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A systematic literature review on STEAM pre- and in-service teacher education for sustainability: Are teachers ready?

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Abstract

Educational interest in sustainable development (SD) and sustainability has increased over the last fifteen years, promoted by international guidelines and agencies such as the UN or UNESCO, or the Incheon Declaration. While the current state-of-art discloses plenty of student-centered proposals in these fields, there is scarce evidence on how these are being addressed in pre- and in-service teacher education programs combining science, technology, engineering, arts, and math (STEAM). Searching to tackle this gap, we performed a systematic literature review based on 207 studies retrieved from the databases Scopus, WoS, and ERIC through PRISMA guidelines. The outcomes foremost reveal the following: (1) Pre-service programs lack courses or subjects that allow integrating sustainability and STEAM areas in an interdisciplinary approach. (2) Interventions for STEAM teacher education are focused on mathematics and statistics typically for the pre-service stage only with a proposal for rural teachers. (3) In-service teachers manifest difficulties in linking theoretical concepts with real-world experiences in classrooms. And (4) educational strategies employ problem-based learning, inquiry-based learning, escape rooms, robotics, or flipped classrooms. The implications of this study can help researchers, teachers, or stakeholders in the co-design of initiatives or methodologies that improve pre- and in-service teacher education programs to cope with STEAM education, sustainability, and SD, highlighting the importance of the teachers' role.

Keywords: pre-service teacher education, in-service teacher education, sustainable development, sustainability, STEAM education, STEM education

INTRODUCTION

During the last two decades, science, technology, engineering, arts, and math (STEAM) education has had an important role in planning, designing, and deploying curricula that respond to the learning needs of students and prepare them for the workforce (Jafarov, 2023). Then, STEAM education becomes a cornerstone for innovation, technology advancement, and economic growth in different countries, especially, in developed ones. Although STEAM education and its diverse educational initiatives have remarked good outcomes for the students, after different reforms, STEAM education faces diverse problems in terms of multidisciplinary integration of its disciplines, STEM-related major enrollment, curricular development, and students' achievement (Kayan-Fadlelmula et al., 2022; Thibaut et al., 2018). At the same time, with these tensions, other curricula requirements have been asked of schools and universities to cope with sustainable development (SD), sustainability, and their integration into STEAM education. SD has been widely promoted mainly by international agencies such as the UN or UNESCO to improve the quality of life of human beings through different actions responsible and respectful for the ecosystems, and which have been framed into the sustainable development goals (SDGs). In this way, SD and SDGs require the intervention and engagement of several actors from macrolevels, e.g., (governments or

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Contribution to the literature

- This systematic literature review (SLR) describes and analyzes teacher-centered initiatives for STEAM education and sustainability. While prior research discusses foremost student-centered proposals, we highlight the importance of teachers' role in sustainability and SD in the STEAM sphere.
- 15 initiatives were identified with nine strategies for teacher education in the pre- and in-service levels for STEAM and sustainability, mainly for math and statistics. Rural STEAM education must be taken more into account as well as the integration of the arts.
- Several issues, suggestions, and opportunities for improvement are discussed to foster the co-design and deployment of methodologies that help to strengthen STEAM teacher education programs considering sustainability and SD.

international agencies) to microlevels (teaching-learning initiatives in classrooms) (De Clercq et al., 2021).

Herein, searching to address the incorporation of SD in STEAM education, the current state-of-art reports several approaches (Stratton et al., 2015). The first one, education about sustainability, is an accommodation of the curricula and pedagogy, barely to incorporate sustainability with minimum educational effects on schools or universities as well as in the behavior of teachers or students (Stratton et al., 2015). The second one, education for sustainability, is also an adaptation of educational systems, but adding critical reflection on issues or practices, affecting sustainability and SDGs. Finally, sustainable education engages the whole person and the whole learning community in sustainable living and the ways to negotiate its meaning through real-world experiences and transformation (Stratton et al., 2015). Besides, sustainable education helps to foster in the students critical thinking and reflection about the current societal problems including the environmental ones and allows for accepting different views about the world.

It is supposed that the design of different curricula should tend to develop the latter approach through real-world experiences that connect with knowledge, hands-on activities, and students' behaviors regarding sustainability. However, some studies assert that it is necessary to articulate SD with STEAM disciplines such as, i.e., statistics wherein students can read and analyze critically information in tables, reports, charts, etc., connecting it with real-world contexts (Vásquez et al., 2023). In this, educators have a crucial role in achieving the far-reaching purposes and goals regarding sustainability and its implications in the educational process of the students. There, much debate has been brought about teacher education for sustainability (TEfS) and how to train effectively pre- and in-service teachers to cope with it. For instance, Brand et al. (2019) discuss the diverse approaches to being a competent teacher on sustainability, which include the development and critical reflection on content knowledge (CK) and pedagogical content knowledge (PCK) while at the same time, there is an interest in producing behavioral, attitudinal, and motivational changes in the courses promoting SD competences for teacher education. Certainly, an essential fact discussed in the same study is that teachers who have knowledge about SD and have developed PCK are more confident in enacting education for sustainable development (ESD) initiatives in schools (Brandt et al., 2019).

Conversely, whereas this is expected from teachers and teacher training programs, some studies have evinced a limited number of teacher-centered proposals regarding sustainability and STEAM education (Su et al., 2023; Vásquez et al., 2023). So, in the systematic review carried out by Su et al. (2023) only 16 proposals were identified for mathematics teachers in ESD during 2015-2021. Also, in the study, it is highlighted the need to bring methodologies such as problem-based learning, cooperative learning, and educational robotics to facilitate the development of sustainability-related competencies in the continuous training and education of mathematics teachers. Also, Vásquez et al. (2023) discuss the challenge to foster changes in the mindset of students that should be promoted by methodologies entailing socio-environmental and socio-constructivist dimensions. Similarly, while several documents uttered by UNESCO or the UN such as the guidelines and recommendations for reorienting teacher education to address sustainability (UNESCO, 2005), the SDG 4 (quality education, target 4.c) (UN, 2024), or the Incheon Declaration (Mundial & Unicef, 2016) put forward the importance of educators in all levels from early childhood to tertiary education as change agents for SD, the number of proposals or initiatives for teacher education is scarce and even more if we analyze the integration of the different STEAM disciplines into ESD. Then, it seems to be that after more than 15 years of promoting ESD, there is little evidence of how ESD is being developed in pre- and in-service STEAM teacher education. Then, without educators' voice and agency in ESD, how can we expect a real educational transformation regarding SD in new student generations? How is expected that STEAM educators teach SD and sustainability to students without proper formation in the pre- and in-service stages? So, what might be happening is a disarticulation between international agencies, policymakers, and instructional designers in contrast with what is really going on at the

