"

The suggested reflections could approach themes such as consumerism, planned obsolescence, and waste generation, based on the presentation and dialogue of these topics, as well as in screening documentaries and activities that use technological tools to promote healthier behaviors (e.g., videos teaching physical exercises). Resolutions proposed by the undergraduates included regular physical activities, healthy eating, and changing small daily actions (using a bike or walking for transportation, taking stairs instead of elevators, etc.), and reflecting on the consumption of technologies.

These resolutions were based on the Principles of Green Chemistry and the Sustainable Development Goals. According to the students, the prevention principle is related to health care and attention to quality of life, considering the human body as an "energy-efficient machine" that must be constantly evaluated (energy efficiency and real-time analysis principles). Regarding the SDGs, good health and well-being, quality education, responsible consumption and production were associated with the topics, as well as sustainable cities and communities, pondering over the infrastructure of cities (good mobility on sidewalks, equipment for physical exercises in public places, etc.).

4.2. Case Study: Oily Holiday

Oily holiday was inspired by the oil spill that occurred in 2019 on the northeast coast of Brazil [23]. A fictional story used to introduce the socio-scientific question told of the crisis faced by a chemistry student who, unaware of the situation, traveled with her family to one of the affected beaches during her holiday and witnessed the despair of people and the socio-environmental impacts. Upon returning, the student reports what she experienced to one of her professors, who informs her about the collaborative efforts between different universities to mitigate the problem. In the end, the following question is presented: "*You are part of a research group and must propose solutions to remediate the oil on the beaches. It is important to consider the 2000 km already affected and, above all, the amount of available financial resources*". It is worth mentioning that the reported dimension was real and updated daily at the time.

In relation to contents that could be addressed, the students suggested the production and use of petroleum, organic chemistry, and socio-environmental imbalances caused by water contamination. They also recommended an initial questionnaire to assess prior knowledge, role-playing [24,25], and experimentation [27]. Role-playing would enable the collaborative and democratic construction of knowledge, as it would involve the participation of different social sectors (a representative from an oil company, a chemist, an environmentalist, a fisherman, and a politician). Furthermore, the students proposed the synthesis of magnetite as a solution to remediate water contamination [27].

In addition to this idea, other potential solutions were identified in their case resolution, such as the implementation of sea barriers and/or bioremediation. These alternatives align with the Principles of Green Chemistry and the SDGs, where the students mentioned the principles of prevention, energy efficiency, and use of renewable feedstocks—relating to the optimization of available energy and substitution in the case of non-renewable resources; as well as monitoring, evaluation, and the use of less harmful products and processes (real-time analysis for pollution prevention and security chemistry to prevent accidents). As for the SDGs, they cited good health and well-being, quality education (mainly associated with access to information), affordable and clean energy, industry innovation and infrastructure (with the development of accident prevention and remediation measures that do not cause additional damage), sustainable cities and communities, responsible consumption, and

production (re-evaluating the consumption of unnecessary products), climate action, life below water, and life on land.

5. Conclusions and Perspectives

Due to the importance of chemistry in the construction of modern life and the development of greener and more sustainable products and processes, discussions about contemporary challenges are increasingly present in chemistry education curricula, in order to train professionals and leaders committed to a better present and future [4,9,10].

Some experiences developed at the Federal University of São Carlos (Brazil) were shared in this text, based on teacher training as a self-reflective praxis on reality. The activities developed were positively evaluated by the undergraduates and provided the opportunity to create didactic sequences with potential application in schools. These developments allowed a systemic perspective about chemistry, as well as a reflection on more benign habits and decisions (environmentally and socially). The way the course was structured, especially regarding the case studies of socio-scientific issues, offers a possibility for green and sustainable chemistry education, integrating chemical knowledge with the 2030 Agenda for Sustainable Development [2]. This applies to both teacher training and the education of chemists, engineers, and other related fields [2,9,28].

Regarding the challenges, while the adoption of innovative methodologies is crucial, it is equally important to promote traditional activities, such as reading. This is particularly significant because active participation in society presupposes this skill [10]. The difficulty in contextualizing chemical knowledge in the case studies highlights the importance of deepening the discussion on the desired education and, based on that, questioning approaches grounded in instrumental rationality. This underscores the need for an emancipatory education that transcends specific disciplines or courses and permeates the entire curriculum [9,10]. However, changes in the way chemistry is perceived at teaching institutions are necessary, disrupting old teaching and learning paradigms that provide a fragmented view of knowledge. It implies the (re)construction of new and different ways (many not tracked yet), encouraging curiosity, transformation, and basing educational activities on reality.

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