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Solving a socioscientific issue in different social contexts of primary education: a STEM approach to transformative environmental education

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It is necessary to work on environmental education in the classroom through scientific practices with a STEM (Science, Technology, Engineering, and Mathematics) and transformative approach in order to understand and address current eco-social issues from a critical and systemic perspective. This study presents the analysis of three questions from a case study conducted by primary school students on water pollution caused by pharmaceuticals. Resolving the issue requires the use of data in different semiotic modalities, such as graphs, maps, texts, and videos, as well as the application of STEM knowledge and skills to provide reasoned answers. The research was carried out with students aged 8 to 12 enrolled in mainstream schools or schools in challenging circumstances. To this end, we analyzed the content of their answers and group discussions, as well as performed different statistical tests to compare the results according to context, educational level, and work modality (individual or group). The results show that students' use of evidence based on texts and graphs depends on their socioeconomic and academic level. Students aged 10–12 from mainstream schools performed better. However, in general terms, group work does not improve performance levels compared to individual results. Some students achieved medium-high- and high-performance levels; however, they generally had difficulty handling information from maps and graphs because few students used these materials. Instead, they preferred texts or videos. In conclusion, this study exemplifies how socio-scientific issues can be incorporated into primary school classrooms from an early age. It also shows that this practice should be extended to all types of social and educational contexts, since the current way of teaching how to handle these materials does not seem to be effective enough to promote STEM-focused science education.

KEYWORDS
didactic of environmental education, mainstream schools, middle childhood education, schools in challenging circumstances, scientific and mathematical skills, scientific reasoning, socioscientific issue

1 Introduction

Environmental education (EE) is an essential part of civic education because it helps people understand the complexity of environmental issues and encourages them to make sustainable behavioral changes (Prada da Silva et al., 2025). In fact, the international educational framework emphasizes the importance of students understanding the interactions between science, technology, society, and the environment (OECD, 2023). In the Spanish context, EE has also been progressively incorporated into educational curricula. According to current regulations, EE is incorporated into the Early Childhood Education stage (Ministerio de Educación y Formación Profesional, 2022b), the aim is to promote exploration of the environment and the adoption of responsible and sustainable consumption habits. Subsequently, the aim of Primary Education (Royal Decree 157/2022, MEFP) is to encourage identifying eco-social problems, searching for solutions, and implementing behaviors that preserve and care for the environment.

Despite these recommendations aimed at promoting a more interrelated and participatory EE, the teaching approach remains primarily ecological, focusing on transmitting knowledge and ready-made solutions. Therefore, it fails to change citizens' behavior (Pérez-Martín and Esquivel-Martín, 2024). Given the context of the eco-social crisis and to overcome limitations in EE teaching, authors such as Casinader (2021) and Guevara-Herrero et al. (2024) highlight the need for transformative environmental education (TEE). In addition to imparting knowledge, this approach should promote social justice and the ability to make decisions on controversial issues. It should also encourage critical and systemic reflection on these issues from all perspectives, including environmental, social, economic, and health perspectives, as well as from different scales (Bächtold et al., 2022). Only then will students be able to identify risks and respond to challenges such as global pandemics, climate change, and biodiversity loss (Zhang and Hsu, 2025).

For it to be effective, it is essential that EE begin at an early age, since the emotional connections that promote behavioral change and action are formed during childhood (Nepraš et al., 2022). At the same time, these stages lay the foundation for understanding abstract concepts and prepare students for future academic success (Zamalloa et al., 2025). However, these stages have traditionally been neglected (Aguilera-Morales et al., 2021; Davis, 2009). To overcome this limitation and make TEE accessible at any age, educational researchers have been proposing activity designs based on scientific practices (argumentation, inquiry, and modeling) for years. These activities promote an understanding of natural phenomena by applying knowledge in context. They also foster curiosity and enable the development of cognitive skills, as well as a positive attitude toward science and action-taking (Osborne, 2014; Zamalloa et al., 2025; Zhang et al., 2023). In this sense, argumentation promotes critical thinking and evidence-based reasoning, both of which are essential for understanding the complexity of environmental issues. Addressing socio-scientific issues (SSIs) broadens the scope of science education and EE by connecting content to real and controversial issues.

SSIs are defined as real-world problems with a scientific basis that involve social, ethical, political, and environmental dimensions (Dawson, 2025). Because these problems do not have a single solution, students must analyze scientific information, consider values, and make informed decisions (Sadler and Dawson, 2012). Several studies have shown that working in primary school classrooms with SSIs fosters rational decision-making, critical thinking, and an understanding of science (Dawson, 2024, 2025; Evagorou et al., 2012; Fernández-Huetos et al., 2025), improving academic performance among students (Akyol and Kanadli, 2022; Brush et al., 2021). However, most research is conducted with preservice teachers and in secondary education (Kumar et al., 2024). Furthermore, the inclusion of SSIs in Spanish curricula is very limited (Puig et al., 2024). Although it is occasionally considered indirectly (e.g., sustainable urban development), it does not end up reaching the classroom due to teachers' need to cover all the curriculum content without time to go into depth (considering that activities based on scientific practices are time-consuming), their belief that it is too difficult for their students, or a lack of training (Chen and Xiao, 2021; Hodson, 2013). However, the Sustainable Development Goals (SDGs) (specifically SDG 4) feature prominently in the curriculum and advocate ensuring that all students have access to a quality education that enables them to become responsible citizens committed to environmental issues (Stouthart et al., 2023). Therefore, for SSIs to reach the classroom, teachers must be confident and receive training in both content and didactic knowledge related to SSI (Lee, 2016; Mathers et al., 2024).

The connection between EE, scientific practices, and SSIs naturally converges within the framework of STEM education. STEM education is an interdisciplinary approach that integrates science, technology, engineering, and mathematics in real-world problem-solving contexts (Calvo Utrilla et al., 2025; Kelley and Knowles, 2016). Although STEM education has gained prominence in recent years, it remains a complex concept to define (Calvo Utrilla et al., 2025). Some authors argue that it consists of integrated teaching of all four disciplines (Akgündüz, 2018), while others argue that integrating at least two is sufficient (Breiner et al., 2012; Kelley and Knowles, 2016; Wahono et al., 2021), as is done in this work. An E-STEM approach has emerged that combines STEM with EE to promote scientific and technological literacy (Garner et al., 2018). This study also agrees with this notion.

