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Research article

Promoting interdisciplinary connections in STEM education: A study with preservice chemistry teachers

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Abstract: Integrated science, technology, engineering, and mathematics (STEM) education is essential for preparing students to address real-world challenges through interdisciplinary thinking and problem-solving. However, preservice teachers (PSTs) often face challenges in integrating STEM disciplines, particularly engineering, technology, and mathematics. This study explores how Arduino-based problem-solving activities enhance interdisciplinary STEM integration in PST training, focusing on the epistemological, psychological, and didactic dimensions of STEM education. Conducted within a chemistry teacher training course, the study involved eight PSTs in theoretical and practical activities, including designing experiments on ocean acidification. The findings reveal that Arduino-based activities effectively foster interdisciplinary connections by integrating chemistry with technology and engineering while bridging theoretical knowledge and practical applications. Persistent challenges, such as limited mathematics integration and familiarity with engineering concepts, highlight the need for targeted interventions in teacher training. This study underscores the potential of problem-solving and technology-enhanced approaches to equip teachers with the skills to design and implement interdisciplinary STEM lessons, preparing them for the demands of 21st-century education.

Keywords: integrated STEM, problem-solving, Arduino-based, chemistry education, preservice chemistry teachers

1. Introduction

The Science, Technology, Engineering, and Mathematics (STEM) approach is recognized for its potential to equip students with essential skills for a technologically advanced and interconnected world. By fostering interdisciplinary thinking, STEM education connects knowledge across subjects, preparing students for real-world challenges and promoting the development of critical skills such as creativity, problem-solving, and collaboration. As society increasingly relies on technological and scientific advancements, the ability to integrate these areas becomes a fundamental component of education. In integrated STEM education, at least two STEM subjects are combined, integrating engineering practices, using relevant technologies, and linking content to a real-world context and/or problem within a single lesson [1–3]. This approach not only enriches the learning experience by making it more engaging and relevant but also helps bridge the gap between theoretical concepts and their practical applications. Moreover, integrated STEM activities can be an effective way to encourage students to see the connections between disciplines and understand how these skills apply to real-life problems.

However, implementing integrated STEM education involves challenges, particularly for educators. Teachers must not only master the content of individual STEM disciplines but also develop pedagogical strategies that encourage interdisciplinary thinking. Given the traditional separation of subjects in teacher training, developing the capacity for integrated teaching requires targeted professional development. To increase the use of this teaching approach in schools, by integrating two or more of the STEM areas into the same lesson or activity [2], special attention should be paid to teachers' initial training [4].

Recognizing these challenges, this study aimed to analyze how future chemistry teachers engage with problem-solving laboratory activity using Arduino and generative artificial intelligence (GAI) systems. By examining this specific context, the study seeks to provide insights into the implementation of integrated STEM education and how teacher training programs can better prepare educators for interdisciplinary teaching.

2. Literature review

The perspective of implementing the STEM proposal for education has historically involved a broad discussion of the objectives of including these disciplines in an articulated manner in the curriculum. As described by different authors, STEM education is not a reform movement independent of others, but one that brings complementarity and the intention of developing knowledge with students for work in areas that include STEM disciplines [5]. In this way, different authors bring discussions about ways to integrate STEM disciplines and proposals for activities included in the curriculum [6].

The literature identifies different approaches to designing the objectives of STEM education [7]. There are approaches that focus on improving knowledge in the disciplines, particularly through student engagement and working to awaken interest in STEM careers, as well as the development of diverse skills such as creativity and problem-solving [8,9]. These perspectives have in common the idea of integrating conceptual domains while respecting the epistemological characteristics of each discipline [10].

STEM education is often applied through practical, laboratory, and/or project-based activities

[11–13]. Such integration can contextualize learning and introduce real-world problems enhancing STEM teaching [14]. Research points to the positive effect of integrated STEM teaching on students' problem-solving skills, scientific creativity, and critical thinking [15,16].

Integrated STEM activities can also increase students' interest in science by showing how it relates to other areas of knowledge and to real-world problems [2]. In addition, interdisciplinary and integrated STEM approaches contribute to the construction of interdisciplinary and integrated knowledge and, for this reason, should take place in the traditional and routine teaching and learning activity of schools [17].

Despite these benefits, implementing interdisciplinary STEM teaching presents significant challenges for educators. Future teachers, in particular, often face difficulties when engaging with more integrated teaching methods [18,19]. For example, during an engineering education with single board computers (SBCs), future teachers face significant challenges, including a lack of experience with engineering concepts, difficulties in integrating chemistry and engineering content knowledge, and the need for better project management skills [11]. Additionally, there are teachers who find it difficult to give examples of STEM approaches integrated into chemistry due to their limited experience in the field [20].

Several studies are showing that incorporating engineering practices or SBCs, such as Arduino, fosters greater student interest in STEM subjects while simultaneously equipping teachers with practical skills for delivering integrated content [11,21,22]. The inclusion of projects involving SBCs (e.g., Arduino) in initial teacher training offers an opportunity to improve understanding of the integration of engineering into chemistry teaching [11]. In addition, the integration of technology and innovative pedagogical strategies have the potential to improve chemical knowledge among future teachers [23–26]. The integration of engineering practices in STEM teaching, especially using tools like Arduino, offers a practical approach to overcoming interdisciplinary challenges. However, there are barriers related to the knowledge required to use this technological resource [26].

In this sense, working with modules on the use of Arduino in specific courses for teachers is a necessary action for teachers to use this resource. Since this interface requires knowledge of programming, another challenge is faced that can currently be overcome with the use of GAI systems. The literature has pointed out numerous uses for GAI in educational contexts [27–30]. As it is a recent technological resource in the educational field, it is also essential for teachers and future teachers to understand it in didactic contexts. In this sense, in the research proposal, we consider work with GAI systems as a technological resource with the aim of understanding the obstacles, challenges, and learnings faced by preservice teachers (PST) in the integration of Arduino and GAI in a STEM context involving chemistry laboratory practices during initial training [11].

Research shows that for PSTs, engaging with STEM learning activities has been linked to increased motivation, confidence, and enthusiasm in designing and implementing interdisciplinary lesson plans [31]. These findings underscore the importance of targeted teacher training programs designed to address such challenges and build interdisciplinary competencies. Furthermore, professional development programs enriched by skills-based STEM models have been shown to enhance STEM self-efficacy and enable PSTs to create effective STEM activity sets for classroom use [2,4,31,32], bridging the gap between theoretical knowledge and practical application, a critical component of teacher training [33].

