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How Can Socio-scientific Issues Help Develop Critical Thinking in Chemistry Education? A Reflection on the Problem of Plastics

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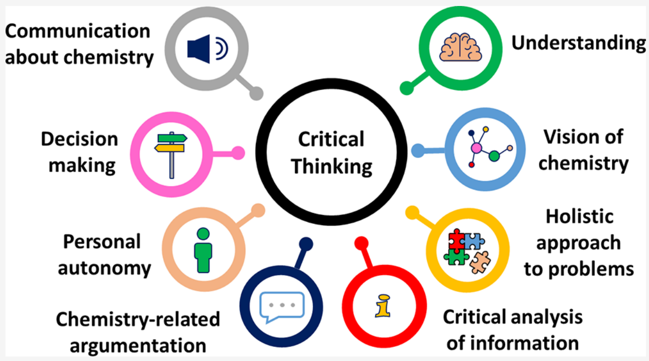
ABSTRACT: Socio-scientific issues demonstrate the relationship between science, technology, and society by considering currently unresolved questions. The problem of plastics and their pollution is just one example with important implications for the planet. The aim of this paper is to revisit socio-scientific issues and see them as a way of developing citizens' critical thinking skills through chemistry education. In light of the problems posed by plastics, we present evidence tested with Spanish grade-8 students of how critical thinking skills can be developed through chemistry education in terms of the vision of chemistry, understanding acquisition, a holistic approach to problems, critical analysis of information, argumentation, decision making, personal autonomy, and communication. This study also presents some examples of how progress in the development of critical thinking by students has been evaluated.



KEYWORDS: *First-Year Undergraduate/General, High School/Introductory Chemistry, Graduate Education/Research, General Public, Student-Centered Learning*

■ PLASTICS AND POLLUTION, A CURRENT SOCIO-SCIENTIFIC ISSUE

Socio-scientific issues (SSIs) are real, unresolved, complex, and controversial problems. They are linked to the close relationship between science, technology, and society[1] and can be considered from different perspectives (social, ethical, economic, environmental, political, etc.). However, there are no definitive answers for some of these issues, and the debate around them will continue no matter what stance is taken by individuals or society. Many SSIs stem from new scientific and technological breakthroughs (stem cells, nanotechnology, etc.), while others are related to health (cloning, disease transmission, etc.), environmental issues, and the efficient use of resources and raw materials.

One such problem is plastics, widely used polymer-based materials that are flexible, elastic, cheap, strong, durable, and ubiquitous in today's society. However, the use of plastics has harmful environmental consequences. First, the fossil fuels used as raw materials for plastics are a limited resource. In addition, the recycling rate for used plastics is low, and recycling is often poorly managed. Moreover, because plastics are not readily biodegradable, they leak into the environment, causing ecological damage as they fragment, and they can also enter the food chain.[2] Concern is growing around the fragmentation of plastics and the buildup of microplastics because of the way they move around different areas of the planet, circulating between land habitats, soils, freshwater bodies, oceans and their sediments, the air, and even living organisms.[3]

■ SOCIO-SCIENTIFIC ISSUES AND CITIZENS' CRITICAL THINKING

Chemistry education is key to educating students about these SSIs, and raising awareness of environmental issues in the case of plastics, in their role as citizens. Several authors have highlighted the importance of creating context-based learning environments in science as conduits for learning, both in terms of knowledge, skills, attitudes, and values.[4−6] Moreover, these learning environments lead to a better understanding of chemistry and help students to relate chemistry to their daily lives.

The teaching of SSI in the chemistry classroom can help develop critical thinking skills in students, a complex process that includes cognitive, attitudinal, and affective aspects. Critical thinking is essential in today's society. Education should train students to become competent citizens who can make reasoned decisions in different situations or when facing

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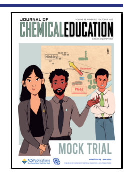