In practice, this variety of definitions results in a wide range of classroom experiences. For example, a study by Hacioglu and Gulhan (2021) in Istanbul shows that integrating mathematics and engineering into school projects on urban sustainability fosters critical thinking. However, despite efforts to promote participation in STEM projects, educational and professional inequalities persist based on socioeconomic status or cultural background, and such projects often fail to establish meaningful connections with students' lived experiences (Grimalt-Álvaro and Couso, 2025; Marco-Bujosa et al., 2020). In this context, integrating SSIs into STEM projects is useful for engaging marginalized groups. This was demonstrated in a study by Johnson et al. (2022), which included nearly 3,000 secondary school students from disadvantaged communities in the United States. Through SSIs analysis, improvements in scientific skills, participation, and sense of belonging were evident among groups that are usually distant from these disciplines. Similarly, Benek and Akçay (2022) developed a STEM program combining science and technology around environmental issues for 12-year-old Turkish students living in a socio-culturally disadvantaged neighborhood. They found significant improvements in critical thinking, creativity, and cooperation. These results demonstrate that STEM education does not require costly resources or restrict itself to technological or robotic activities. Rather, it can be effectively implemented in low-resource school settings when related to meaningful student learning experiences (Akgündüz, 2018). However, working only with hands-on activities is insufficient; minds-on activities are also necessary to help students gradually and actively build complex concepts (Castillo-Hernández et al., 2025).

In short, we can draw on some essential STEM education concepts proposed by Aguilera-Morales et al. (2021): "integrate," "approach," "contextualize," and "problem." These concepts align with the proposals of Özturk and Roehrig (2025), who define STEM as involving real contexts, connections between disciplines, development of 21st-century skills, and use of student-centered teaching methods. Therefore, promoting TEE in this context, which involves SSIs and STEM education, enables the application of scientific concepts and practices to real-world decision-making, thereby fostering critical citizenship. Roberts and Bybee (2014) refer to this as Vision II of scientific literacy. For these reasons, an activity aligned with this vision has been designed and implemented, as students must apply their knowledge to a real and controversial context: water pollution by pharmaceuticals. This teaching proposal requires students to solve a case, applying scientific and mathematical skills to support their answers with the available evidence. This approach allows students to address the complexity of a meaningful real-world problem (Alcaraz-Dominguez and Barajas, 2021). The starting point is a relevant environmental problem, and higher-order thinking skills are encouraged as necessary tools for addressing it successfully (Högström et al., 2024).

In this context, this study aims to analyze how the designed teaching proposal promotes scientific argumentation and reasoning in students in the 2nd and 3rd cycles of primary education (PE) (ages 8–12) enrolled in mainstream schools (MS) or schools in challenging circumstances (SCC). Through answering questions about the case study, we will evaluate students' performance in argumentation and their understanding and use of materials presented in different semiotic modalities (textual, numerical, or visual). This activity promotes science education based on a STEM approach to improving understanding and use of graphs and maps in context.

Additionally, the goal is to compare the development of the activity among different educational centers, cycles, and methods of work (individual and group). To this end, we propose the following research questions (RQ):

- RQ1: What levels of performance do students from different contexts and educational cycles show in the use of graphs to solve an SSI when working individually (RQ1a) and collaboratively (RQ1b)?
- RQ2: What levels of performance do students from different contexts and educational cycles show in the use of maps to solve an SSI when working individually (RQ2a) and collaboratively (RQ2b)?
- RQ3: What levels of performance do students from different contexts and educational cycles show in the combined use of materials to solve an SSI when working individually (RQ3a) and collaboratively (RQ3b)?
- RQ4: How do the variables (work modality, context, cycle) influence the performance of all students when solving a STEM activity?

2 Method

2.1 Context

This study is based on the multiple-case-study research method (Yin, 2018). A total of 197 students from four public schools in the Community of Madrid, Spain, participated. Specifically, two schools had a medium-high socioeconomic level (estimated annual household income: €61,000), and two had a low socioeconomic level (estimated annual household income: €34,000). In fact, the income levels in the areas surrounding the two centers with the highest socioeconomic status are approximately twice those in areas surrounding other educational centers with lower socioeconomic status.

For this reason, two educational contexts were considered: an MS context and an SCC context. 49 students from the 2nd cycle (8–10 years old) and 65 students from the 3rd cycle (10–12 years old) of MS PE participated, as well as 43 students from the 2nd cycle and 40 students from the 3rd cycle of SCC PE. In the MS context, most families are employed and have a high percentage of university education. It is an environment with good availability of educational and technological resources, access to various cultural and leisure activities, and a marked family interest in learning and monitoring their children's education. In the SSC context, there is great cultural diversity and a significant percentage of immigrant students of different nationalities. Many families face economic and social difficulties, including family breakdown, unstable incomes, and the need for state support. Likewise, there are linguistic and technological barriers, as well as a notable involvement of social services in supporting minors.

The students first worked individually and then in their usual classroom groups. The activity entitled "Pharmaceuticals in the River?" (Supplementary material 1) consists of seven questions. This study analyzes students' responses to three questions that require them to interpret graphs, relate information from different sources, and apply spatial orientation skills to understand maps. The questions are: Q1 ("Based on what you have read and seen, what is polluting the river?"), Q2 ("Based on what you have read and seen, where do the pharmaceuticals in the river come from?"), and Q4 ("If the pharmaceuticals most commonly found in the Bodonal stream are not the best-selling ones, how and why do they end up in such large quantities in the stream?"). The skills that these three questions require students to apply are closely linked to the STEM approach, mainly in the areas of science and mathematics. Thus, implementing and analyzing this proposal allows us to determine the extent to which PE students use graphs and maps.

2.2 Data analysis

This study employed qualitative content analysis of written responses (Schreier, 2012) and discourse analysis of group discussions (Gee, 2014). All the questions were analyzed using the categorization presented in Supplementary material 2. Then, absolute and relative frequencies were calculated. During these processes, three authors of this study participated in triangulating the presented data. First, they analyzed the responses independently. Subsequently, they held a session in which the results were compared, reaching an agreement rate of over 90%.

Specifically, to assess each student's performance level (RQ1, RQ2, RQ3), their responses were graded on a scale from 1 to 5, where 1: zero level, 2: low level, 3: medium-low level, 4: medium-high level, and 5: high level. The reference response was used as a benchmark (see Supplementary material 1). Furthermore, to analyze students' use of and understanding of the materials, we used different individual categories (e.g., graphs, maps, reports, leaflets, and videos) or combinations thereof, all of which were defined in interaction with the data. Additionally, two reference taxonomies were applied: one for texts

(Barrett, 1968) and one for graphs (Curcio, 1989). The Chi-square test (χ^2, $p \leq 0.05$) was used to evaluate differences in the use of materials.