Building on the aspects discussed, STEM education calls for a cohesive interplay between disciplines, framed within an interdisciplinary perspective. This perspective emphasizes the integration and development of knowledge across STEM fields, and a possible effective STEM framework is built on three key dimensions: epistemological, psychological, and didactic [33]. The epistemological dimension focuses on addressing empirical problems encountered in daily life, requiring scientific explanations. Despite unique approaches across STEM disciplines, commonalities in problem-solving methodologies enable their integration. The psychological dimension emphasizes fostering connections between prior knowledge, new concepts, and evolving representations, creating meaningful learning experiences. The didactic dimension supports these through strategies such as inquiry-based, experimental, and socio-scientific methods, addressing misconceptions and promoting deeper understanding [2]. Together, these dimensions bridge the gap between theoretical knowledge and practical application, a critical component of teacher training [33].

The relevance of this framework is further supported by recent studies in the field of integrated STEM education. Rumjaun et al. [34] emphasize the importance of interdisciplinary approaches, highlighting the need to balance disciplinary expertise with cross-disciplinary applications. Their study identifies STEM education as a critical tool to prepare students for complex, real-world challenges, reinforcing the epistemological dimension by showing how shared methodologies can address empirical problems effectively. Similarly, Baptista et al. [35] explored the role of explanations in integrated STEM education (I-STEM), analyzing how students solve interdisciplinary challenges. Their findings show that most students provide descriptive or relational explanations, often failing to integrate knowledge from all STEM disciplines. However, exemplary responses, which align closely with the psychological and didactic dimensions, demonstrate intentional and explicit mobilization of conceptual knowledge and processes across all fields. Baptista et al. [35] concluded that deliberate pedagogical strategies are essential for helping students to synthesize interdisciplinary knowledge, supporting the idea that the didactic dimension plays a crucial role in addressing misconceptions and fostering deeper understanding. By integrating insights from these studies, the three key dimensions framework gains further relevance as a robust model for guiding STEM education practices. The emphasis on interdisciplinary approaches, meaningful learning, and targeted pedagogical strategies underscores its potential to bridge the gap between STEM theory and practice, effectively preparing educators and students for the complexities of modern challenges.

Other work proposals also investigate and propose integration tools, considering other axes. Ortiz-Revilla et al. [33], in their proposal for the integration of STEM disciplines in the epistemological, psychological, and didactic axes, also mentioned the need to think about theories, methods, and aims. Other works postulated other axes that can be considered in the construction and analysis of proposals and that, in our understanding, align with this work. Work dimensions such as "design thinking in authentic contexts, content integration, STEM practices and 21st century skills, and exposure to professional practice" [36] and proposals that present tools with greater flexibility and considering different factors are also reported and can be considered in different contexts [37].

Considering the work already developed and the theoretical perspective of the different axes mentioned above, it is important to develop and investigate practices that seek to develop knowledge about the different disciplines and enable future teachers to try to integrate them. One approach in this direction is to promote courses involving didactic approaches/pedagogical practices and specific technologies aligned with the development of STEM literacy.

Some studies have shown that practices that involve real or simulated problems and strategies that aim toward active participation have promoted greater development in the field of STEM education [38–40]. The problem-solving teaching approach can, in this sense, enable students to develop skills focused on creativity, critical thinking, and planning and can, therefore, mobilize content from different disciplines in an integrated manner. This approach engages students in real-world challenges, requiring them to mobilize content from various fields to develop comprehensive solutions. Through this process, students enhance their ability to analyze complex problems, apply interdisciplinary knowledge, and collaborate effectively, preparing them for dynamic and interconnected challenges [41,42].

The reviewed literature highlights the critical role of integrated STEM education in fostering interdisciplinary competencies, problem-solving abilities, and engagement with real-world challenges. Frameworks such as the one proposed by Ortiz-Revilla et al. [33], emphasizing epistemological, psychological, and didactic dimensions, provide a robust foundation for designing effective STEM practices. Additionally, studies underscore the importance of active, problem-based, and technology-enhanced strategies, such as those incorporating Arduino and artificial intelligence (AI) systems, in addressing the complexities of interdisciplinary teaching and equipping future educators with practical tools for implementation.

Considering technology as one of the STEM disciplines, it is important to think about teacher training strategies that use diverse technological resources so that this component can be developed and integrated into other disciplines. In this sense, some works involving prototyping systems with Arduino have been reported. Among these are works that aim at the use of constructed resources and works with reflection on the possibility of implementation as future teachers [25,43,44]. In this sense, it is important to include and investigate how conceptual domains of technologies are learned by future teachers and integrated into other STEM disciplines.

However, despite these advancements, significant challenges persist, particularly in preparing PSTs to integrate disciplines effectively while managing technological and conceptual barriers. These gaps underscore the necessity of targeted interventions that bridge theoretical knowledge and practical application, ensuring that teachers are equipped to embrace the full potential of STEM education.

2.1. Objectives and research questions

The objective that drives this study is to investigate how Arduino-based problem-solving activities, supported by GAI systems, can enhance interdisciplinary STEM integration in preservice chemistry teacher training, through the epistemological, psychological, and didactic dimensions.

To achieve this, the study is guided by the following research questions:

1. How can Arduino-based problem-solving activities support the integration of technology, engineering, and mathematics into preservice chemistry teachers' STEM teaching practices?
2. What barriers do preservice chemistry teachers face in effectively integrating STEM disciplines, particularly in connecting chemistry with engineering, technology, and mathematics?

3. Methodology

3.1. Context and research design

For this research, data were collected during a didactic intervention inserted in an undergraduate chemistry course for training chemistry teachers in a Brazilian university. The entire course is 60 hours long and is divided into 15 classes of 4 hours each. Different topics are covered in the course, including the origin and evolution of digital technological resources and different technological resources for chemistry education. The didactic intervention for this research involved five classes (20 hours). Activities were carried out individually and in groups of four students.

This research is characterized as a qualitative study and from the perspective of a case study, understood from the approach that is justified by its constructivist epistemological conception, aligned with the objective of this work to understand interpretations regarding the use of technological resources and the ability of subjects to carry out designs using new knowledge [45]. In this qualitative approach, we sought to collect the data through instruments that allowed content analysis, understanding the limitations of a qualitative approach but recognizing the potential that the practice developed can generate, with the didactic action itself and the possible understandings of the subjects being the results of the research.