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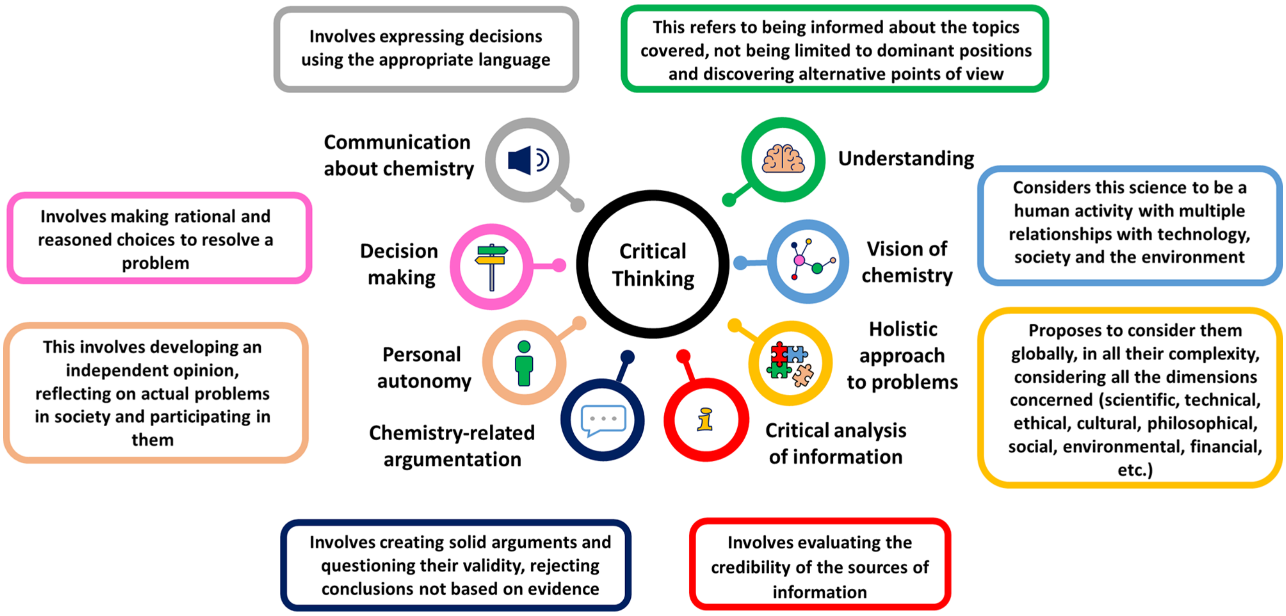

Figure 1. Dimensions of critical thinking according to the proposal of Blanco, España and Franco-Mariscal[12] (author's own artwork).

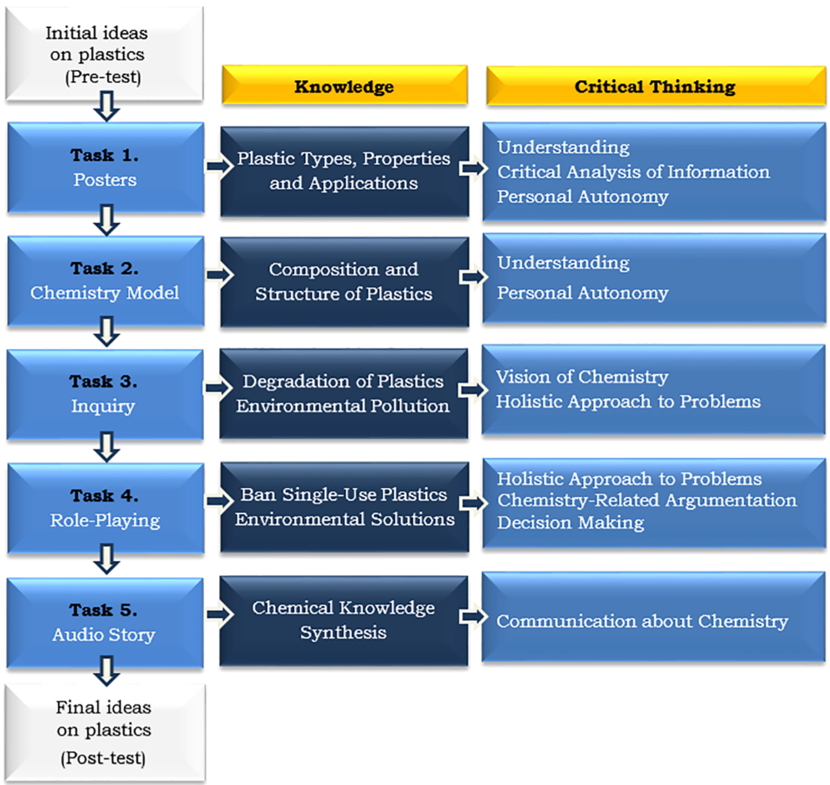

Figure 2. Scheme of the teaching–learning sequence.

everyday problems in which science and technology in general, and chemistry in particular, play an essential role.