Descriptive and inferential statistical analyses were performed using statistical tools from Microsoft Excel ™ and IBM® SPSS® Statistics 19 (2010). To analyze individual (RQ1a, RQ2a, RQ3a) and group performance levels (RQ1b, RQ2b, RQ3b), the different groups were compared for each question. First, Levene's test was used to assess the homogeneity of variances. After confirming that these were not parametric variables, Welch's ANOVA test ($p \leq 0.05$) was applied, along with Games-Howell's *Post Hoc* analysis ($p \leq 0.05$), when necessary. On the other hand, we analyzed individual versus group average performance using Student's T-test ($p \leq 0.05$). Finally, the data were processed to model all data for Q1, Q2, and Q4 together using multivariate linear regression (Multivariate Linear Regression, ANOVA, $p \leq 0.05$) (RQ4).

3 Results

3.1 Analysis of the performance of students from different contexts and educational cycles in the use of graphs (RQ1)

To determine the level of performance in the use of graphs, we analyzed students' responses to Q1: "Based on what you have read and seen, what is polluting the river?". For this question, students should answer that the river is polluted by the most commonly found pharmaceuticals in the graph, specifically carbamazepine (MS 3rd cycle: *From different pharmaceuticals like fluoxetine, citalopram, venlafaxine, nordiazepam, oxazepam and carbamazepine, which is the most common*).

3.1.1 Analysis of individual performance in the use of graphs (RQ1a)

The average performance level achieved by the students in this question, in ascending order, is as follows: MS 2nd cycle < SCC 3rd cycle < MS 2nd cycle < MS 3rd cycle (Table 1). In other words, students in the SCC context performed worse than those in the MS context. Within the latter context, students in the 3rd cycle demonstrate the best performance.

When analyzing the maximum performance level achieved by students in each cycle and context, it can be seen that six MS 3rd cycle students and one SCC 2nd cycle student identified carbamazepine as the most common drug, thus achieving the highest level of performance in this question. These results demonstrate that students with lower overall performance levels (SCC 2nd cycle) can still answer this question correctly. Additionally, five MS 2nd cycle students and seven SCC 3rd cycle students achieved a medium-high performance level by mentioning all the pharmaceuticals present in the river without highlighting carbamazepine (SCC 3rd cycle: *Carbamazepine, oxazepam, nordiazepam, venlafaxine, fluoxetine, and citalopram*). It should be noted that students from all cycles and contexts analyzed in PE achieved the same level of performance (Table 2), except for the MS 3rd cycle students, who performed best (Levene test, $p \leq 0.05$; ANOVA-Welch test, $p \leq 0.05$; *Post hoc* Games-Howell test, $p \leq 0.05$). Thus, except for the latter, they all solve Q1 in the same way, which requires the use of graphs.

TABLE 1 Average individual performance levels in Q1.

Individual performance level (Q1)			
ID	*N*	Mean	Deviation
MS 2nd cycle	49	2.94	0.59
MS 3rd cycle	65	3.32	0.71
SCC 2nd cycle	43	2.65	0.78
SCC 3rd cycle	40	2.78	0.80

Regarding the individual use of materials, differences are observed among students in different cycles and types of centers (χ^2, $p \leq 0.05$). In the 2nd cycle of MS, text is used more frequently than in the 3rd cycle of SCC, where text and video are used equally. In the 2nd cycle of SCC, most students do not use any materials. In the 3rd cycle of MS, video use prevails, followed by graphics. It should be noted that graphics are the most appropriate material for answering this question, and MS students use them the most. According to Curcio's (1989) taxonomy for understanding graphs, achieving the maximum level of performance on this question requires level 2 understanding, which involves selecting the appropriate bar graph and comparing the values of each drug. However, except in the MS 3rd cycle, all students who use graphs extract data from the "Y" axis (level 1, read the data). In the MS 3rd cycle, 26% of students reach level 2 (reading through the data), while 74% remain at level 1 (Curcio, 1989).

3.1.2 Analysis of group performance in the use of graphs (RQ1b)

The average performance level achieved by the different groups of students in this question, in ascending order, is as follows: SCC 2nd cycle < SCC 3rd cycle < MS 3rd cycle < MS 2nd cycle (Table 3). Specifically, the SCC context groups performed lower than the MS context groups. This suggests that group work in a challenging context leads to poorer performance than in MS centers. Likewise, within the SCC context, the 3rd cycle groups show higher performance than the 2nd cycle groups. However, in the MS context, the opposite is true. Thus, two SCC 2nd cycle groups achieved a medium-high level (mentioning all the present pharmaceuticals), while the rest, including the 3rd cycle groups, achieved a medium-low level (mentioning that the river is contaminated with some pharmaceuticals) (MS 2nd cycle: *With pharmaceuticals*). No group achieved the high level.

On the other hand, everyone performs at the same level when answering Q1 (Table 4) while working in groups, except for the SCC 2nd cycle groups, which perform worse than the MS context groups (Levene test, $p \leq 0.05$; ANOVA-Welch test, $p \leq 0.05$; *Post hoc* Games-Howell test, $p \leq 0.05$).

Regarding the use of materials, differences were detected between the groups (χ^2, $p \leq 0.05$). In the SCC context, most groups do not use materials, while most MS groups do. Specifically, video predominates in MS 2nd cycle, and graphs stand out in MS 3rd cycle. Graphs are the most appropriate material for answering this question. According to Curcio's (1989) taxonomy, all groups that use graphs reach level one of understanding, which is reading the data. These groups limit themselves to copying the data from the "Y" axis.

TABLE 2 Individual performance differences in Q1 (Levene test, $p \leq 0.05$; ANOVA-Welch test, $p \leq 0.05$; *post hoc* Games-Howell test, $p \leq 0.05$).

Individual	MS 2nd cycle	MS 3rd cycle	SCC 2nd cycle	SCC 3rd cycle
MS 2nd cycle		**0.018***	0.293	0.818
MS 3rd cycle	**0.018***		**0.000***	**0.006***
SCC 2nd cycle	0.293	**0.000***		0.953
SCC 3rd cycle	0.818	**0.006***	0.953	

The dark gray shade serves to clarify that cell is null. The light gray shade serves to highlight that significant differences are detected there, as indicated by the bold font and asterisk.
* = significant differences.

TABLE 3 Average group performance levels in Q1.