3.2. Participants

The group of PSTs participating in the research was composed of three women and five men between the ages of 20 and 23 participating in the discipline and, therefore, in the investigation. They were enrolled in the last year of an undergraduate teacher training chemistry course. The discipline in which the research took place was created in 2022, which is recent. Therefore, there is still a low number of students who need to take it.

In other parts of the course, students had contact with a few subjects involving educational technologies. However, they had already studied topics on learning assessment and teaching methodologies. Participants also had previous contact with content from chemistry, physics, and mathematics. In Brazil, the teacher training course lasts four years, and the participants in this study are in their final year. All participants signed the informed consent form, a requirement of the research ethics committee, registered under the code CAAE 79480924.7.0000.5404.

3.3. Classes and data collection instruments

In this work, we explored the data that originated from the following classes: Class 1 – STEM education (one theoretical class); Class 2 – use of Arduino and AI systems (one theoretical class); Classes 3, 4, and 5 – use of Arduino and GAI systems and experimentation in chemistry education (three practical classes). Before the first class of the course, the PSTs were asked to answer a questionnaire about their knowledge and use of the different technologies covered in the course (diagnostic questionnaire – Q1). After the intervention, the PSTs were asked to answer a questionnaire containing questions about the understanding and integration of STEM disciplines (Q2). Table 1 describes the activities carried out by the PSTs and the data access instruments used in the research. The activities and materials are detailed below, and the entire protocol is available in the supplementary information material.

Table 1. Description of activities, tasks performed, and data collection instruments.

Class	Description of activity	Tasks performed by teachers in training	Objectives
Prior to Class 1	Diagnostic questionnaire on knowledge of and contact with course contents (Q1)		Analyze previous knowledge
1	Reading and discussion of articles on Arduino and the STEM proposal. Theoretical conceptualization of the STEM proposal and discussion of works that implemented experiments focusing on the STEM perspective.	Text with critical analysis of STEM education. Material analyzed in the research: Text 1 (T1) produced by PSTs	To develop and identify STEM and technological knowledge.
2	Reading and discussion of articles on the use of Arduino and AI systems in education and discussion of works that implemented these technologies in teaching or research on the teaching of chemistry.	Text with critical analysis about the use of Arduino and AI systems in the teaching of chemistry. Material analyzed in the research: Text 2 (T2) produced by PSTs.	
3	Assembling systems with LEDs, temperature and pressure sensors, using AI systems. (material provided: personal notebook; various glassware (Erlenmeyer flasks, beakers, Kitasatos); Uno R3 board with a USB cable; Breadboard; red LEDs, resistors of different values up to 220 Ω; male-to-male/male-to-female jumpers; temperature, humidity, and DHT11 sensors; MQ-135 gas pressure sensor)	Preparation of a document including the experimental description prepared and the codes used. Proposal of an experiment to study the topic of ocean acidification.	To develop and analyze STEM contents and their integration by PSTs
4	*Development of an experimental didactic proposal involving the topic of ocean acidification. *Assembling circuits involving various sensors. *Adjustments to the experimental system and carrying out tests. (material provided: all the material of Class 3; BME280 temperature and pressure sensors; standard solutions at pH 4.0, pH 7.0, and pH 10.0; pH sensor module sensor kit – pH 4502 C)	*Preparation of a document including the experimental description prepared and the codes used. Preparation of a STEM concept map.	To develop and analyze STEM contents and their integration by PSTs.
5	*Adjustments to the experimental system and carrying out tests. Debate on the possibilities of the proposal in relation to STEM education.	*Finalization of the document containing the experimental description prepared and the codes used. Improvement of the STEM concept map. Material analyzed in the research: concept map produced by PSTs.	
Post class 5	STEM discipline questionnaire (Q2)		To develop and analyze STEM contents and their integration by PSTs and recognize their perceptions of the activity.

* Activities carried out in groups of four students

With a focus on theoretically grounding future teachers about the conceptualization of STEM education, in Class 1 the PSTs read two articles involving STEM education, and a discussion about the origins, definitions, potentialities, and limitations was promoted in the classroom and coordinated by the teacher of the course. The PSTs produced a critical text presenting the main ideas about STEM education after the class (T1). In Class 2, the PSTs read two articles about the use of Arduino and GAI systems in teaching chemistry, and a theoretical discussion about the definitions, potentialities and limitations of the use of these resources was developed, then the PSTs produced a text analyzing the articles (T2).

To support a smooth transition from theory to practice, the chosen texts were selected not only for their conceptual value but also for their practical relevance. The classroom discussions aimed to ensure that PSTs understood the pedagogical and technical specificities of Arduino and GAI tools, including how they function and how they could be integrated into chemistry teaching. Moreover, these sessions were structured as a scaffolded learning process: the reading, followed by critical and analytical writing (T1 and T2), served to consolidate the PSTs' understanding and prepare them for the experimental stage.

The practical classes (3 and 4) were developed in a teaching laboratory. In Class 3, the PSTs were provided with the materials mentioned in Table 1. Initially, an explanation of the Arduino operating structure – the different inputs and outputs, power supply, connection to the computer via cable, the protoboard, and the Arduino software (IDE - Integrated Development Environment). During the explanation on how to generate and upload the codes, an explanation was introduced on how to create codes using GAI tools, particularly the free version of ChatGPT. After this stage, the PSTs were asked to assemble a system involving a flashing LED and one of the sensors (either the DHT11 or the MQ-135).

In Class 4, all materials were made available, and PSTs were required to create an experimental setup that could be used in a basic education teaching context to study the influence of the presence of atmospheric carbon dioxide on the acidity of river and ocean waters. The experimental design and the generated code were recorded in a text document. In the fifth class, the PSTs had time to improve, test and finalize the experimental setup.

These three classes (3 to 5) aimed to make the PSTs face the challenge of manipulating technological resources through investigation and problem-solving. In Class 3, the PSTs were able to understand the basic concepts of how Arduino works and how to generate scripts/codes using the GAI system. In this class, a simple experimental setup was also carried out so that the PSTs could familiarize themselves with the tools. In Class 4, the problem-solving approach was introduced, involving aspects related to the experimental setup and to the didactic context. In this way, the experience of this activity could make PSTs familiar with the technological resources through problem-solving, a pedagogical practice that, in this case, was being used to mobilize their professional knowledge. Furthermore, in the fourth and fifth classes, the students were faced with the problem of thinking of an experimental proposal that could be used to teach a chemistry topic involving a real problem. In this way, the aim was to mobilize knowledge from different STEM disciplines and, within the perspective of problem-solving, pedagogical intentionality.