Table 1. RQs for the SLR with their description

RQs	Description
RQ1. What are the bibliometric features of the studies in terms of authors, countries, citations, and topic trends thereof?	Identify the current scenario for STEAM teacher education and sustainability through bibliometric features of the studies with their cluster topics.
RQ2. What are the characteristics of the strategies and interventions for STEAM teacher education and Sustainability with their main outcomes?	Analyze and describe the characteristics of the interventions and/or strategies developed by the researchers with their outcomes.
RQ3. What issues, suggestions, or opportunities for improvement were identified in the studies?	Describe issues, suggestions, or opportunities for improvement detected from the perspective of the researchers in the studies.

practical level in educational settings. This context led us to ask ourselves: Are teachers ready?

To clarify these seemingly contradictory issues, we performed an SLR of STEAM TEfS in pre- and in-service levels during 2013-2024. Our interest in the review was to analyze and describe educational interventions and strategies that involved or integrated sustainability or SD with STEAM, as well as inform researchers, educators, and other stakeholders about the different pedagogical approaches that have been constructed in this matter. Altogether, our lens is put on STEAM initiatives wherein the arts have been integrated to foster creativity and expression for teacher education. Nevertheless, we also include the traditional STEM approach where the focus is on the resolution of problems based on concepts and procedures from science and mathematics, which incorporate the strategies applied in engineering and the use of technology (Aguilera & Ortiz-Revilla, 2021; Shaughnessy, 2013). Besides, we explain several problems, suggestions, or opportunities for improvement detected, which can help contextualize other researchers to tackle them in their studies. We expect that this systematic review helps to unveil and reflect critically on how to integrate sustainability and SD in educational programs for STEAM teachers' formation that leads to a change in educational environments.

METHODOLOGY

Systematic reviews search to answer a set of questions to identify and reveal current gaps, contrast hypotheses, or expand the scope of topics in a particular knowledge area (Gough et al., 2017). The information provided by the systematic reviews allows stakeholders, practitioners, and researchers to make decisions and plan future studies to close breaches based on the collected evidence (Petticrew & Roberts, 2006). This SLR was carried out through the stages provided by Gough et al. (2017), which are summarized, as follows:

(1) formulate research questions (RQs) and conceptual framework;

(2) search and screen for inclusion with eligible criteria;

(3) code to match a conceptual framework;

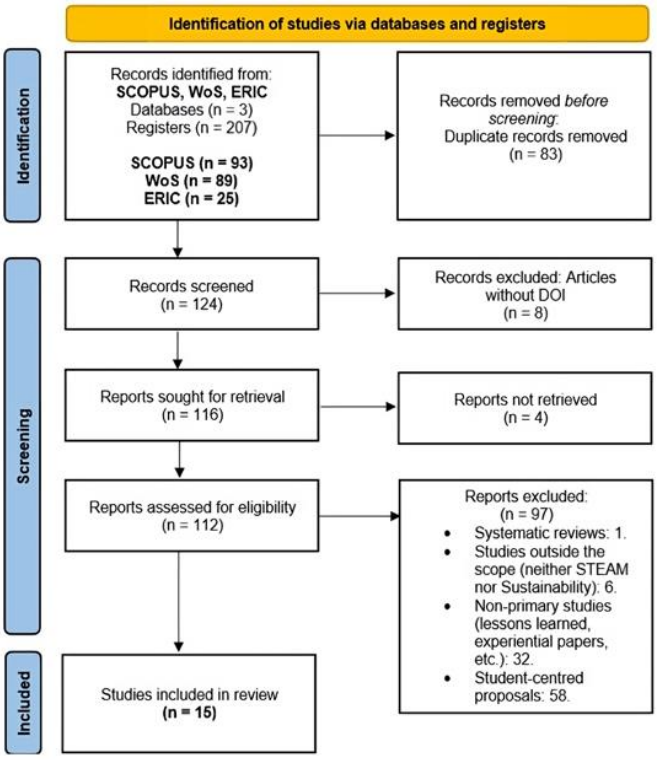

Figure 1. PRISMA flow diagram tailored to the SLR (Page et al., 2021)

(4) apply quality appraisal criteria;

(5) synthesize the studies using a conceptual framework or study codes; and

(6) interpret and communicate the findings.

All the process was accompanied by preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines (Page et al., 2021). PRISMA is an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses (Page et al., 2021). For the study, we proposed the RQs indicated in **Table 1** with their description. **Figure 1** depicts the PRISMA flow diagram tailored to the SLR.

Searching Criteria

The searching process for the SLR was carried out in three databases, .viz., Scopus, WoS, and ERIC during 2013-2024 with the string queries, inclusion, and exclusion criteria reported in **Table 2**.