Group performance level (Q1)			
ID	*N*	Mean	Deviation
MS 2nd cycle	11	3.18	0.40
MS 3rd cycle	15	3.00	0.00
SCC 2nd cycle	11	2.45	0.52
SCC 3rd cycle	10	2.67	0.50

TABLE 4 Group performance differences in Q1 (Levene test, $p \leq 0.05$; ANOVA-Welch test, $p \leq 0.05$; *post hoc* Games-Howell test, $p \leq 0.05$).

Group	MS 2nd cycle	MS 3rd cycle	SCC 2nd cycle	SCC 3rd cycle
MS 2nd cycle		0.590	**0.013***	0.188
MS 3rd cycle	0.590		**0.038***	0.353
SCC 2nd cycle	**0.013***	**0.038***		1.000
SCC 3rd cycle	0.188	0.353	1.000	

The dark gray shade serves to clarify that cell is null. The light gray shade serves to highlight that significant differences are detected there, as indicated by the bold font and asterisk.
* = significant differences.

Finally, a comparison of individual and group performance shows that all students perform at the same level in both contexts, except 3rd cycle students, who perform better individually (Student's *t*-test, $p \leq 0.05$). Below is an example of SCC 3rd cycle, where one member of the group individually responds with a medium-high level (S5), but the rest of the group detracts from their response and imposes what the majority believes, even if it is incorrect and of a low level:

- S1: *Everyone has to say what they have put in and then we'll discuss it.*
- S2: *I say that the river is polluted with grease, sand, waste, and microorganisms.*
- S1: *Ok, and what have you put in?*
- S3: *I've put in wastewater.*
- S4: *I wrote water, grease residue, sand, and plastic.*
- S1: *I wrote about wastewater. What did you write?*
- S5: *I wrote all the medicines (…). I think we should take one piece of information from each of us and put it in the answer (…). Although I do not agree with the wastewater part.*
- S1: *I disagree with what S5 says, because according to what I've read about what contaminates water, he has put medicines.*
- S2: *Medicines are not pollution.*
- S5: *According to what it says here, they are medicines frequently used in hospitals and prescribed for home use, and if you look at the graph…*
- S1: *I've thought about it and medicines do not pollute the river, in my opinion, right?*
- S5: *And they help us with anxiety problems (…) and the text says that they cause side effects in fish and chickens.*
- S1: *I think S3 and S2 are better. What do you think?*

(Everyone agrees with that opinion).

3.2 Analysis of the performance of students from different contexts and educational cycles in the use of maps (RQ2)

To determine the level of performance in the use of maps, we analyzed students' responses to Q2: "Based on what you have read and seen, where do the pharmaceuticals in the river come from?". For this question, students should identify the source of the pharmaceuticals (domestic consumption) and locate the geographical area of origin [Tres Cantos, Soto de Viñuelas, Tres Cantos Wastewater Treatment Plant (WWTP)], making appropriate use and interpretation of the maps (MS 3rd cycle: *The pharmaceuticals are produced in all pharmaceutical laboratories in Spain and are used in hospitals or prescribed for home use. In this case, the pharmaceuticals probably come from Tres Cantos or Soto de Viñuelas, since they are close to the river*). Additional materials, such as leaflets or video explaining how WWTPs work, can help students understand how pharmaceuticals reach rivers: people consume them and eliminate them through urine or feces. However, relying solely on these visual materials does not allow for a high-level response.

3.2.1 Analysis of individual performance in the use of maps (RQ2a)

In ascending order, the level of performance achieved by the different students in Q2 is as follows: SCC 2nd cycle < SCC 3rd cycle < MS 2nd cycle < MS 3rd cycle (Table 5). In other words, students in the SCC context perform worse than those in the MS context. Within the latter, students in the 3rd cycle perform better. The same order is maintained in Q1, though the average performance level is significantly lower in Q2.

The results show that, in the SCC context, students achieve at most a medium-low performance level (SCC 3rd cycle: *The pharmaceuticals come from the WWTP*). This indicates only an awareness of domestic drug consumption or their origin from WWTP. In the MS context, however, a 3rd cycle student achieves a high level by considering both the geographical area and domestic consumption. In the 2nd cycle, three students achieved a medium-high level, indicating a specific geographical area but not domestic consumption (MS 2nd cycle: *From Soto de Viñuelas*). Furthermore, except for the 2nd cycle SCC, which has the lowest average performance level, all the students analyzed have the same performance level in this question (Table 6) (Levene test, $p \leq 0.05$; ANOVA-Welch test, $p \leq 0.05$; *Post hoc* Games-Howell test, $p \leq 0.05$). These results show that most students find this question very complex.

TABLE 5 Average individual performance levels in Q2.

Individual performance level (Q2)			
ID	*N*	Mean	Deviation
MS 2nd cycle	49	1.61	0.98
MS 3rd cycle	65	1.97	1.07
SCC 2nd cycle	43	1.28	0.67
SCC 3rd cycle	40	1.55	0.88

TABLE 6 Individual performance differences in Q2 (Levene test, $p \leq 0.05$; ANOVA-Welch test, $p \leq 0.05$; *post hoc* Games-Howell test, $p \leq 0.05$).

Individual	MS 2nd cycle	MS 3rd cycle	SCC 2nd cycle	SCC 3rd cycle
MS 2nd cycle		0.350	0.308	0.998
MS 3rd cycle	0.350		**0.001***	0.196
SCC 2nd cycle	0.308	**0.001***		0.516
SCC 3rd cycle	0.998	0.196	0.516	

The dark gray shade serves to clarify that cell is null. The light gray shade serves to highlight that significant differences are detected there, as indicated by the bold font and asterisk.
* = significant differences.

Significant differences in the use of materials were observed among students in different cycles and types of schools (χ^2, $p \leq 0.05$). In the MS context, 2nd cycle students predominantly used maps, which were the appropriate material for Q2. 3rd cycle students either used text or did not use any material. In the SCC context, most students in both cycles did not use any materials; however, in the 3rd cycle, text predominated. These results suggest that students have limited proficiency in interpreting maps and compensate by extracting information from more accessible sources, such as texts.

3.2.2 Analysis of group performance in the use of maps (RQ2b)

The level of performance achieved by the different groups of students in this question, in ascending order, is as follows: MS 2nd cycle = SCC 2nd cycle < SCC 3rd cycle < MS 3rd cycle (Table 7). In other words, the 2nd cycle groups in both contexts demonstrate the same level of performance, which is the lowest. Next are the SCC 3rd cycle groups, followed by the MS 3rd cycle groups with the highest level of performance. One of the groups in this cycle achieved the highest level of performance because it could understand the direction of the river's course and detect which areas of the map the pharmaceuticals came from (MS 3rd cycle: *The pharmaceuticals are consumed in Tres Cantos and then reach the WWTPs through urine*). In the other cases, the highest level achieved was medium-low because they did not use the maps.