3.4. Data analysis

The materials analyzed in this investigation to understand how the integration between STEM disciplines occurs consisted of questionnaires (Q1 and Q2), texts produced by the PSTs (T1 and T2), the final questionnaire about the practice carried out, and the concept maps. The final questionnaire contained questions about the understanding and integration of STEM disciplines, and the concept maps were used to obtain an overview of the concepts raised by the PSTs regarding each discipline and with them to demonstrate the relationship between these concepts.

The documents were analyzed using the content analysis (CA) technique of Bardin [46] and MAXQDA Pro software version 24.0.0. Through this analysis, we sought to identify concepts that the PSTs associated with each of the STEM disciplines, the relationships among them, and what declarative knowledge the PSTs reported having understood through the activity, considering the integration references.

The content analysis was performed by considering the reading and re-reading of the PSTs' responses and the establishment of prior and post categories. That is, for the materials produced by the future teachers in all five classes, we sought to identify elements of the three axes highlighted by Ortiz-Revilla et al. [33], which consisted of a priori categories. The pedagogical axis was associated with aspects focused on the listed teaching and learning methodologies; the psychological axis was related to contextual aspects; the epistemological axis related to aspects directed at the origin of the concepts and the nature of the knowledge of each discipline. We chose to create emerging subcategories, according to the responses obtained. The analysis units are characterized by fragments of the associated responses that represent the meaning of a given category. Thus, this study is characterized as a case study, with qualitative analysis involving mixed categories [47,48].

In the same way as the answers to the questions, the emerging concepts in the maps were also analyzed by unitarization and associated with emerging categories. In addition, the connections among the concepts in the map were observed and analyzed in order to create interpretations that could suggest the integration of different disciplines, supported by the answers to the questions.

The validation of the units of analysis and the emerging categories was carried out by peers – that is, the process was read by another researcher in the area and, after the analysis, some units of meaning were adjusted. In general, there was coherence and validation of the initial analysis. The validation process followed the assumptions of content analysis based on a qualitative analysis [48]. The answers to the questions in the final questionnaire are shown in full and in the form of raw data in the supporting material, with all of this material being analyzed using MAXQDA software.

4. Results and discussion

With the dataset, we decided to begin the analysis by interpreting the concept maps presented by the PSTs to have an overview of the concepts associated with each discipline and how the PSTs related them. Following the analysis of the maps, we present the categorization of the documents considering the axes mentioned in the methodology and the subcategories.

It is important to highlight that with the data, we sought to understand how a proposal for a training activity involving theoretical and practical discussions can help in the integration of knowledge of the different STEM disciplines for teachers in training and what barriers and limitations are encountered. It is worth noting that the context involves PSTs who had already had contact with different chemistry contents and with pedagogical proposals. However, these PSTs came in contact with educational technologies in the training course for the first time.

4.1. Diagnostic questionnaire

Initially, in the diagnostic questionnaire, all PSTs stated that they did not know about STEM education. Regarding the use of Arduino, only one PST had knowledge of how to use this resource; four PSTs stated that they recognized the term but did not know how to use it, and three stated that they did not know this resource. About Arduino, none of PSTs indicated that they had used it in their tasks. They also stated that they use GAI systems to search for information, carry out searches, and assist in various tasks such as summarizing texts, planning routines, planning classes, etc. Table 2 shows the responses regarding Arduino and about the use of AI systems.

Table 2. Responses about Arduino knowledge and use of AI systems.

Arduino knowledge
I have no knowledge about Arduino.
As I studied industrial automation, I used several Arduinos and programs for industrial problem situations, so I have already had contact with the microcontroller.
I don't know how to assemble it and I have never used this type of tool, but I know that it is related to the area of robotics and computing.
I used it once, but I don't remember, and I don't remember what it is.
I know little about Arduino; I don't know how to describe its functionality well.
I have never heard of Arduino.
I don't know about it.
I don't know. I have only heard about it and it seems to be something related to programming.
Use of AI
I have used it to search for sources, ask questions, and brainstorm ideas to carry out some activities that I was unable to start.
I have used ChatGPT to help me increase or reduce the size of texts and to provide me with step-by-step instructions for something, and I used the Canva image generator for research purposes.
Yes, I have used it for lesson planning, innovation in activities, and resources that I can use in class; writing documents or messages; and understanding how artificial intelligence works.
Yes. I have used it to obtain information from different perspectives than those found in the literature.
Yes, I have used it for quick and specific research purposes, as well as for filtering information.
Yes, I currently use ChatGPT PRO. With it I have had support in building spreadsheet formulas, reading and writing assistance, and generating images.
Yes, I have used it to help me determine the topic I needed to research about and divide into topics
Yes, it helps me with developing texts, resolving issues, answering questions and planning activities.

As can be seen in the responses, Arduino, despite being a resource that has been used in different teaching projects in different areas, is still little known and used by the group of PST subjects in this research, even though this resource is not recent. GAI systems, on the other hand, have been used in the subjects' daily lives, possibly due to the wide dissemination of some platforms and due to their easy access. However, the uses do not have a direct focus on teaching or derived actions, which is possibly also a reflection of the contemporaneity of this technology.

This information is important because although the PSTs had had contact with teaching proposals and methodologies previously, they had not had contact with STEM education, were not familiar with Arduino prototyping, and made various uses of GAI systems but not with a focus on the activity that would be developed. Therefore, the activity would be the PSTs' first contact with different fields of knowledge. This fact may be one of the difficulties encountered in the articulation between areas, namely the objective of the practice.

4.2. Concept map analysis

For the concept maps, PSTs were requested to identify the concepts associated with the STEM disciplines, and more focus was requested on technology, engineering, and mathematics. The concepts related to chemistry (pH, acidification of the oceans, and chemical equilibria, among others) were identified during the classroom when the context of acidification of the oceans was presented.

The objective was to identify concepts within the disciplines and the relationships that were established between them. The concepts were also considered in the content analysis, but we sought to use the maps to verify that there was no isolated content, which could indicate a lack of connection.