Although there is no unanimously accepted definition of critical thinking,[7] several authors have offered a number of suggestions. According to Dekker,[8] it is a way of approaching SSI from many different perspectives while being skeptical of absolute statements, and seeking to understand these issues in order to come to a final decision about them. Renatovna and Renatovna[9] see it as a skill that helps people learn to analyze, express their opinions objectively based on evidence and conclusions, reflect on their own way of thinking and stereotypes, and correct mistakes when necessary. Jiménez-Aleixandre and Erduran[10] define it as the ability to develop an independent opinion, thus acquiring the capacity to reflect on and participate in society. They also point out that critical thinking contains elements of argumentation, such as the search for and use of evidence. It is, therefore, a crucial ability if we are to have a society made up of competent, participatory, thoughtful citizens who have a scientific attitude in general, and a scientific attitude toward chemistry in particular. One of

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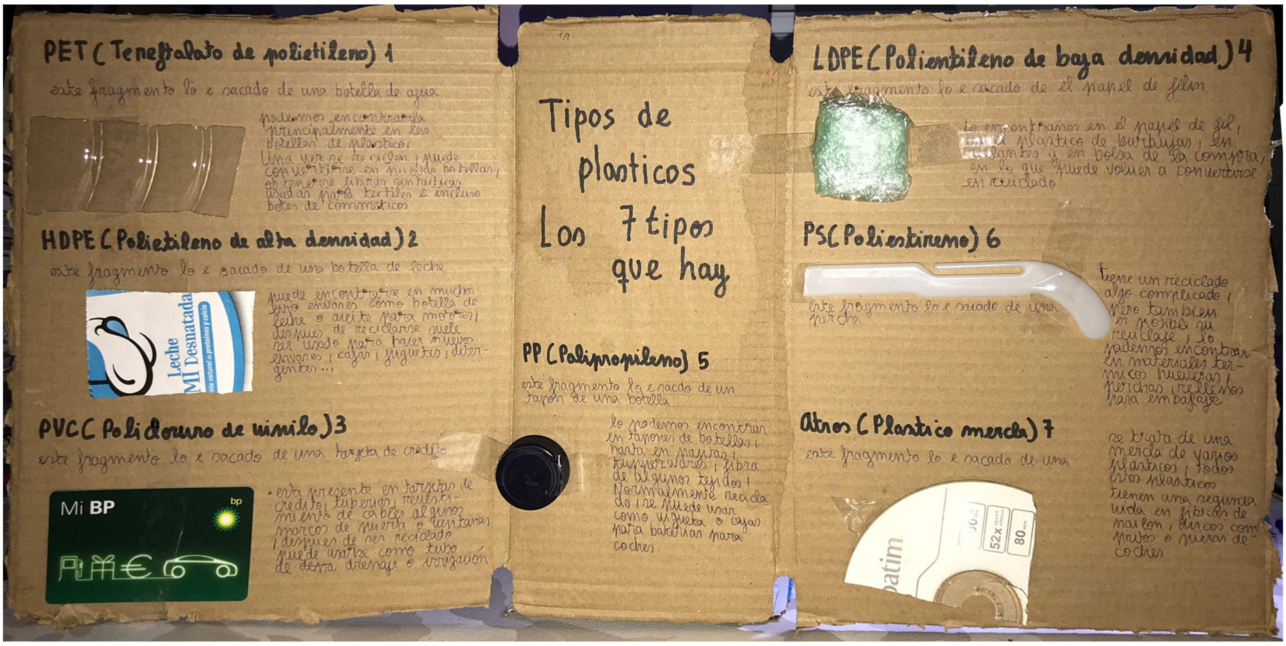