On the other hand, all the groups analyzed answered Q2 in the same way, demonstrating the same level of performance in terms of map handling and interpretation (Levene test, $p \leq 0.05$; ANOVA-Welch test, $p \leq 0.05$). Furthermore, although the use of maps predominates in the MS context groups and most of the SCC context groups do not use any materials, no differences have been found in the use of maps (χ^2, $p \leq 0.05$).

Finally, no significant differences were detected when comparing individual performance with group performance (Student's *t*-test, $p \leq 0.05$). This means that all students achieved similar levels of performance when working individually or in groups on a question requiring the use of maps.

TABLE 7 Average group performance levels in Q2.

Group performance level (Q2)			
ID	*N*	Mean	Deviation
MS 2nd cycle	11	1.45	0.82
MS 3rd cycle	15	2.13	1.36
SCC 2nd cycle	11	1.45	0.69
SCC 3rd cycle	10	1.67	1.00

3.3 Analysis of the performance of students from different contexts and educational cycles in in the combined use of materials (RQ3)

To determine the level of performance in the use of combined materials, we analyzed students' responses to Q4: "If the pharmaceuticals most commonly found in the Bodonal stream are not the best-selling ones, how and why do they end up in such large quantities in the stream?". In this question, students are expected to use the graphs and the report to conclude that the most prevalent pharmaceuticals in the river, such as carbamazepine, cannot be effectively removed in WWTPs. They should also consider that these pharmaceuticals are used for chronic treatments, an idea they will acquire while carrying out the activity that they can extract from the leaflet. Therefore, their release is constant.

3.3.1 Analysis of individual performance in the combined use of materials (RQ3a)

The level of performance achieved by the different students in this question, in ascending order, is as follows: SCC 2nd cycle < MS 2nd cycle < SCC 3rd cycle < MS 3rd cycle (Table 8). In other words, 2nd cycle students perform worse than 3rd cycle students, with MS students consistently performing at a higher level.

Specifically, in the 2nd cycle of MS and the 3rd cycle of SCC, the maximum level achieved is medium-low (three and four students, respectively) (SCC 3rd cycle: *Due to the poor quality of drug removal in wastewater*). This is because students only indicate the ineffectiveness of WWTPs in removing certain pharmaceuticals. In the 2nd cycle of SCC, four students reach the low level because they provide some data without establishing any valid relationships (*Because there are some medicines that many people buy*). Only one student in the MS 3rd cycle achieves the maximum level of performance on this question (*Because the best-selling ones are easier to eliminate, the others arrive because the WWTP cannot eliminate them and they are discharged all the time to treat diseases*). As can be seen in Table 9, MS 3rd cycle students perform better than the others, who all perform at the same level when working on Q4 (Levene test, $p \leq 0.05$; ANOVA-Welch test, $p \leq 0.05$; *Post hoc* Games-Howell test, $p \leq 0.05$).

Regarding the individual use of materials, differences exist between students from different contexts and cycles (χ^2, $p \leq 0.05$). Most students do not use materials to answer Q4, except in the 3rd

TABLE 8 Average individual performance levels in Q4.

Individual performance level (Q4)			
ID	*N*	Mean	Deviation
MS 2nd cycle	49	1.16	0.51
MS 3rd cycle	65	2.17	1.24
SCC 2nd cycle	43	1.09	0.29
SCC 3rd cycle	40	1.30	0.65

TABLE 9 Individual performance differences in Q4 (Levene test, $p \leq 0.05$; ANOVA-Welch test, $p \leq 0.05$; *post hoc* Games-Howell test, $p \leq 0.05$).

Individual	MS 2nd cycle	MS 3rd cycle	SCC 2nd cycle	SCC 3rd cycle
MS 2nd cycle		**0.000***	0.925	0.814
MS 3rd cycle	**0.000***		**0.000***	**0.000***
SCC 2nd cycle	0.925	**0.000***		0.357
SCC 3rd cycle	0.814	**0.000***	0.357	

The dark gray shade serves to clarify that cell is null. The light gray shade serves to highlight that significant differences are detected there, as indicated by the bold font and asterisk.
* = significant differences.

cycle of MS, where students predominantly use the report. The most appropriate materials for answering Q4 are a combination of the graph and the report. Ten students in that cycle used these materials. It should be noted that the leaflet could be useful for achieving the highest level of performance on this question; however, in this case, students hardly made use of it.

On the other hand, the extent to which students understand the graphs they use was analyzed using Curcio's (1989) taxonomy. Among students using graphs in different cycles and contexts, 100% of students in the 2nd cycle of both contexts and the 3rd cycle of SCC do not reach the necessary level of understanding to respond adequately. However, in the 3rd cycle of MS, 5.9% connected the information in the graphs with the rest of the materials, reaching the maximum level of comprehension (level 3: reading beyond the data) and demonstrating a high level of performance. 29.4% compared the best- and worst-selling pharmaceuticals (level 2: reading between the data), and 64.7% did not reach the minimum level of comprehension.

The level of comprehension of students using the report was also analyzed using Barrett's (1968) taxonomy. In the 2nd cycle of MS, 60% identified some data in the report (level 1: literal), and 40% did not reach the minimum level of comprehension required. In the 3rd cycle of SCC students are distributed similarly: 44.4% reach level 1 (literal), and 55.6% do not reach the minimum required. In the MS 3rd cycle, there is a wider range of responses: 2.9% correctly inferred that these pharmaceuticals are used to treat chronic mental health conditions with constant use (level 3: inferential or interpretive), reaching the maximum level of comprehension for this question. 32.4% were able to combine information to establish relationships between best-selling and least-selling pharmaceuticals (level 2: reorganization of information). 38.2% percent only identified some of the data in the report (level 1: literal), and 26.5% did not reach the minimum level of comprehension. Finally, in the SCC 2nd cycle, no student reached the minimum level of comprehension.

3.3.2 Analysis of group performance in the combined use of materials (RQ3b)

In ascending order, the level of performance achieved by the different groups of students in this question is as follows: SCC 2nd cycle < MS 2nd cycle < SCC 3rd cycle < MS 3rd cycle (Table 10). In other words, the 2nd cycle groups performed lower than the 3rd cycle groups, and the MS context groups performed higher within each cycle.