After a discussion about the possible effects of carbon dioxide on ocean acidification and the survey of possible concepts to be worked on in chemistry teaching, a concept map was presented to the PSTs (present in the teaching protocol), and the students were asked to try to make connections among the concepts related to the disciplines of technology, engineering, and mathematics. With this, we sought to promote the reflection of PSTs on the areas that are the most difficult to integrate, as reported in the literature.

The maps revealed a set of concepts related to the disciplines and one could also observe the connections that the PSTs make. Table 3 illustrates the different concepts emerging from the maps, including concepts isolated in one area and those that appeared to be linked to more than one area.

Table 3. Emerging concepts in technology, engineering, and mathematics disciplines after the activity.

		Technology	Engineering	Mathematics
Terms cited on the map	Programming and scripts	X	X	X
	Sensors and hardware	X	X	
	Arduino	X	X	
	Data processing		X	X
	Experimental design*		X	
	Artificial intelligence/ChatGPT	X		
	Graphics and tables			X
	Logarithm			X
	Henry's law			X
	Concentration			X

* Term associated with the arts in some of the concept maps.

It is noted that the term “programming and scripts” occurred in common for engineering, technology, and mathematics. The terms “sensors and hardware” and “Arduino” appeared for both technology and engineering, and “data processing” was associated with engineering and mathematics simultaneously. The term “ChatGPT and artificial intelligence” occurred specifically for technology. Despite it being associated with programming, due to its recurrent occurrence, we chose to highlight it as an item in its own right. In all maps, “experimental design” occurred in association with engineering and for mathematics. Some specific concepts were identified and can be associated with tools used in chemistry, such as calculations of “concentration”, “logarithm” (for calculating pH), and “Henry's law”, which is represented by a mathematical expression that relates the pressure of gases with the concentration of the same dissolved in a liquid. Figures 1 and 2 represent two examples of concept maps prepared by the PSTs.

Specifically for technology, the terms “sensors” and “programming and codes” were cited frequently. The association of technology and engineering with science topics occurred through the use of sensors for measurement and through experimental planning. Mathematical concepts emerged less frequently and were associated with data processing, graphics, and programming.

In the context of this research, concept maps are important because they reveal which concepts the PSTs associate with the proposal developed in the training. These concepts are fundamental for understanding how the different disciplines are understood by students in epistemological terms, that is, how students observe the presence of knowledge from STEM disciplines and how they relate these different concepts. However, we noticed some terms that still appeared without many connections or were not very expressive for a more integrated proposal. For example, the terms “glassware systems” connected to engineering, “acids and bases” connected to chemical concepts, or “greenhouse effects” associated with ocean acidification, although they may be part of the general concepts associated with different disciplines, seem to be “loose” on the map. Therefore, the analysis of the other documents, through categorization, sought to deepen this interpretation and is presented below.

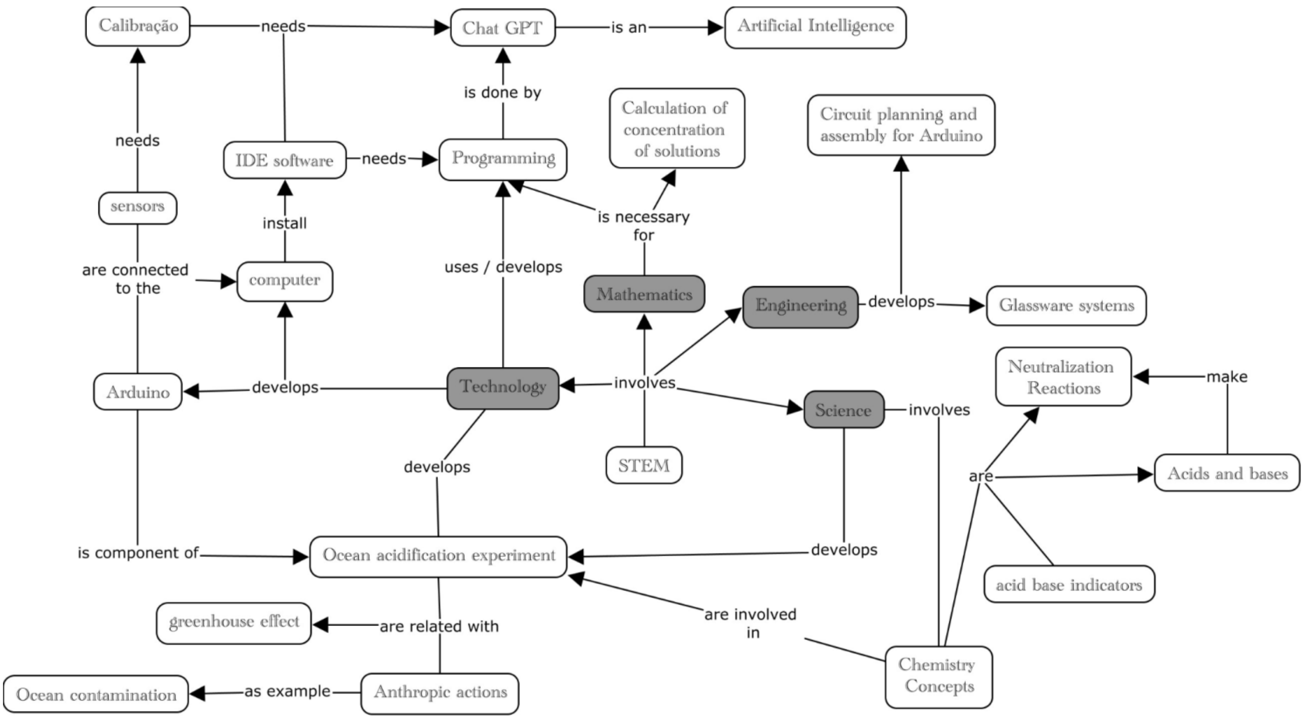

Figure 1. A PST's concept map indicating the terms associated with the activity.