Figure 3. Poster concerning the types of plastics prepared by grade-8 students. [(1) PET (polyethylene terephthalate): mainly found in plastic bottles. Once recycled, it can be converted into new bottles, synthetic fibers for textiles, or cosmetics packaging. (2) HDPE (high-density polyethylene): found in packaging such as bottles for milk or engine oil. After being recycled, it is usually used to make new packaging, boxes, toys, detergents, etc. (3) PVC (poly(vinyl chloride)): found in credit cards, pipes, cable coatings, or door and window frames. After being recycled, it can be used as drainage or irrigation pipes. (4) LDPE (low-density polyethylene): found in kitchen film, bubble wrap in insulation, and shopping bags. (5) PP (polypropylene): found in bottle tops and drinking straws. Once recycled, this plastic can be used as boxes for car batteries. (6) PS (polystyrene): found in coat hangers, insulation materials used in fridges, for example, or filling for packaging. Difficult to recycle. (7) Others (mixed plastics): this is a mixture of several plastics that can be reused in nylon fibers, compact discs, or car parts.]

the main aims of science education[11] is to develop a student's capacity for critical thinking, and school curricula include it as one of their objectives. As such, chemistry education should contribute to producing well-informed citizens who can analyze problems, seek solutions, make good decisions, and take on social responsibilities.

But how can addressing the SSIs of plastics help develop critical thinking skills in chemistry education? To answer this question, we must ask ourselves what dimensions of critical thinking can be developed by teaching chemistry using SSIs. The proposal by Blanco, España, and Franco-Mariscal[12] shows that SSIs can contribute to developing skills related to the dimensions shown in Figure 1.

The scheme in Figure 1 is an attempt to demonstrate that the eight dimensions of critical thinking are mutually interconnected and are all equally important. Similarly, the order does not suppose a sequence in which these dimensions should be developed, nor does it imply that all of them should be considered in the same activity. For instance, we can use understanding and then a critical analysis of information to argue about chemistry, thus leading to decision making and then communication. In summary, the development of critical thinking in students will be related to the progress in each dimension.

In addition, to ensure the correct development of critical thinking skills, it is important to create a spiral scaffolding with a systems thinking-based approach.[13] An SSI must be the center where these dimensions are developed and the scenario that ties all chemistry concepts to it, much like a context-based approach. It is necessary to subdivide major concepts in order from least to most complex, scattered across multiple units or activities, thereby maintaining the interconnectivity of major units.[14] Initially, we should start by working on both understanding and critical thinking skills in a simple manner, gradually increasing the complexity thereafter. Subsequently, the content studies will be linked to the initial learning, returning to it and again increasing the complexity gradually. This process continues, repeating the same topic, to construct new learning.[14] For instance, students need to study the types of plastics; their properties, composition, and structure; and their degradation processes beforehand to understand environmental pollution.

■ EVIDENCE FOR THE DEVELOPMENT OF CRITICAL THINKING SKILLS IN GRADE-8 STUDENTS IN A TEACHING−LEARNING SEQUENCE ON PLASTICS

This section provides some evidence for how the dimensions indicated may help to measure the development of critical thinking in Spanish grade-8 students, who participated in a teaching−learning sequence (TLS)[15] about plastics and contamination, specifically designed to develop such skills. The TLS was carried out over the course of a Spanish academic year. Figure 2 shows a scheme for the TLS that relates the dimensions of critical thinking to the knowledge about plastics and the tasks proposed.

The questionnaire used as pretest and post-test has been included in Supporting Information.

Understanding, Critical Analysis of Information, and Personal Autonomy

First, a number of skills we need to consider are related to acquiring scientific understanding on the issue so that students can form their own independent opinion (personal autonomy) on the SSI by gathering information from different sources and

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analyzing it critically. In short, one of the skills needed for critical thinking is the systematic analysis of information and opinions that we accept as true. Developing this skill is essential in societies facing an infodemic and the worrying consequences of an overabundance of information, some of which is rigorous but some of which is false or misinformed.