Table 2. Description of searching criteria for the SLR

Aspect	Description
Timeframe	2013-2024
Databases	Scopus, WoS, and ERIC
Searching strings	▪ WoS: TS=((“STEM education” OR “STEAM education”) AND (“sustainability”)) ▪ Scopus: TITLE-ABS-KEY({sustainability} AND ({STEM education} OR {STEAM education})) ▪ ERIC: Abstract:((“STEM education” OR “STEAM education”) AND (“sustainability”))
Inclusion criteria	▪ Primary studies on STEM or STEAM teacher education and sustainability ▪ Studies in English
Exclusion criteria	▪ Studies outside STEM or STEAM teacher education and sustainability ▪ Not in English ▪ Not primary research, e.g., literature reviews, metanalysis, books, etc. ▪ Preprints or gray literature
Total records obtained	Scopus (93), WoS (89), and ERIC (25): Total (207)

We decided not to include terms such as “teacher education”, “in-service teachers”, or “pre-service teachers” in the search strings because when we included these terms only a few records were retrieved. Also, we noticed that the term “sustainability” is broader than “sustainable development” in education studies. Then, a general string was created for each database to collect more studies and identify other relevant ones that could serve us in the SLR. We identified that an important number of studies were either student-centered illustrating how students learn sustainability in STEAM education, or experiential papers that describe the experience and lessons learned to integrate sustainability into the STEAM curriculum. Also, we used the tags “TS”, “TITLE-ABS-KEY”, or “abstract” to identify studies with the exact words concerning the scope of the study. Through the string queries reported in **Table 2**, we obtained 207 records in the mentioned databases. It is worth mentioning that the SLR focused only on peer-reviewed journal articles since these could incorporate better analysis, reflection, and conclusions than other resources, e.g., proceedings in conferences.

Screening, Eligibility, and Appraisal Criteria

The screening process of the 207 records started by applying the inclusion and exclusion criteria reported in **Table 2**. First, the records were added to Elsevier Mendeley software through the research information systems (.RIS) extension. Second, missing information for each record such as DOI, keywords, title, etc., was completed. Third, the duplicated records were eliminated. After this process, n = 124 records remained according to **Figure 1**. Also, in the process, other articles without DOI or unavailable were discarded. Then, the remaining n = 112 records were read in their title and abstract by both authors to identify if they were in the scope of the SLR. For each one of these articles, it was applied some orienting questions available in **Appendix A**. The primary objective of these questions was to identify if each study was in the scope of the SLR in the key concepts: STEAM teacher education and sustainability. When a controversial article was found, both authors discussed their inclusion or exclusion. We noticed that the reports excluded contained systematic reviews, non-primary studies such as lessons learned, experiential papers (studies based on experiences from teachers but without intervention), or critical papers whose emphasis is on showing reflection on related topics to sustainability and STEAM. In addition, plenty of the proposals were student-centered ones from early childhood to tertiary education. Those articles that did not meet the inclusion criteria were discarded, while for the approved ones, a survey was created to extract their features with components such as study aim, research approach, educational level for teacher education (primary, secondary, or tertiary), educational outcomes, STEAM area, SDGs addressed, and conclusions. In addition, we classified each article according to the type of research, for instance, in survey research (investigations performed mainly through surveys), interview research (investigations performed primarily through interviews), or interventions (educational methodologies or strategies implemented with teachers). It is essential not to be confused about these types of research. In the case of survey and interview research, researchers did not forward interventions directly with teachers only they used instruments or techniques such as surveys or semi-structured interviews to collect information about attitudes, perceptions, etc. Conversely, interventions imply direct work with teachers using a variety of methodologies. Finally, n = 15 studies focused on STEAM teacher education, sustainability, and SD were included in the SLR, as **Figure 1** depicts.

Data Extraction and Analysis of the Studies

As mentioned, a survey collected the main information of each approved article. This was our main instrument to identify relevant features of the studies. With this information, we could respond to **RQ1-RQ3**. Besides, to support this information, we employed the software VOSviewer v.1.6.14 to identify the cluster topics of the proposals. VOSviewer is a software for bibliometric analysis based on network data that is

focused on items and clusters with two overall functions: create maps and visualize them (van Eck & Waltman, 2018). Complementary, to analyze the bibliometric features of the studies, we employed the Python Crossref REST API 1.5.0 (Lammey, 2016). The Python Crossref REST API is a tool that allows extracting bibliometric information such as citations, authors, publishers, type of study (journal article, conference proceedings, book chapter), or articles per year, among others. The API was used with Python language to extract the bibliometric features of the studies.

Reporting the Results

Guidelines proposed by (Webster & Watson, 2002) were considered for writing the review in aspects such as identifying relevant literature, review procedure based on a concept-centric approach, tables and figures presentation, tone, and structure of the synthesis. Results are presented according to the described RQs. A complete list of the proposals with information such as study aim, DOI, educational outcome domain (cognitive, affective, psychomotor, behavioral), teacher education level (pre- and in-service), main conclusions, among others, can be consulted in the link: https://docs.google.com/spreadsheets/d/1_fxd5N1q5tpkXGR6Fr42R1ugJ0KhB5obxGaIZp6zZtQ/edit?usp=sharing

Limitations

Although the SLR was performed through a rigorous protocol according to PRISMA guidelines, there are some limitations to expose. The first one is regarding the type of studies retrieved in the selected databases. We only selected peer-reviewed journal articles, in form of primary research, searching to incorporate robust studies in the scope of the SLR. We do not discard that other important studies have been excluded in the process, e.g., in conferences, gray literature, or in other languages. For instance, we detected in our preliminary searches some articles from non-indexed journals in the selected databases that we consider important in the discussion. In this regard, see the studies (Iturbe-Sarunić & Silva-Hormazábal, 2022; Silva-Hormazábal & Alsina, 2023). Also, we identified one study for mathematics after performing the SLR process (April 2024) related to teacher agency, see study (Alsina & Vásquez, 2024). Nonetheless, we think that the current corpus of proposals describes the context of STEAM TEfS and SD. We encourage other researchers to forward investigations that help to nurture the findings of this study. The second one is concerning the SLR process. We tried to follow a rigorous process to select the studies and screen them through an objective criterion as much as possible. However, we do not discard a certain load of subjectivity in the results, even though we selected some software tools such as VOSviewer or the Crossref API to guarantee the data integrity.