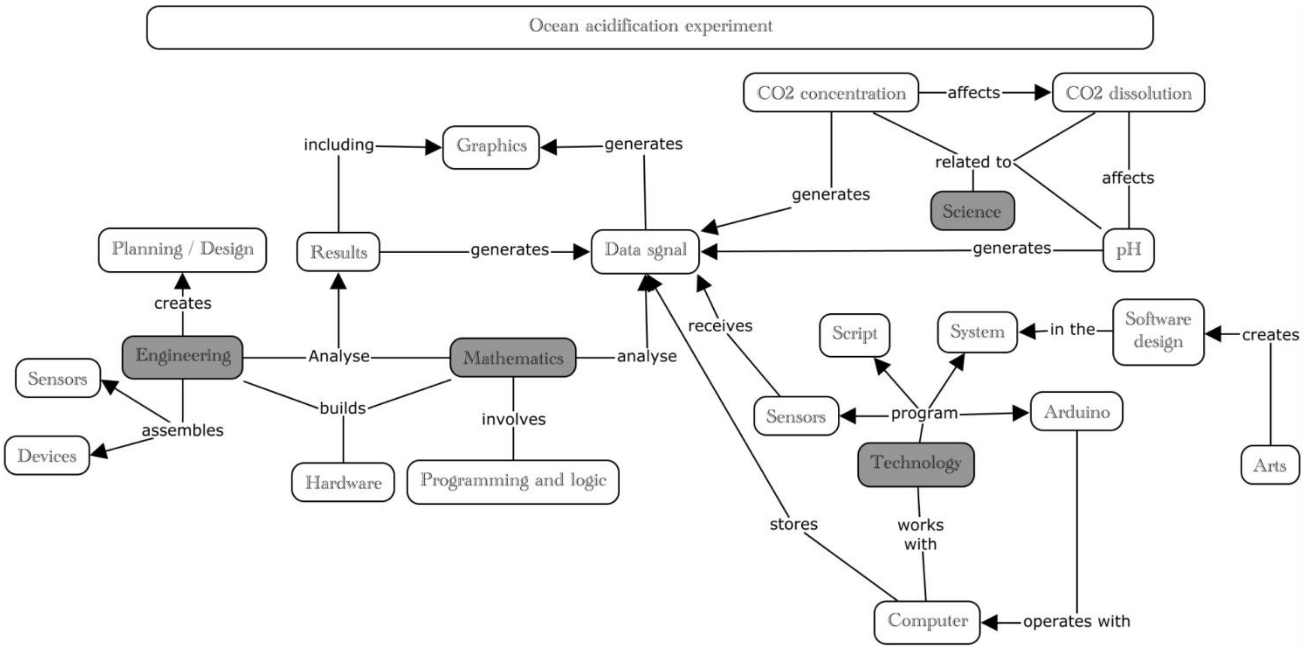

Figure 2. A PST's concept map indicating the terms associated with the activity.

4.3. Categorization of documents prepared by PSTs

As previously mentioned, we analyzed the documents T1 and T2, the questionnaires, and the concept. We sought to try, through the analysis of the materials, to interpret the units of meaning that can provide information on how the PSTs associated the concepts related to the different STEM disciplines. Considering our references, we sought to identify aspects related to the pedagogical, psychological, and epistemological axes [33]. In the epistemological axis, it is considered that there are specificities in the knowledge in different areas but although there are epistemological differences in the type of problems solved in science, engineering, mathematics, and technology, it is recognized that there are common points between scientific problems and connections between the concepts. For example, when we approach a problem whose solution involves testing hypotheses associated with an experimental process, the practical thinking may involve aspects of chemical science and experimental planning, control of variables/commands (scored in the area of engineering). In this way, it is also possible to associate aspects of technology that could provide support in this case.

The psychological axis considers that a variety of situations foster the construction of knowledge in a STEM proposal, and the pedagogical axis is related to different approaches (investigative, experimental, and socio-scientific, for example) that aim to overcome epistemological obstacles and mistakes. In our study, the problem-solving approach was designed to intentionally encourage PSTs to seek for ideas and concepts from different disciplines.

During the analysis, we noticed some units of meaning that involved more than one of these categories and, therefore, we created a new category called “integration components”. For the category linked to the epistemological axis, we chose to create subcategories in this axis, considering each of the disciplines because, especially for technology and engineering, many specific units emerged. Another category created was “difficulties and limitations”, since the PSTs pointed out aspects in this direction. Table 4 illustrates the categories and some examples of representative units of meaning. In total, 90 units of meaning were generated.

When interpreting the data, it is possible to highlight that some aspects that are considered problematic in studies with STEM proposals were initially highlighted by the PSTs. Engineering topics are generally seldom reported and related to other disciplines by teachers or students who develop STEM proposals [22,49].

However, it was possible to note that this relationship was established with both technology and science. This aspect may be the result of the construction of the proposal by the students, considering the perspective of a real problem (ocean acidification) and that it was designed for an educational context with an investigative didactic perspective. This scenario of proposal development follows the epistemological and didactic assumptions, which consider that STEM proposals become potentially more assertive when they involve the experimental, investigative perspective and have an approach based on problem-solving [33].

One aspect that should be paid attention is the lack of connections with the area of mathematics. In this case, the proposal's emphasis on experimentation, planning, and context may have generated less attention from PSTs to this area. Thus, in future implementations, the discussion of aspects related to this discipline may be more prominent, seeking to integrate this area as well.

Table 4. Categories C1, C2, C3, C4, and C5; Subcategories SC1.1, SC1.2, SC1.3, and SC1.4; and quantity of meaning units; and description of some units.