For students to critically analyze information, they need to be equipped with criteria that will allow them to evaluate the quality and reliability of sources, especially online sources. These criteria include the following: (a) the identification of the author, whereby the information provided by collective decision-makers is more highly valued than that of an individual, and, of the latter, more weight is given to information provided by those with specialist expertise; (b) the intelligibility of the message, whereby importance is attached to the correct wording of the message and the separation of information from opinion; (c) the independence of the message, whereby particular importance is attached to the separation of information from possible advertising messages; and (d) the use of bibliographical references.

With regard to the SSI concerning plastics, the TLS included tasks 1 and 2 to contribute to the acquisition of chemistry-related understanding, critical analysis, and personal autonomy.

Task 1 involved searching for and analyzing information on the types of plastics, their composition, properties, and possible applications, thus allowing the creation of posters or infographics and their subsequent display and oral presentation. Students specifically used items destined for the recycling bin/garbage or household objects to convey information. In addition, the information they included on the posters had to be found on the internet, taking into account the criteria to critically analyze the information mentioned above.

Smolkin and Donovan[16] have suggested that posters created by teachers and students are helpful for exploring ideas about a specific topic, whereas Guron and Slentz[14] provide some student work samples showing the diversity of connections made between plastics and issues in the community and the wider world.

The poster in Figure 3, which was prepared by various students in the TLS, highlights the connections between the knowledge covered in class and plastics in real life. When preparing it, the students developed their personal autonomy by considering, choosing, and deciding which everyday objects they could include in the poster to represent the different types of plastics and the critical analysis of the information to be presented. In this way, students were able to understand the diversity of plastics and their limitations in the processes of recycling or degradation.

After the activity, and based on the information they obtained, students made a critical and personal assessment of plastic production despite its problems regarding degradation and contamination.

The posters were presented in the chemistry classroom so that other students and teachers could see them and undertake to recycle plastics. This activity helped the recycling programs already underway at the school.

A rubric that included aspects related to the poster and its oral presentation was used to evaluate the task. Specifically, the chemical understanding shown in the poster (types of plastics, composition, properties, and applications), the quality of the scientific information, and the oral communication skills were evaluated. All items were scored at one of three levels: high, medium, and low.

As indicated, the understanding must be sequenced using a systems thinking approach, which is why it is essential to have both a macroscopic and submicroscopic vision of the chemistry of plastics. An understanding of their composition and internal structure will allow the slow degradation of plastics and their environmental effects to be understood. Task 2 in the TLS helps to acquire this understanding by modeling the internal structure of plastics, in other words, how the monomers are linked to obtain the polymer, with paper clips, thus allowing this structure to be linked to the chemical properties and different types of plastics (Figure 4).[17]

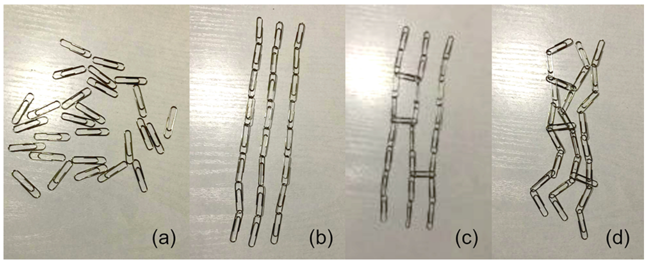

Figure 4. Modeling plastics using paper clips: (a) monomers, (b) linear polymers, and (c and d) cross-linked polymers.

Schiffer et al.[18] confirmed the efficacy of this type of task in a similar study in which chemistry model kits were used to explain the structure and polymerization of plastics from polyethylene and poly(vinyl chloride) monomers by way of hands-on demonstrations. In that study, the students concluded that the chemistry of plastics guides the breakdown into microplastics and, therefore, the environmental effects.

At the end of the TLS, the understanding acquired, the critical analysis of information, and the personal autonomy shown by the participants in the TLS were evaluated using a questionnaire (Supporting Information) that included open questions(What have you learned?) and multiple-choice questions (Do you think all plastics are the same? [Post-test, question 2] Can all plastics be reused and recycled? [Post-test, question 3] or Can all plastics be used to manufacture water bottles? [Post-test, question 4]).