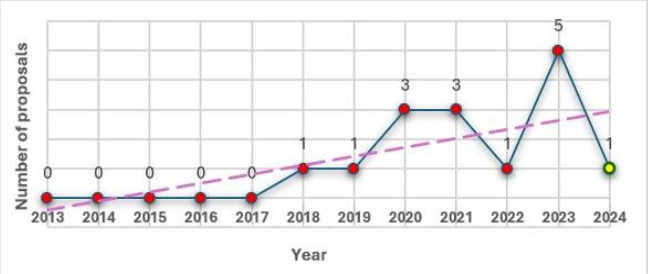

Figure 2. Number of articles per year (trend line is marked in purple & in yellow, one proposal was identified in January 2024) (Source: Authors' own elaboration)

RESULTS AND DISCUSSION

RQ1. What are the bibliometric features of the studies in terms of authors, countries, citations, and topic trends thereof?

Bibliometric Trends

Figure 2 shows the number of articles per year. In the chart, it is noticed a trend to increase the number of articles from 2018 to 2024 (see dashed purple line) with a relative peak of five proposals in 2023.

This turns out partially that the interest in STEAM TEfS has been gaining strength in recent years. For instance, in 2023, Alsina and Silva-Hormazábal (2023) proposed an initiative for mathematics teacher education for sustainability (MTEfS) with the cooperation of 23 Chilean in-service teachers focused on the SDG5 (gender quality) and SDG7 (climate action). In parallel, Brown et al. (2023) and Merritt et al. (2023) show two studies that explore how teacher agency (the likelihood to take action and initiative through autonomy and skills) can help teachers to create educational materials about sustainability integrating technologies such as geographical information system (GIS) in classrooms (Brown et al., 2023), and how bringing teacher personal rich experiences into classrooms is a crucial factor for students' engagement and development of concept understanding about energy sources (Merritt et al., 2023). Besides, Han et al. (2023) describe a funded project called TRAILS that analyzed how shared practices between in-service science teachers influenced academic students' achievement. It is worth mentioning that for 2024 (January), one proposal was identified at the moment to perform the search process (see study Franco Seguí et al., 2024).

Table 3 depicts the list of top-cited articles in the SLR according to Crossref altogether with their type (intervention, interview, or survey). Herein, the most cited article (Wahono & Chang, 2019) evaluates the attitudes, knowledge, and application of STEM education using the instrument attitudes, knowledge, and applications (AKA) (survey) in Indonesia. In addition, the study depicts some remarkable aspects

Table 3. List of top-cited articles in the SLR with their research type

Title	Authors	Year	Citations	Research type
1. Assessing teacher's attitude, knowledge, and application (AKA) on STEM: An effort to foster the sustainable development of STEM education	Wahono and Chang (2019)	2019	34	Survey
2. New trends in higher education in the globalizing world: STEM in teacher education	Türk et al. (2018)	2018	25	Interview
3. An online-based edu-escape room: A comparison study of a multidimensional domain of PSTs with flipped sustainability–STEM contents	Yllana-Prieto et al. (2021)	2021	21	Intervention
4. Sustainable and flipped STEM education: Formative assessment online interface for observing pre-service teachers' performance and motivation	Jeong et al. (2020)	2020	17	Intervention
5. Integrating mathematics and science teaching in the context of education for sustainable development: Design and pilot implementation of a teaching-learning sequence about air quality with pre-service primary teachers	Rico et al. (2021)	2021	11	Intervention
6. Building a sustainable model of integrated stem education: investigating secondary school STEM classes after an integrated STEM project	Han et al. (2023)	2023	8	Intervention

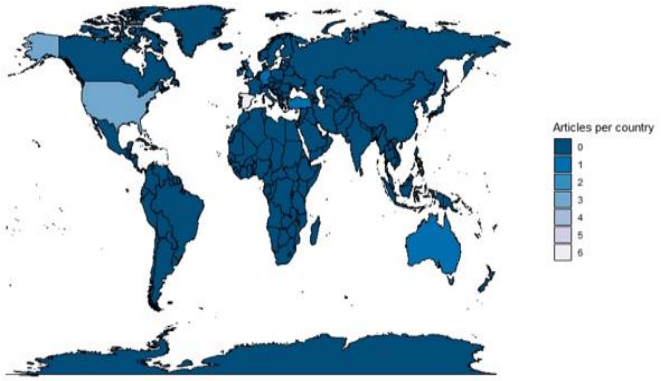

Figure 3. Distribution of number of articles per country (N = 15) (Source: Authors' own elaboration)

regarding STEM education, e.g., the fact that most science teachers who participated in the study do not know what STEM education is, even though, contradictorily, 75% of science teachers have a good attitude towards STEM fields. This reveals that teachers can apply STEM principles in classrooms, e.g., hands-on activities or technology-based learning without knowing that this is STEM (Wahono & Chang, 2019).

Although we synthesized only the top six cited articles in **Table 3**, the articles in the citations (Brown et al., 2023; Fernández-Martín et al., 2020; Han et al., 2023; Howley & Roberts, 2020; Merritt et al., 2023; Turner et al., 2022) have four to two citations.

In particular, the most prolific journals are MDPI Sustainability, six articles and 69 citations; the Universal Journal of Educational Research, one article and 25 citations; MDPI Education Sciences, one article and 17 citations; the International Journal of Technology and Design Education from Springer, two articles and 12 citations; and finally, the International Journal of Science and Mathematics Education from Springer, one article and four citations. Regarding the geographical distribution of the proposals, **Figure 3** shows its distribution with Spain in first place with six proposals, followed by the US with three proposals. The remaining countries such as the UK, Ireland, Turkey, Australia, Taiwan, and Germany, count with one proposal.

SDGs Entailed, Participants, and Research Approach

Table 4 reports the SDGs addressed in the proposals with the number of participants (pre- and in-service teachers) and the research approach (qualitative, quantitative, or mixed). Most of the proposals addressed SDG 4 (quality education) altogether with SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities), and SDG 13 (climate action).