It can be seen that two groups of 2nd cycle SCC achieve a low level of performance by failing to establish coherent relationships between the data. One group of MS 2nd cycle students achieved a medium-low level, as they limited themselves to using the report to refer to the inefficiency of WWTPs. Meanwhile, in the 3rd cycle, two MS context groups and one SCC group achieved a medium-high level, adding to their response the relationship between the most and least sold pharmaceuticals and how they are disposed of in WWTPs (SCC 3rd cycle: *Some of the best-selling medicines are paracetamol and nolotil, and since they dissolve, the least sold ones are the ones that remain*). Despite this, with the exception of SCC 2nd cycle, which has the lowest average performance level, all the groups analyzed have the same level of performance in this question, never reaching the high level (Table 11) (Levene test, $p \leq 0.05$; ANOVA-Welch test, $p \leq 0.05$; *Post hoc* Games-Howell test, $p \leq 0.05$).

Significant differences were detected in the group's use of materials (χ^2, $p \leq 0.05$). In the 3rd cycle of SCC, one group combined the essential materials needed to answer the question: the report and the graph. The MS 3rd cycle groups primarily used the text, while the other groups did not use any materials. Regarding understanding these materials, it is evident that only one group of students from each cycle and context used the graphs. According to Curcio's (1989) taxonomy, the SCC 3rd cycle group achieves level 2 (reading between the data), while the MS context groups do not reach the minimum level of understanding necessary to answer this question. It should be noted that, in the SCC 2nd cycle, no group used the graphs or the report. Following Barret's taxonomy (1968), the group that used the report in the MS 2nd cycle achieved level 1 (literal comprehension). In the SCC 3rd cycle of the two groups that used the report, one achieved level 1 and the other achieved level 2 (reorganization of information). Meanwhile, in the MS 3rd cycle, more groups use the report: 70% reach level 1 (literal comprehension), 20% reach level 2, and 10% do not achieve the minimum comprehension required. Overall, these results indicate that no group reaches the level of comprehension associated with the highest level of performance when working in groups, whether using the graphs or the text.

Finally, no significant differences were detected when comparing individual performance with group performance (Student's *t*-test, $p \leq 0.05$), indicating that students achieve the same level of performance when working individually or in groups on a question requiring the simultaneous handling of graphic and textual material.

3.4 Analysis of variables in student performance when solving a STEM activity (RQ4)

Overall, for Q1, Q2, and Q4, the performance levels shown by students indicate that they are highly dependent on their educational level (cycle) ($\beta = 0.459$, ANOVA $p \leq 0.0001$) (Multivariate

TABLE 10 Average group performance levels in Q4.

Group performance level (Q4)			
ID	*N*	Mean	Deviation
MS 2nd cycle	11	1.27	0.65
MS 3rd cycle	15	2.33	1.18
SCC 2nd cycle	11	1.18	0.40
SCC 3rd cycle	10	1.56	1.13

TABLE 11 Group performance differences in Q4 (Levene test, $p \leq 0.05$; ANOVA-Welch test, $p \leq 0.05$; *post hoc* Games-Howell test, $p \leq 0.05$).

Group	MS 2nd cycle	MS 3rd cycle	SCC 2nd cycle	SCC 3rd cycle
MS 2nd cycle		0.052	0.994	0.960
MS 3rd cycle	0.052		***0.018**	0.512
SCC 2nd cycle	0.994	***0.018**		0.873
SCC 3rd cycle	0.960	0.512	0.873	

The dark gray shade serves to clarify that cell is null. The light gray shade serves to highlight that significant differences are detected there, as indicated by the bold font and asterisk.
* = significant differences.

Linear Regression, $R^2 = 0.044$, ANOVA $p \leq 0.0001$). Therefore, 3rd cycle students perform better in the use of maps, graphs, and combined materials in STEM activities, regardless of their socioeconomic background and the type of work (individual or group). Consequently, belonging to a disadvantaged background does not justify neglecting these skills in the classroom, as the results show that the most decisive factor is age.

4 Discussion

This study presents a STEM-based teaching proposal that aims to promote literacy and awareness of environmental issues and strengthen the acquisition of scientific and mathematical skills. Additionally, analyzing the responses obtained allowed us to evaluate its effectiveness with PE students. The inclusion of the STEM approach in the activity complements other teaching tools and approaches (use of SSIs, solving a real-life case, argumentation as scientific practice, data in different semiotic modalities, storytelling, thought-provoking questions, etc.) that are used in teaching EE with a transformative approach to move away from more traditional teaching methods. This fusion can positively impact on science education and pro-environmental attitudes, as demonstrated in Alkair et al. (2023) study with 9-10-year-old students (4th PE, 2nd cycle). In that study, the researchers used a STEM-based problem-solving method to analyze the impact of learning about sustainability. In contrast, the activity presented in this paper, "Pharmaceuticals in the River?", involves solving a case based on an SSI at various primary school levels and in different contexts. This requires students to deploy their socioscientific reasoning (Sadler et al., 2007) by integrating the ability to model, argue, and analyze information from a systemic and critical approach. Furthemore, this activity aligns with vision II of scientific literacy in that students apply knowledge to a real and controversial context. Similarly, Özturk and Roehrig (2025) worked with 12-13-year-old students from diverse socioeconomic backgrounds on another SSI (sulphide mining), and the students improved their socioscientific reasoning and understanding of the issue from different perspectives.

In addition, it should be noted that the STEM skills required for this activity align with the Spanish educational curriculum (Royal Decree 157/2022, MEFP). In first place, mathematical abilities throughout PE are not limited to calculation, as they also include graphic, spatial, and representational skills. For instance, students must be able to communicate and represent information using graphical language, compare data sets, create visual representations, and apply graphs to real-life problems. Second, map-related skills are not limited to the subject of Natural and Social Environment Studies, spatial awareness is also part of the basic knowledge covered in the subject of Mathematics. All of this continues to be developed in secondary education, with the addition of the use of scales and mapmaking. Therefore, it is important for students to consolidate skills by integrating the reading and interpretation of graphical representations and maps to adequately progress in their learning. The teaching proposal in this study allows for the development of conceptual and procedural content applicable to various levels of PE. Teachers do not need to design different activities for each year group; rather, they can design the same activity with necessary adaptations for various stages. Furthermore, through this STEM activity, students can acquire this knowledge in an integrated way in real-world contexts and understand its relevance in their daily lives (Eshaq, 2024) and establish links between different disciplines, such as mathematics and science (Craig and Marshall, 2019).