Students indicated that they had learned how to gather information and analyze it critically, with 60% (N = 40) of them showing their learning with statements such as "I have learned how to search for and analyse information about types of plastics, their composition, properties and applications in a reliable manner" or "to identify different types of plastics at home and search for their characteristics correctly".

The tasks proposed helped the majority of students to correctly recognize, in the multiple-choice questions, that not all plastics are equal and that there are different types with different properties (100% of students); that not all plastics can be reused or recycled as this depends on their chemical structure (82.5%); or that not all types of plastics can be used to manufacture objects destined for food use (72.6%).

Understanding and Vision of Chemistry

The acquisition of understanding must allow students to obtain a global view of chemistry, i.e., one that identifies its multiple relationships with society, the environment, and technology. In the SSI that we use as an example, students could ask themselves why plastics are a problem for the environment, relating this to their composition and chemical properties, how long they take to degrade, and what effects

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microplastics appear to have on the health of people and animals.

The inquiry task concerning the consumption or degradation of plastics, or how they pollute (task 3), was intended to provide this global overview of chemistry. As a scientific activity, inquiry is a complex process of constructing meanings and conceptual models, formulating questions, designing procedures to find answers, understanding and building new knowledge shared with others, and productively applying knowledge to unfamiliar situations.[19]

Carrying out an inquiry shifts the focus onto the student, with the teacher acting as a facilitator or guide in the learning construction process. In the TLS, students find out if different types of plastics degrade on their own, how long they take to degrade, and what environmental impact this might have if the decomposition time is lengthy.[20] To that end, they place equal samples of these materials on an outdoor clothesline for 100 days and keep a daily record of how their properties change (whether they crease, bend, get wet, become stained, etc.).[20]

Students develop arguments to reach agreements on how to carry out the inquiry and propose different explanatory models to explain the changes that occur at the molecular level. Students did not receive initial information on degradation and related issues. However, they were able to draw conclusions. The most relevant evidence obtained by students in their studies includes identification of the following relationships: a loss of elasticity of plastics produces creases and folds; water causes the appearance of stains or dirt; the chemical reactions of oxidation or degradation of pigments cause color changes; some microorganisms degrade some components of plastics, causing smells; and the loss of cohesion is responsible for the separation of fibers or for pieces falling off.[20]

The scope of the understanding about plastics in grade-8 students (N = 54) as regards their views of chemistry was evaluated by applying a questionnaire before and after the TLS. The results showed that although students had an important initial understanding of this topic, the TLS helped them to improve their view of chemistry, with higher correct response percentages being found in the post-test for the items' origin of plastics [pre/post-test, question 5] (pre: 72.7, post: 83.3), degradation of plastics [pre/post-test, question 8] (pre: 85.2, post: 85.1), effects of contamination with plastics [pre/post-test, question 9] (pre: 96.3, post: 100.0), presence of plastics in oceans [pre/post-test, question 10] (pre: 72.2, post: 90.5), and formation of microplastics [pre/post-test, question 7] (pre: 33.3, post: 76.2), for which a marked improvement was observed.[21]

Chemistry-Related Argumentation and a Holistic Approach to Problems

Some two decades ago, Driver, Newton, and Osborne[22] illustrated the central role that argumentation should have in science education, both in the social construction of scientific knowledge and the interpretation of empirical data. Hence, it is important to provide opportunities in chemistry education to address argumentation, as it is not a skill that emerges spontaneously. For this, young people need to be able to identify claims, evidence, and warrants in different arguments, and to construct arguments and counter-arguments.[23] Several authors have suggested that, through students' engagement with the topic and their powers of reasoning, SSIs are ideal for fostering the insight and reasoning underlying science.[24]

The TLS provides different opportunities for students to prepare both oral and written arguments, including role-playing (task 4). This activity is ideal as it requires students to prepare arguments and exposes them to conflicting positions and their rationale, which in the SSI for plastics may be expressed by an environmental activist or a chemist working for a plastics company when asked about the options for eliminating these materials.