Table 4. List of the proposals classified by SDG entailed, number of participants, and research approach

Proposal title	Citation	SDG	Participants	Research approach–Instruments
1. Promoting mathematics teacher education for sustainability through a STEAM approach	Alsina and Silva-Hormazábal (2023)	SDG 5 (gender equality) SDG7 (climate action)	23 in-service primary Teachers	Mixed (pre- & post-survey + rubric based on SDGs)
2. The role of teacher agency in using GIS to teach sustainability: An evaluation of a lower secondary school story mapping GIS initiative in Ireland	Brown et al. (2023)	SDG 2 (zero hunger) SDG3 (good health) SDG7 (affordable & clean energy) SDG11 (sustainable cities and communities) SDG 13 (climate action)	Two in-service teachers	Qualitative (semi-structured interviews)
3. Making STEM education objectives sustainable through a tutoring program	Fernández-Martín et al. (2020)	SDG 4 (quality education)	26 pre-service teachers	Quantitative (academic report and survey [BIP])

Table 4 (Continued). List of the proposals classified by SDG entailed, number of participants, and research approach

Proposal title	Citation	SDG	Participants	Research approach–Instruments
4. A usability study of classical mechanics education based on hybrid modeling: Implications for sustainability in learning	Guadagno et al. (2021)	SDG 4 (quality education)	12 high school in-service physics teachers	Quantitative (pre- & post-implementation surveys)
5. Engaging school students and educators with the practice of statistics	Howley and Roberts (2020)	SDG 4 (quality education) SDG7 (affordable and clean energy) SDG 13 (climate action)	85 in-service rural teachers	Quantitative (pre- & post-survey)
6. Building a sustainable model of integrated stem education: Investigating secondary school STEM classes after an integrated STEM project	Han et al. (2023)	SDG 4 (quality education)	30 in-service teachers (15 science teachers, 15 engineering technology teachers)	Quantitative (survey: 21st century skills pre- & post-survey, D-BAIT instrument to measure STEM knowledge)
7. Sustainable and flipped stem education: Formative assessment online interface for observing pre-service teachers' performance and motivation	Jeong et al. (2020)	SDG 4 (quality education)	70 pre-service teachers	Quantitative (survey + analysis of students' grades during pre- & post-implementation)
8. Exploring energy through the lens of equity: Funds of knowledge conveyed through video-based discussion	Merritt et al. (2023)	SDG 4 (quality education) SDG7 (affordable and clean energy)	38 pre-service teachers	Qualitative (analysis of assignments and Flipgrid post and replies)
9. Integrating mathematics and science teaching in the context of education for sustainable development: Design and pilot implementation of a teaching-learning sequence about air quality with pre-service primary teachers	Rico et al. (2021)	SDG3 (good health) SDG 4 (quality education) SDG11 (sustainable cities and communities) SDG 13 (climate action)	24 pre-service teachers	Mixed (pre- & post-implementation surveys, open-ended question analysis)
10. Planting food sustainability thinking and practice through STEM in the garden	Turner et al. (2022)	SDG 4 (quality education) SDG 13 (climate action)	Six in-service teachers (three in-service teachers, three pre-service teachers)	Mixed (survey + interview)
11. Assessing teacher's attitude, knowledge, and application (AKA) on STEM: An effort to foster the sustainable development of STEM education	Wahono and Chang (2019)	SDG 4 (quality education)	137 in-service teachers (biology, chemistry, physics, integrated science)	Quantitative (survey: AKA questionnaire)
12. Promoting pre-service teachers' professionalism in steam education and education for sustainable development through mathematical modelling activities	Wiegand and Borromeo Ferri (2023)	SDG 4 (quality education)	14 pre-service mathematics teachers	Qualitative (written report analysis)
13. An online-based edu-escape room: A comparison study of a multidimensional domain of PSTS with flipped sustainability-stem contents	Yllana-Prieto et al. (2021)	SDG4 (quality education) SDG7 (affordable & clean energy) SDG13 (climate action)	42 pre-service teachers	Quantitative (survey, pre- & post-test)
14. New trends in higher education in the globalizing world: STEM in teacher education	(Türk et al., 2018)	SDG 4 (quality education)	14 pre-service teachers, 15 in-service teachers, 12 lecturers	Qualitative (interviews)
15. Teaching statistics for sustainability across contexts: Exploring the knowledge and beliefs of teachers	Franco Seguí et al. (2024)	SDG 4 (quality education)	25 in-service primary teachers	Quantitative (survey: MTSK-stochastic statistics questionnaire)

Similarly, 46.66% of the proposals have a quantitative approach, 26.66% a qualitative approach, and 26.66% a mixed one. The number of participants vary from 2 to 137 teachers.

In some cases, the mixed approach studies used surveys and semi-structured interviews to know the attitudes and perceptions of the teachers regarding STEM and sustainability. For instance, the study carried out by Franco Seguí et al. (2024) investigates the beliefs of statistics teachers regarding sustainability and how they incorporate it in their courses. Two questionnaires were administered by the researchers to know these beliefs. Besides, the study puts forward an itinerary for teachers with activities for statistics to cope with ESD.

In the case of quantitative studies, pre- and post-surveys were applied to know the teachers' perception regarding the methodology implemented for sustainability. Here, several surveys have been constructed or employed by the researchers. In this way, Fernández-Martín et al. (2020) used the instrument business-focused inventory of personality (BIP) to identify personality and key competencies for employment in the study's participants. Another example is shown in the study (Han et al., 2023) where two instruments were designed in the framework of the program teachers and researchers advancing integrated lessons in STEM (TRAILS), which have been awarded by the National Science Foundation in the US. The first one is the D-BAIT STEM knowledge test which is a survey created by STEM experts with 20 multiple-choice items with three subject domains: biology, engineering design, and physics. The second instrument was a survey (the 21st century skills survey), which consists of 30 items divided into the constructs of critical thinking, collaboration, communication, and creativity. Similarly, Wahono and Chang (2019) utilized the instrument AKA, guided by the STEM education quality framework. The survey was split up into three overall subdomains, namely, the STEM attitude (SAt), STEM knowledge (SK) domain, and STEM applications (SAp). At last, Franco Seguí et al. (2024) employed an instrument called the MTSK-stochastic statistics questionnaire to measure the mathematics teacher's specialized knowledge. As for the qualitative studies, they employed semi-structured interviews, written reports, and video analysis. Merritt et al. (2023) analyzed students' assignments in an energy unit through Flipgrid posts and replies. The authors argue that with this method, the teachers' voices regarding energy inequalities are heard. Wiegand and Borromeo Ferri (2023) examined written reflections about the connections between mathematical modeling and the promotion of ESD. Brown et al. (2023) explore the concept of teacher agency through semi-structured interviews within the framework of the project 5*S (space, surveyors, and students–STEM and the SDGs), which is an initiative of Science Foundation Ireland. Concerning mixed studies, they combined surveys, comments analysis, pre- and post-tests (Alsina & Silva-Hormazábal, 2023; Türk et al., 2018; Turner et al., 2022).