Category or subcategory	Description
C1. Epistemological axis (40)	
SC1.1 Math (4)	US1. Quantitative analysis of desired variables; US2. Calibration of sensors; US3. Data interpretation and calculations (such as pH).
SC1.2 Engineering (14)	US4. Engineering to set up the process, thinking about the chemical reactions we want to happen (reaction between carbon dioxide and water) so that the gas will not escape; US5. Construction of the system and correcting the problems that it presented throughout the process. US6. Development of systems that integrated the areas to make the experiment work, that is, the assembly of the glassware and instrument system with the Arduino and its sensors.
SC1.3 Technology (16)	US7. How to use ChatGPT to program, how to use Arduino, how to assemble the Arduino system, how to calibrate the Arduino pH sensor, and how to transfer the data generated by the Arduino to Excel; US8. The use of software such as Arduino and how it can replace conventional devices used, such as a thermometer, for example. US8. Use traditional tools with perspectives and objectives that are different from those we use in everyday life, for example, the use of ChatGPT to provide codes to use Arduino correctly. US9. Use of equipment and software, such as Arduino, Excel, and ChatGPT, opening up the possibility of quantitative analysis of the desired variables.
SC1.4 Science (6)	US10. Phenomenological aspects with other aspects of chemical knowledge. US11. Various experiments and attempts to generate and store CO_2. US12. Understanding the ocean acidification process.
C2. Pedagogic axis (9)	US13. The multidisciplinary approach enables discussion, construction, and organization of students' thinking, and visualization at the macrolevel contributes to understanding the microlevel. US14. Guiding students towards more reflective, comprehensive learning that is connected to their reality, breaking with traditional fragmented approaches.
C3. Psychological axis (15)	US15. Interdisciplinary aspects help students delve deeper into contextualized and, in most cases, more complex issues. US16. We start from an initial situation and then use the potential of each area to unravel ways of studying the established problem.
C4. Integration components (15)	US17. The proposal for multidisciplinary teaching is demonstrated in different ways in the work, but without having an exactly fixed structure for it to occur; US18. The multidisciplinary approach allows for discussion, construction, and organization of the students' thinking; US19. There is communication among the knowledge to be able to program, interpret data, recognize errors, and assemble the experimental apparatus in a way that is dependent on each other. US20. Engineering was applied for the development of systems that integrated the two previous areas to make the experiment work, that is, the assembly of the glassware and instrument system with Arduino and its sensors. US21. In the field of science, with the objective of forming CO_2, several experiments and attempts were carried out to generate and store CO_2. Since it is difficult to store CO_2, engineering mechanisms were used, which involves finding actions to avoid losing the gas. Later, technology using equipment and software, such as Arduino, Excel, and ChatGPT, opens up the possibility of quantitative analysis of the desired variables and thus developing the objectives of the proposal.
C5. Difficulties and	US22. Mathematics ends up becoming more of a prerequisite than directly integrating with the

limitations (11)	proposal; US23. The students themselves will not realize that they are using knowledge from different areas. US24. Mathematics was the area that would have been least used, possibly involved in the calibration of the sensors and in the calculation of pH.

4.4. Discussion

We understand that STEM education also encompasses other aspects associated with the development of skills and, therefore, we adopt the perspective of problem-solving and interpretation based on Ortiz-Revilla et al. [33], and also with a focus on the STEM learning design principles [50]. This dual focus on problem-solving and interdisciplinary design provides a framework for analyzing how STEM practices can foster meaningful connections across disciplines. Therefore, we sought to bring into this discussion the aspects that we assess to have potentially contributed to the training of future teachers in understanding the STEM proposal based on the formative intervention carried out.

From a more general analysis, it is noted that the idea of multidisciplinarity and communication between disciplines appears in the PSTs' responses as can be seen in US17–US21 (Table 4). This primary aspect is important, since it is necessary to recognize that the STEM proposal does not consist of the individual development of each of the disciplines, but an understanding of how the integration of areas occurs [51].

These units about how the PSTs understand the integration of areas makes it possible to infer that there was, in addition to an individualized view of the concepts within each discipline (see the conceptual maps), a view of complementarity, which is a central aspect of an interdisciplinary perspective [50]. This complementarity aligns with findings in the literature that emphasize the need for explicit connections across disciplines to build an integrated STEM perspective [52].

As has already been pointed out, knowledge of the different disciplines is necessary for the integrated view of STEM knowledge for teachers [52]. Therefore, training and explicit work with the concepts of the different disciplines are important, and this was the aim of the didactic approach. To this end, the classes aim to explore the concepts of technology and experimental design and, through a problem-solving approach, provide connections between these concepts and scientific content by using a real problem in a didactic situation. This approach not only reinforces interdisciplinary connections but also enhances PSTs' engagement by grounding STEM education in real-world challenges.

Considering the activity and the results, in the epistemological axis, the two disciplines with the greatest difficulty in developing concepts, engineering and technology, were highlighted by the PSTs [21,53]. The terms associated with technology were expected in the results, since the discipline was specifically about educational technologies. However, we emphasize that these occurred in association with other disciplines during the development of the classes. This suggests that targeted interventions can help PSTs overcome barriers in integrating technology with other STEM disciplines.

Since the development of STEM literacy involves knowledge of the contents of specific areas, it is worth noting that units of meaning such as those highlighted in SC1.2 and SC1.3 (Table 4) may indicate that some conceptual domains were understood within the disciplines of engineering and technology, based on the proposed approach. In terms of technology, the PSTs initially indicated that they did not know Arduino tools, or, in the case of the GAI system, they used it for other purposes. However, the practical applications explored in this intervention could help PSTs understand and connect these tools to teaching contexts, a key aspect for developing STEM literacy [50]. Therefore, knowing the concept and understanding its multiple applications is a factor that can contribute to the development of the epistemological axis and, in this way, can contribute to the appropriate use and application of technology [50].

In terms of engineering-related domains, the task of addressing content from this area in teacher training courses can be complex, since it is not content commonly included in curricula. However, a problem-solving approach has the potential to develop aspects of design. We believe that there are contributions to specific aspects of design and engineering practices, which also contribute to aspects of STEM literacy [6].

One specific aspect that we sought to address in this work is the use of GAI systems. Because they are recent but widely disseminated, a body of research has been dedicated to investigating its possibilities in education [29,54–56]. In STEM education, there are possibilities of using GAI systems to improve some aspects of experimental design, which is an aspect related to the critical and reflective use of technology. In our case, using GAI to generate code was something new for the PSTs and helped them face a challenge in using Arduino, highlighted in US7–US9. Another aspect was the approach of PSTs to the programming area, which contains aspects of technology, engineering, and mathematics.

Once we look at how these concepts are considered and inserted into an educational perspective, we notice that the pedagogical and psychological axes sometimes overlap. The idea of interdisciplinarity and multidisciplinarity occurs in the statements of the PSTs, but is associated with the idea of real contexts and problems. Some units of meaning reinforce this fact.

Experiencing teaching strategies throughout training can support the development of professional knowledge in PSTs [57]. In our research, we consider that there is potential for practice involving problem-solving to articulate pedagogical and scientific knowledge (chemistry) with engineering and technology domains. Another answer provided by a PST that corroborates this idea is shown in US20 and US21.