However, although this educational framework assumes that students will become more skilled as they progress through school, the reality revealed by this study is that upper PE students continue to have difficulty working with graphs and maps (RQ1, RQ2). All students aged 8–12 in both contexts (mainstream schools and schools in challenging circumstances) show the same difficulties when working in groups and using maps. This situation reflects significant limitations in students' cartographic literacy levels, which carry over to all stages of education, from childhood to university (Ayuldeş and Akbaş, 2023). In fact, most geography teachers have a limited understanding of map teaching and therefore attach insufficient importance to map-based argumentation skills (Kunze and Budke, 2025). These deficiencies can be explained, in part, by the type of teaching they receive. Teachers tend to use maps in the classroom only to demonstrate geographical distribution, focusing on memorization of geographical elements and neglecting interpretation of space (Hanus and Havelková, 2019). According to our results, MS 2nd cycle students use maps the most to solve the case. This could be linked to the educational curriculum's structure (Ministerio de Educación y Formación Profesional, 2022a), as this cycle focuses on spatial knowledge and representation, familiarizing students with maps, globes, and plans. In contrast, the 3rd cycle of PE focuses more on geographical diversity, such as memorizing rivers, mountains, and countries. This was the case with secondary school students, who demonstrated poor spatial skills and only recognized the closest and largest territorial units (Pons et al., 2024). Therefore, there is a clear need to rethink how these concepts are taught, given that maps are essential tools for developing spatial awareness and facilitating the learning of geographical concepts (Jonuzi and Selvi, 2023). Some studies have demonstrated their benefits, for example through drawing to learn the location, size, and shape of continents, which is recommended for children aged 7 and older (Harwood and Rawlings, 2001), or through the use of atlases, which increased PE students' ability to read and use maps (Bugdayci and Selvi, 2021).

In terms of graph handling, participants in this study also experience some difficulties depending on the cycle and context, although less so than with maps. Specifically, 3rd cycle students in mainstream context were the most proficient in using graphs (RQ1) and combining graphs with text (RQ3), enabling them to perform better in the activity than others. However, despite being included in the curriculum from the 2nd cycle PE, virtually no student (except for a minority of MS 3rd cycle) can integrate data from different sources to support their answers (RQ3). This indicates a tendency to search for a single answer among all the available data rather than analyzing the information in depth and critically selecting the necessary information to answer the question. Specifically, PE students do not reach the highest level in reading graphs and experience difficulties in reading them, interpreting their variables, and selecting the most appropriate one for a real-life situation, and this task is rarely addressed in textbooks (Arteaga et al., 2021). They also have more difficulty with dot plot and pie charts, as well as with constructing graphs when frequencies are not provided (Arteaga et al., 2020). In fact, activities in textbooks generally encourage textual reproduction (Pérez-Martín et al., 2019), and many teachers still use textbooks as their main science learning resource (Tasyani et al., 2025). Nevertheless, more educational research is needed, and teachers must be taught alternative teaching methods that differ from and/or complement textbooks. In STEM education, mathematics must be integrated into real-life contexts so students can apply what they have learned to practical problems and improve their performance (Eshaq, 2024).

Similarly, it was observed that students from schools in challenging circumstances faced more challenges when analyzing data in different semiotic modalities and interpreting it to complete the activity. This situation occurs not only in this study but also in other contexts. At the national level, the TIMSS 2023 (Instituto Nacional de Evaluación Educativa, 2024) results show a significant correlation between socioeconomic status and academic performance in mathematics and science in the 4th year PE. Students from higher socioeconomic and cultural backgrounds tend to perform better, while those from disadvantaged backgrounds tend to perform worse (Instituto Nacional de Evaluación Educativa, 2024). This tendency continues throughout PE, demonstrating the influence of socioeconomic background from an early age. In the same way, PISA 2022 results confirm that, in secondary education, students with higher socioeconomic status continue to perform better in mathematics, reading, and science. This reinforces the idea that socioeconomic context impacts academic performance (OECD, 2024). In terms of social justice, these findings underscore the need for educational policies that reduce socioeconomic inequalities to promote greater equity in school outcomes (Molina-Muñoz et al., 2025) and offer all students a quality education (SDG 4).

Nevertheless, this situation does not mean that students from disadvantaged backgrounds cannot participate in or solve STEM or SSIs projects. Educational researchers have implemented and analyzed various teaching proposals in a wide variety of contexts. For instance, Dawson and Venville (2020) collaborated with 12-year-olds from underprivileged schools on SSIs projects. The results showed that all students could construct evidence-based arguments, make decisions, and justify their positions. Similarly, a more recent Australian study by Dawson (2025) analyzed how 11- and 12-year-old science students from a rural region with a low socioeconomic status improved their argumentation skills after working with a case study related to water and SSI. Oliver et al. (2012) also observed improvements in reasoning, literacy, and numeracy skills in 12- to 14-year-old students who participated in guided inquiry activities. These results align with Zohar and Ben-David's (2008) findings that teaching higher-order thinking skills benefits low-achieving students. These students developed more sophisticated reasoning skills and improved their academic performance in science. More recent research corroborates these findings, showing that low-achieving students can participate in and lead discussions on SSI (Lee and Yang, 2019). Furthermore, the benefits are not limited to the end PE or the beginning of secondary education. Manuel Perez-Martin et al. (2022) showed that working with contextualized activities in early childhood education and in different socioeconomic contexts promoted scientific reasoning and increased interest in science equally, with no significant differences based on gender or ethnic origin. Overall, scientific evidence shows that contextualized activities focused on problems or case solving have a positive impact on student learning, especially in vulnerable groups.

While it is true, this research shows that, in general, students in the 2nd cycle PE and those from challenging circumstances have greater difficulty completing the activity. This may be influenced by difficulty finding and critically analyzing information. Furthermore, students are not accustomed to this type of activity or working cooperatively. Consequently, they often ask the teacher for instructions on how to answer each case study question (Ideland et al., 2011). Therefore, it is necessary to systematically carry out this type of activity in the classroom. We must overcome our fear of designing activities on unfamiliar or seemingly difficult topics, such as water pollution by pharmaceuticals, for younger students. The scientific topic, socio-economic context, or level of knowledge of students or teachers cannot prevent this from happening in the classroom. In fact, research shows that students with a low knowledge of socio-scientific topics have more positive attitudes (Stenseth et al., 2016). Additionally, working on regional problems improves students' scientific thinking and increases their sensitivity (Wiyarsi and Çalik, 2019). As previously mentioned, a key aspect to reconsider is when to begin incorporating EE into STEM classrooms. Most research is carried out in secondary education, but it can also be carried out in PE (Fernández-Huetos et al., 2025), even in the 2nd cycle, as evidenced by the results obtained. Regarding changes in pro-environmental behavior, Olsson and Gericke (2016) point out that starting at an early age increases the impact. Although our results indicate that students' STEM performance on this SSI is statistically determined by their academic level rather than by group work or socioeconomic status, it is not easy to predict what will occur in the classroom. This is because other factors, such as the nature of the topic addressed, may play a relevant role in different contexts. In fact, the limited influence of socioeconomic variables and group work could be explained by the overall low level of performance shown by students when solving this type of issue.