Topic Trends

Figure 4 depicts the cluster map for the keywords for the studies produced by VOSviewer, and **Figure 5** shows the evolution of these terms by year. From a pedagogical

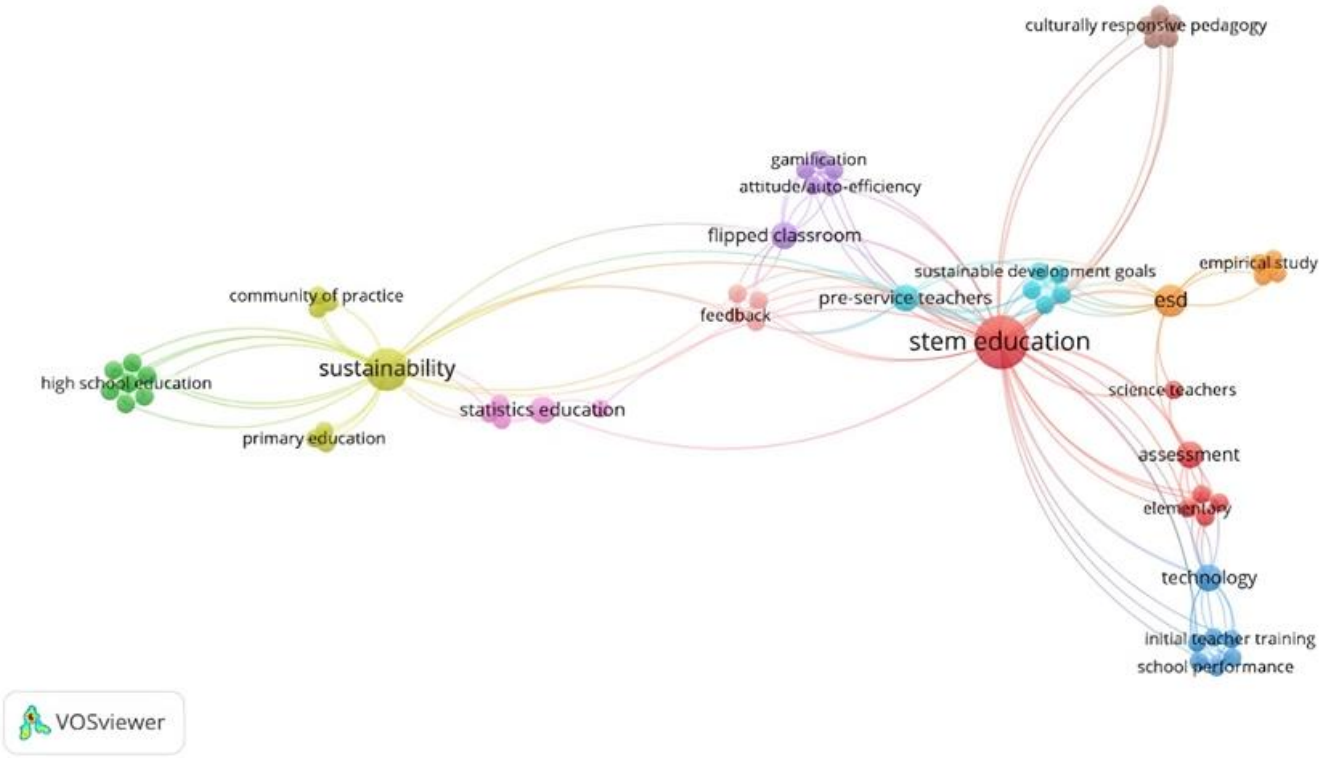

Figure 4. VOSviewer keyword cluster map for the studies (Source: Authors' own elaboration, using VOSviewer software)