A role-playing activity allows students to acknowledge the existence of opposing points of view, search for information, rationalize, discuss, and finally take a definite standpoint and reasoned decision on the SSI. A role-playing activity around plastics would allow students to learn about the chemistry of these materials, formulate arguments about everyday issues, relate those arguments to public policy, and think critically about how the history of science and technology provides insights into contemporary life and considers multiple points of view.[25]

The role-play in task 4 is based on the use or nonuse of single-use plastics and the passing of a hypothetical law that would regulate this. This is a simulation game in which students take on the roles of characters directly involved in the SSI, such as the owner of a plastics company, a worker in a factory making disposable plastic products, a fisherman concerned about the presence of microplastics in fish, or an environmental scientist, among others. Thus, the introduction of roles that voice opinions for and against the SSI is beneficial in raising awareness of different positions and providing opportunities to develop arguments and counter-arguments. Preparation of the role-playing activity also requires the search and critical analysis of information. It is also of value that students are able to defend a position with which they disagree. The interested reader can find the complete implementation of the role-playing in an article previously published in this *Journal*.[26]

Students had previously worked in the subject on constructing arguments using a simplification proposed by Erduran[27] for the Toulmin model,[28] in which the main elements of a good argument are claim, evidence, warrant, and rebuttal. The progress made by students in argumentation about chemistry in this task was evaluated using Erduran's approach.[27] The quality of the arguments provided by the students was analyzed by categorizing them into four levels: arguments corresponding to experiences (level 0); arguments that included claim and evidence (level 1); arguments that included claim, evidence, and warrant (level 2); and arguments with claim, evidence, warrant, and rebuttal (level 3). Moreover, the type of evidence used will give some idea as to what degree the student understood the problem in general.

As an example, the progress made by a student in terms of ability to argue about chemistry before and after role-playing can be seen when that person was asked to argue whether he was in favor of banning single-use plastics or against. Before role-playing, the quality of the argument given ("I'm in favor of the ban. I think that plastics will be removed slowly or that will be attempted.") was level 0 as this only showed his stance in favor of a ban based on his opinion, with no supporting evidence or warrant. However, after role-playing, the argument was level 2 ("I'm in favor of a ban as objects made from these plastics can be manufactured using other materials, such as cardboard, paper or biodegradable plastics and, although this may be slightly more expensive, it will help to reduce plastic production and environmental damage."). As can be seen, the

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claim is still in favor, but the student now justifies the reduction in plastics and environmental benefit based on two pieces of evidence (alternatives made from other materials and financial aspects). Although the first piece of evidence is in favor of his argument and the second against, the student was able to prioritize them to arrive at a claim.

Generally speaking, the majority of students made progress in terms of their level of argumentation. Moreover, it was found that those students who used arguments with evidence relating to the chemical properties of plastics or their molecular structure presented higher argumentation levels.

In addition, another measurement of the quality of argumentation is given by the ability of students to incorporate the different dimensions involved in the SSI (chemical, environmental, financial, social, healthcare, etc.) into their arguments. This was achieved partially; therefore, we must continue to make an effort to ensure that students are able to offer arguments that provide a holistic vision of the SSI.

Decision Making

Applying scientific knowledge in the decision making process regarding SSI is essential nowadays.[29] Decision making is becoming increasingly important in chemistry education because citizens are confronted in their daily lives with chemistry-related situations, the repercussions of which have an impact both on individuals and across the globe. Regarding the SSI we are focused on, one example of decision making is the question of whether to take a shopping trolley to the supermarket or buy a plastic bag. Decision making does not always have an impact at the scientific-technological level, but it can have repercussions at the social, ethical, or economic level, hence the importance of approaching the SSI from all perspectives. According to Sadler,[30] the decision made by students depends on whether the problem is local or global, since in the first case, their personal factors predominate to the detriment of scientific knowledge, while in global issues, personal factors mediate scientific knowledge. Decision making is a complex skill as it is highly interdependent on other skills. Thus, acquiring knowledge about an SSI, gaining a holistic insight into the problem, analyzing information, debating with others to discover reasoned alternative positions, and having personal autonomy all play a major role.