Different authors have also pointed out potential practices in STEM proposals, considering implementation with secondary education students [38–40]. These practices involve case studies, problem-based learning or project-based learning, and predict–observe–explain strategies, among others. It can also be targeted to teacher training, as we present in this work. This experience of training strategies seeking to involve problem-based approaches and contextualization with real problems can help in the development of integrated curricular knowledge, overcoming barriers pointed out for work with STEM education, which involve, in addition to the curriculum, thinking about potential strategies and overcoming the conceptual and pedagogical-methodological domain in addition to enabling critical thinking and the use of technological resources [58–60].

There are still limitations regarding the integrations proposed by the students. Some terms cited in the maps are still fragmented and isolated, and mathematics is still seen as an area that is only instrumental for use in chemistry. The programming logic and questions associated with how it is possible to establish mathematical models for studying the problem, which could have been developed, did not appear.

4.5. Limitations of the study

It is important to highlight some limitations of the study, considering the new implementations and reformulations. We present a proposal that seeks to understand how the integration of knowledge from different STEM disciplines by PSTs occurs in a training course. We emphasize that the number of participants is low, which led us to an analysis with a greater qualitative focus. In this sense, we aimed to describe in detail the didactic protocol and the set of qualitative data. We assess that, as a case study, there are limitations regarding possible generalizations, but we understand that both the didactic protocol and the results of the content of the disciplines and the way in which the PSTs describe the relationship between them, can be useful within the field of STEM education research.

Also considering potential improvements, we note that for mathematics, less emphasis was given by the PSTs. Mathematics as a tool for chemistry concepts was raised by the students, but other epistemological aspects, focused on the deductive logic characteristic, were not mentioned. Therefore, one aspect to be considered in new initiatives would be to focus more on this subject.

Another limitation is the lack of an arts approach. Although it was discussed during classes with the PSTs, this subject was not given any evidence throughout the course. In new implementations, the arts subjects could be considered at times during classes.

We also consider that there are aspects that may lead to possible biases in the responses. Since the PSTs had their first contact with STEM proposals and the use of Arduino systems in this course, it is possible that a positive evaluation is more prominent than the limitations. The prevalence of this positive evaluation can be studied in later studies with the subjects or in other analyses with other subjects participating in the course in future offerings.

We believe that future improvements are not factors that mitigate the promising results, but are rather aspects that allow reflection for the improvement of both the training practice developed and the way of accessing and processing future data.

5. Conclusions

This study investigated how Arduino-based problem-solving activities, supported by GAI systems, can enhance interdisciplinary STEM integration in preservice chemistry teacher training, guided by the epistemological, psychological, and didactic dimensions of STEM education. Through this research, we have addressed two key research questions, offering some insights into the opportunities and challenges in fostering interdisciplinary STEM teaching practices.

The first research question explored how Arduino-based problem-solving activities support the integration of technology, engineering, and mathematics into chemistry teaching. The results revealed that the use of hands-on activities based on Arduino prototyping provided a strategy that has the potential to connect STEM disciplines. PSTs used Arduino to design experiments, engage in programming, and analyze data, addressing real-world challenges such as ocean acidification. This process highlighted the tool's capacity to foster interdisciplinary connections by blending theoretical knowledge with practical applications. Importantly, the activities emphasized engineering and technology, which are often underrepresented in traditional chemistry education, showcasing how Arduino can act as a bridge between these fields and science.

The practice involved the study and use of technological resources not yet studied for education by the PSTs, such as GAI systems, sensors, and experimental design. Aspects of the epistemology of STEM disciplines were worked on with the future teachers, exploring topics in engineering and technology that are the most problematic areas highlighted in the literature. In this sense, the results demonstrated that these approaches encouraged the PSTs to seek concepts from different disciplines in the elaboration of the proposal. Engaging with tasks that required experimental design, data analysis, and programming encouraged reflective thinking and the application of active pedagogical strategies. By emphasizing real-world problems, the activities can support the development of the psychological and didactic axes, helping PSTs move beyond disciplinary silos to embrace interdisciplinary problem-solving.

According to the STEM integration frameworks considered, the understanding of different disciplines can be improved with practices involving real-world problems, didactic aspects, contexts, theories, methods, and aims [33]. Therefore, we sought to think about the didactic proposal involving these different characteristics and identify how the PSTs reported the different connected concepts and seeking to interpret the integration among the disciplines.

The second research question examined the barriers PSTs face in integrating STEM disciplines. Despite the progress observed in connecting chemistry with engineering and technology, challenges persisted in integrating mathematics. The concept maps and materials produced by PSTs revealed that mathematics was often treated as peripheral rather than central to STEM integration. This limitation underscores the need for explicit strategies to help PSTs recognize and incorporate mathematical principles in interdisciplinary contexts. Additionally, the initial unfamiliarity with Arduino and limited exposure to engineering concepts reflected broader gaps in STEM teacher training programs. These barriers align with existing research, which emphasizes the challenges of equipping PSTs with sufficient interdisciplinary expertise.

The results of this study lead us to reflect on the development of activities that can help develop professional knowledge for teacher training in STEM subjects. Grounded in the epistemological, psychological, and didactic dimensions, these activities can equip preservice chemistry teachers with the tools to design and implement interdisciplinary STEM lessons. By trying to promote a practice involving different elements (technological, didactic, conceptual and contextual concepts, etc.), we seek to assist in the development of knowledge about STEM disciplines and in their integration.

However, the study also highlights persistent challenges, particularly in the integration of mathematics within interdisciplinary activities. These findings emphasize the need for targeted interventions to make mathematical principles more central to STEM education, ensuring a balanced and comprehensive integration of all disciplines. Through intentional design and problem-solving strategies, teacher training programs can empower future educators to overcome these challenges, enabling them to deliver impactful STEM education that equips students with the skills needed for real-world problem-solving.

Author contributions

All authors contributed significantly to the conceptualization, research, writing, and review of this manuscript.

Use of Generative AI tools declaration

The authors declare that they have used AI tools in the creation of this article.

AI tools used: ChatGPT and Grammarly.

How were the AI tools used? AI tools were utilized for language refinement, grammar checks, and enhancing the clarity of the manuscript.

Where in the article is the information located? The AI-assisted refinements were applied throughout the text, specifically in the Introduction and Discussion sections, ensuring coherence and readability.

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Conflict of interest

The authors declare no conflict of interest related to this study.

Ethics declaration

The study adhered to all relevant ethical standards and guidelines. All participants signed the informed consent form, a requirement of the research ethics committee of the State University of Campinas, registered under the code CAAE 79480924.7.0000.5404.

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