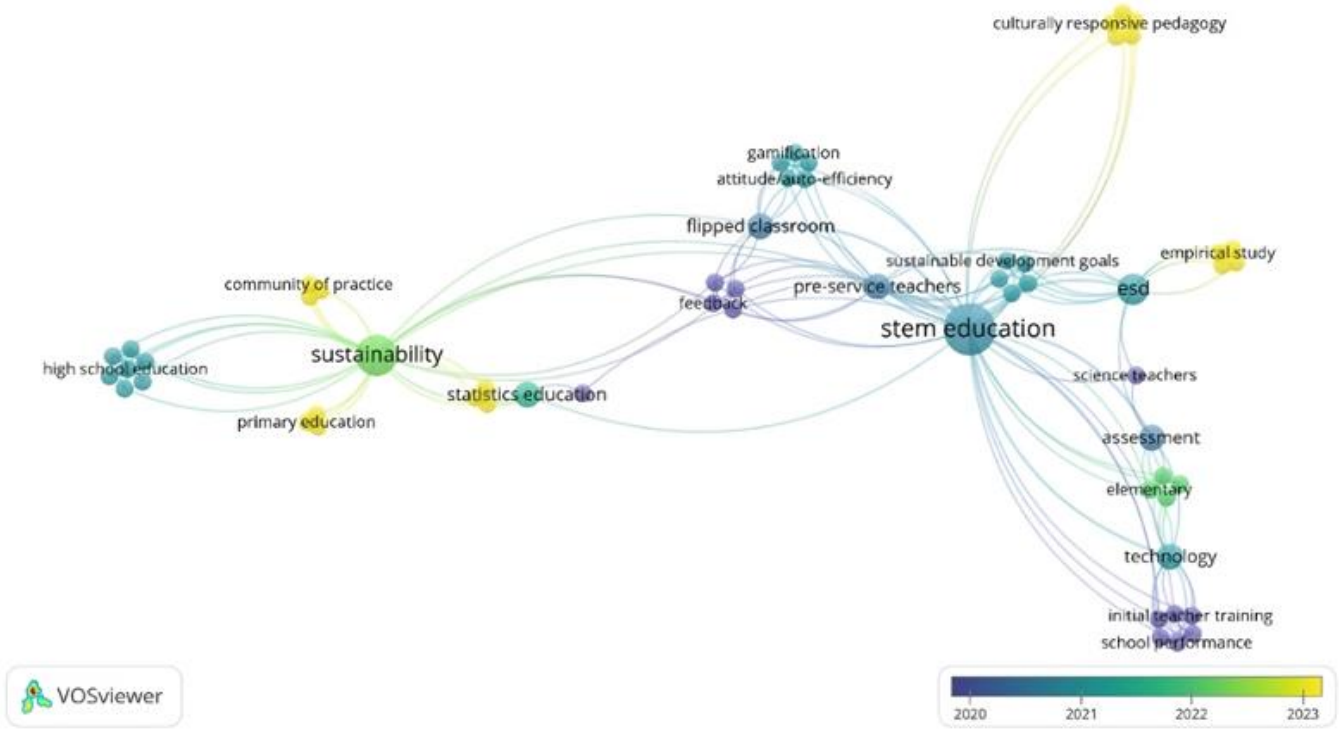

Figure 5. Evolution of the keywords in the studies by year (Source: Authors' own elaboration, using VOSviewer software)

standpoint, there are some representative keywords. For instance, the term culturally responsible pedagogy (see brown cluster) is mentioned in the study (Merritt et al., 2023) concerning funds of knowledge (FoK) in pre-service teachers, that is, accumulated knowledge through experiences in sites, settings, or activities, regarding energy inequalities. The authors assert that it requires educators, the ability to support academic development and sociopolitical consciousness of the students for nurturing and supporting cultural competence, which can lead to more equitable and sustainable energy systems (Merritt et al., 2023). Another term is communities of practice (CoPs) (see yellow cluster). Han et al. (2023) discuss how CoPs in STEM education (communities that share values, practices, and meanings, culturally and historically sustained) can increase self-efficacy and the ability to create STEM lessons in professional development for in-service secondary STEM teachers. Besides, the purple cluster shows the term flipped classroom that was incorporated into an online course for 71 pre-service teachers in Spain (Jeong et al., 2020). The course comprises topics such as primary science teaching and learning, the universe, matter, matter transformation, and energy. The authors highlight the importance of feedback through online-based formative assessment interfaces.

Also, it is relevant in the map the term initial teacher training that was addressed in a tutoring program for primary STEM teachers (Fernández-Martín et al., 2020). Herein, pre-service teachers served as tutors for school students in a program called nurture thru nature. The program was inspired by an environmental educational model based on Dewey's active learning philosophy. Similarly, the term statistics education is noticeable (see pink cluster), which is transversal to several studies (Alsina & Silva-Hormazábal, 2023; Franco Seguí et al., 2024). In these studies, teachers state the importance of navigating from real situations towards more abstract content (connecting content with students' experiences) in statistics education, involving reflection on teaching practices and dialog between teachers and students.

RQ2. What are the characteristics of the strategies and interventions for STEAM teacher education and sustainability with their main outcomes?

As described, the analysis of the proposals shows three overall types of studies: Survey research, interview research, and research-based interventions. Each one of these types will be explained in the next subsections.

Survey and Interview Studies

Two studies were identified that fall into these categories. It is worth mentioning that these articles have the highest number of citations according to **Table 3**. The first study was performed by (Türk et al., 2018) using semi-structured interviews and it describes the perceptions of 12 lecturers, 15 in-service teachers, and 14 pre-service teachers about three overall aspects: STEM education, integration of teaching knowledge into the teaching profession and teaching knowledge into teacher education programs. The lecturers had a wide range of STEAM-related majors, e.g., science education, mathematics education, mechanical engineering, and computer technology education. Three conclusions are remarkable in the study:

(1) Most STEM pre-service teachers do not know what the STEAM approach is, while lecturers know about this approach conducting the thesis process with their students. This could exhibit that the curricula of teacher education programs should include STEAM-related subjects and need reformulation.

(2) Teachers should have knowledge about educational technologies and basic knowledge of STEAM fields.

(3) Educational faculties with national education agencies should determine the qualifications for teachers and perform studies with pre-service teachers as well.

The second study carried out by (Wahono & Chang, 2019) focuses on assessing three domains in STEM teaching, viz., AKA regarding STEM education. To assess the latter domains, the authors employed an instrument (survey) known as AKA which is divided into three categories: SAt, SK domain, and SAp). The Cronbach's alpha coefficient was used to determine the internal consistency of each category and their content was validated by three experts. Then, the instrument was applied to 137 teachers who teach subjects such as biology, physics, chemistry, and integrated science from eight different provinces in Indonesia. The results of the survey indicated that 50% of the respondents are below the average in knowledge about STEM education, even though, the other 50% has implemented this approach in science classrooms. Also, teachers believe that it is difficult to articulate the different STEM areas, as well as the teacher education background does not allow for supporting STEAM education in classrooms.