Task 4[26] required students to make a decision before and after role-playing to determine the impact of the arguments presented by the different characters. The percentage of students in favor of and against the ban during role-playing was compared at both times. The majority of students (77.8%) maintained their original opinion after role-playing, with only 22.2% changing their decision. These changes were from in favor of a ban to against or undecided, but never from against to in favor. After the role-playing, two types of students are against the ban: those initially already holding this position (5.6%) and those who showed a change of opinion after the debate (16.6%).[26] Arguments related to the use of plastics during the COVID pandemic (when the task was carried out) and the power of the debated ideas to convince both influenced the changes of decision.

Communication about Chemistry

Communicating the SSI to society is the last skill that needs to be developed. Such communication allows students to share their experiences and knowledge with their families, other students, and community members. This can be achieved by using different formats (oral presentations, science fairs, etc.). The decisions taken and the results obtained should be communicated.

As a communication activity, an audio story about the SSI was designed and recorded[31] by students (task 5). This activity allowed possible misconceptions about the SSI, the knowledge students considered most important, or the different aspects of the SSI they addressed to be identified. In this case, the protagonist of the audio story had to be a plastic.

A transcribed fragment of an audio story created by a student that shows some physical and chemical transformations undergone by plastics as they slowly degrade is provided below:

> *"Once upon a time there was a plastic called Plasticblue [...] Plasticblue was really bored as he'd been floating in the water for millions of years. He had visited both the North and South poles, the Great Pacific Garbage Patch and even the bottom of the ocean. He left bits of himself behind wherever he went as he was slowly falling apart to form microplastics. One day he began to feel sick and his body wasn't as blue [...] He asked Glassgreen what was happening to him. Glassgreen told him that he had started to degrade as sunlight was breaking his bonds and he should go and recycle himself as soon as possible [...] The recycling plant gave him a new life."*

The chemical communication of students was evaluated by analyzing different aspects of the audio stories ($N = 20$),[31] such as the aspects covered and their chemical suitability, the characters and scenes, or the moral. The understanding included was analyzed initially (second column in Figure 2), finding that many audio stories covered more than one aspect and that the stories concentrated more on environmental (contamination: 53.3%; solutions: 20.1%) rather than chemistry-related (types of plastics, properties and applications: 13.3%; composition and structure: 13.3%) aspects.

The chemical suitability of the understanding was evaluated using the categories: suitable understanding (e.g., "I am a biodegradable plastic made from cellulose and starch"), inaccurate understanding ("while plasticine was floating in water, the sun's rays degraded it", an example that does not use the term photodegradation), or incorrect understanding ("the tortoise told the polystyrene that it should go to the yellow container for recycling and therefore not contaminate any more"), an example which uses a plastic that cannot be recycled instead of one which can.

Analysis of the characters in the stories showed the diversity of the types of plastics and their composition and properties. The natural environment was the main setting (44%) in which the stories were based. The morals transmitted a teaching about plastics related to the environment in most cases ("we should try not to throw plastics on the floor as the journey made by the plastic is very long. If it reaches the sea it may be swallowed by a fish, which will then be eaten by us, and that is how we end up eating our own plastic").

This ability to communicate should be the first step that leads to action. In this way, citizens can be empowered through their active engagement with the SSI[32] and propose initiatives and solutions to the problems involving chemistry.

■ FINAL CONSIDERATIONS

The development of critical thinking skills would allow chemistry education to progress in its ability to propose solutions for some of the SSIs in which chemistry and society are involved, such as the environmental problem caused by

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plastics. Chemistry education should contribute to shaping responsible citizens who are aware of the reality around them, who analyze it critically, and who are conscious of the fact that the decisions they make in their daily lives have global consequences. Given its importance, several authors[29,33] argue that, in order to advance in the development of these skills, opportunities must be offered within science classrooms.

Using different tasks, this study has provided evidence that contributes to the development of critical thinking skills in Spanish grade-8 school students, along with some examples of how the progress of these students can be evaluated. The results showed that significant progress had been made in the development of critical thinking skills by students. In this sense, the ideas presented in the paper are aimed at inspiring other teachers to take action. We can conclude that the development of critical thinking skills in chemistry is complex and can be promoted by reformulating chemistry study plans to concentrate on SSIs.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00223.

Questionnaire for evaluation of the teaching−learning sequence (pretest and post-test) (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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