In contrast, it has been observed that group work is not necessarily more effective than individual work. In fact, it has been found that in the 3rd cycle PE (RQ1b), students perform better when working individually in both educational contexts. When using maps and combined materials, there are no differences in performance between working individually or in groups (RQ2b, RQ3b). Social interaction between peers can sometimes enhance argumentative skills (Chi and Wylie, 2014), although this is not always the case. In other cases, dialogic discourse causes students to consider how others may perceive them, altering their response patterns (Zohar and Nemet, 2002). When students respond individually, they can reflect without social pressure and based on their prior beliefs (Broderick, 2022), whereas in groups, ideas are contrasted and the reliability of each individual contribution can be questioned (Klaver et al., 2023). Therefore, the desire to belong to a group can influence decision-making (Bader et al., 2023). However, the advantages of working individually or in groups may depend on students' age, the topic, each classroom's internal dynamics, and the skills students have acquired and can share with their peers. This is because creating a culture of cooperative work in the classroom requires a combined effort on group cohesion, teamwork as content, and cooperative groups as a teaching resource (Slavin, 2014).

In short, although educational research supports the need to work on scientific practices and EE through real, contextualized problems at different educational levels and in different contexts, its implementation in classrooms is still limited. This situation highlights the discrepancy between the recommendations in specialized science education literature and teaching practices (Högström et al., 2024; Pérez-Martín et al., 2025). Many teachers have not yet incorporated the STEM approach or SSIs into their classes. However, once they learn about these approaches, they view them positively because they recognize the clear benefits for student learning. For instance, consider the development of creative thinking around renewable energies (Tasyani et al., 2025) or inquiry-based learning (Manuel Perez-Martin et al., 2022). Similarly, future science teachers who receive specific STEM and SSIs training tend to rate these methodologies favorably because they consider them teaching models tailored to real-life demands with high interdisciplinary potential (Bozkurt Altan et al., 2018). Conversely, students have a positive perception of integrating STEM into EE. They point out that it improves their understanding of environmental issues and increases their interest in the environment, encouraging changes in their habits (Çürük and Yıldırım, 2025).

For these reasons, we believe that teacher training is key to improving EE teaching and promoting the incorporation of SSIs and the STEM approach in classrooms, both at the initial university level and in the continuing education of practicing teachers (Rivero and López, 2020). Teachers must understand that these practices are not a waste of time and do not prevent them from meeting the requirements of the curriculum. On the contrary, these practices strengthen competency-based learning by integrating the skills, knowledge, and abilities included in the curriculum. In this way, it will be possible to reduce the aforementioned gap and bring research closer to educational practice in the classroom.

5 Conclusion

The results of this study demonstrate that an approach combining SSI and STEM education can effectively incorporate EE into the classroom with a transformative approach. The activity is designed around solving a case study on water pollution caused by pharmaceuticals. This allows students to make connections between different disciplines, such as science and mathematics, while presenting them with a real environmental problem relevant to their context. Thus, this approach enables students to develop scientific reasoning and argumentation skills. Furthermore, the findings support the view that the essence of the STEM approach does not lie in covering a certain number of disciplines or exclusively carrying out practical or technological activities, but rather in creating interdisciplinary and contextualized learning experiences that promote the development of scientific and mathematical competence, which are fundamental for critically addressing real-world problems.

Therefore, PE students in this study have shown:

- An intermediate level of performance in the use of graphs, which does not improve with group work and even worsens (RQ1).
- An intermediate level of performance in the use of maps, which does not improve with group work (RQ2).
- A low level of performance in the use and processing of materials from different semiotic modalities, which does not improve with group work (RQ3).
- Among the factors analyzed (academic level, type of educational context, work modality), academic level is the determining factor in students' performance (RQ4).

For all these reasons, we believe that this activity promotes scientific and environmental education and lays the foundations for improving the teaching of how to use graphs and maps in real-life contexts.

5.1 Limitations and educational implications

Despite the positive results obtained, some limitations should be noted and addressed in future studies:

- It is important to bear in mind that this study was conducted in only one geographical region (Madrid) and on a specific SSI (water pollution caused by pharmaceuticals), so the results cannot be generalized in any context.
- Students' performance was medium to low; therefore, it would be advisable to extend the analysis by including additional questions that allow for a reassessment of performance differences across socioeconomic contexts and between individual and group modalities.
- Students were not provided with common guidelines on how to work effectively in groups; instead, they relied on their prior experience. It might be beneficial to include a preliminary session on how to work cooperatively.

In terms of practical implications, all educational schools, regardless of their socioeconomic context, should promote a greater number of activities based on SSI that require the use of maps, texts, graphs, and a combination of different materials, thereby encouraging critical selection of information and the establishment of relationships. It would also be advisable to offer complementary training to teachers aimed at designing this type of interdisciplinary proposal, moving away from the exclusive use of traditional textbooks.

Finally, in terms of implications for future research, it is necessary to propose and validate activity designs based on scientific practices and SSIs that can be implemented in the classroom. These designs should share common elements, such as the promotion of scientific skills, the use of materials in different semiotic modalities, and the development of argumentation. In this way, even when dealing with activities linked to different topics, it would be possible to comparatively evaluate the performance and scientific skills of students. It would also be interesting to replicate the study in other geographical areas of Spain and at different educational stages, even considering the possibility of differentiating by age rather than by cycle. Likewise, future work could incorporate longitudinal studies that allow for the monitoring of students exposed to this type of activity from an early age, in order to analyze their progression and compare their achievements in the final years of primary education. This would allow us to better evaluate the effectiveness of these interventions and refine our teaching methods.

Data availability statement

The original contributions presented in the study are included in the article; further inquiries can be directed at the corresponding author.

Ethics statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Universidad Autónoma de Madrid (protocol code CEI-137-2954, and date of approval 14 March 2024). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

NF-H: Project administration, Visualization, Formal analysis, Validation, Data curation, Writing – review & editing, Writing – original draft, Conceptualization, Investigation. JP-M: Writing – review & editing, Funding acquisition, Formal analysis, Validation, Supervision, Conceptualization, Investigation. TE-M: Investigation, Validation, Writing – review & editing. IG-H: Conceptualization, Investigation, Writing – review & editing, Validation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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