Research-Based Interventions Studies

Four studies were identified in the areas of mathematics, physics, and statistics. In mathematics, Alsina and Silva-Hormazábal (2023) analyzed the effect of the pro-STEAM training program on promoting MTEfS among Chilean teachers. 23 in-service teachers participated in the methodology during one school semester (65% primary teachers). The methodology was focused on SDG5 (gender quality) and SDG7 (climate action). The methodology consisted of 90-minute sessions within three modules: education for the 21st century, STEAM education, and STEAM implementation. In conclusion, 60% of participants achieved an advanced level in the SDGs (gender quality and climate action). Teachers incorporated strategies to promote SDGs (5 and 7) in their classrooms and they participated in the design of STEM activities focused on sustainability. In parallel, Wiegand and Borromeo Ferri (2023) proposed an ESD framework for pre-service STEAM teachers. Through a seminar, 14 pre-service mathematics teachers presented their views on connecting STEAM education with ESD. Based on the seminar's evaluation consisting of written reports, six teachers' profiles were identified to handle ESD with mathematical education: the bridge builder, the pragmatist, the user, the traditionalist, the networker, and the project manager. Through intensive engagement with mathematical modeling, STEAM, SDGs, and ESD in the seminar, the knowledge of the pre-service mathematics teachers changed (Wiegand & Borromeo Ferri, 2023). Rico et al. (2021) describe a teaching-learning sequence for 24 pre-service primary teachers for a quality air initiative and sustainability in a Spanish university. The research emphasizes co-teaching practices with the students and highlights some crucial factors for teachers such as PCK, teaching competencies for sustainability, active teaching and learning strategies, integration of technology, and reflective learning opportunities.

In statistics, Franco Seguí et al. (2024) present a study about the beliefs of 25 in-service teachers regarding sustainability, statistics, and how they could incorporate them into their courses. Two questionnaires were administered, the first one (MTSK-stochastic statistics questionnaire) to know how statistical teaching influences the specialized knowledge of the teachers and the second one for ESD statistics activities. The study reveals that teachers struggle with applying statistical concepts to real contexts. For this reason, the authors proposed an itinerary with activities for statistics courses and ESD that teachers can draw on. Howley and Roberts (2020) incorporated statistics into STEM education to the students develop an interest in statistics and its combination with environmental sustainability projects. The project was carried out in Australia with 86 students across 5 schools and 85 teachers. Students participated in the national poster competition (NSPC). Teachers reported more positive feelings of connection with and support from participant universities in the project, as well as an increase in their recognition of the value of statistics for the educational process and confidence in connecting students with valuable statistical practice.

Concerning physics, Guadagno et al. (2021) evaluated a 3D modeling software to teach introductory physics to high school students. The program was tested by eight teachers. The researchers analyzed changes in attitudes toward user experience, STEM relevance, and classroom applicability. The engine can facilitate the learning of physics and its enjoyment and 3D representations act as a scaffold for the educational process of the students.

For SDG 7 (clean and affordable energy) and SDG 13 (climate action), four proposals were identified for teachers. Brown et al. (2023) discussed the role of the teacher agency in using GIS software to teach sustainability in a lower secondary school in Ireland in a program called 5*S. The use of GIS in teaching sustainability empowers teachers to integrate new teaching strategies and technological education

platforms into their classrooms, providing effective ways to introduce new concepts around sustainability and STEM education. The study found that in-service teachers participating in the 5*S initiative were eager to integrate GIS into their classrooms but wanted and needed confidence in their understanding of the new software and data to integrate new knowledge and approaches into their teaching. Merritt et al. (2023) explore how FoK which are diverse experiences, perspectives, and understandings that individuals bring to their learning environments can enhance critical thinking about energy systems and their inequities. By drawing on their rich life experiences, pre-service teachers can develop a deeper understanding of energy-related concepts and issues, such as energy sources, impacts, conservation, and industry perspectives. Yllana-Prieto et al. (2021) explained how an online escape room can influence (attitudes, self-efficacy, and emotions) of primary pre-service teachers in an environmental science course. The online-based edu-escape room had a medium effect for items with significant differences except for the emotion "frustration", where the activity had a large effect. Negative emotions such as frustration were frequently viewed as detrimental to motivation and learning, but they were also interpreted under some circumstances as beneficial in the learning process. At last, Turner et al. (2022) evaluated teachers and their students' experiences of an environmental food education program in Australia that involved the application of interdisciplinary (STEM) knowledge and skills. The project gathered hands-on activities with the usage of digital devices and robotics to collect data for soil water, weather conditions, etc.

Han et al. (2023) reported the teachers' experiences in a three-year program called TRAILS. The results indicate that teachers maintained and even improved their teaching in terms of student STEM knowledge achievement even after the project ended. Finally, students exhibit an increase in their confidence in critical thinking. Collaboration with a partner teacher and administrative support seem to facilitate implementing new instructional strategies in teaching STEM curriculum.

Finally, two proposals illustrate how tutoring and flipped classrooms could be crucial educational components for pre-service teacher education. Jeong et al. (2020) outlined a methodology with online flipped classrooms in a STEM course. 71 pre-service teachers participated during 2017-2018. The teachers' backgrounds were social sciences, science, arts, and technology, among others. The teachers reviewed science concepts for primary schools through an online learning platform with an assessment module. The research findings showed that online-based formative assessment interfaces influence positively pre-service teachers' performance and motivation in sustainable and flipped STEM education. Online assessment platforms can promote enhancing active learning, lifelong learning, diagnostic evaluation, increasing engagement and motivation, and improving communication and collaboration among pre-service teachers. Fernández-Martín et al. (2020) investigated the impact of a STEM tutoring education program on school students' academic performance. 50 primary students and 26 pre-service teachers who were volunteers participated in the study. Collaboration and more training on inquiry-based learning are required due to the lack of them in Spanish training programs for teachers. Something remarkable in the study is that before volunteering, pre-service teachers had a high perception of their teaching competence, but afterward the intervention, pre-service teachers were more aware of the pitfalls and difficulties regarding incorporating STEM education, sustainability, and inquiry-based learning in classrooms.

Strategies

Table 5 shows a synthesis of the strategies developed in the proposals that gather STEAM education and sustainability. In this, we identified a variety of strategies such as flipped classrooms, garden projects, escape rooms, or Flipgrid videos and posts. Overall, nine educational strategies were recognized.

RQ3. What issues, suggestions, or opportunities for improvement were identified in the studies?

Issues

Several issues for STEAM teacher education and sustainability were recognized. Each one of these is listed, as follows:

1. Lack of STEM/STEAM subjects incorporated in the curricula of teacher education programs: According to Türk et al. (2018), teacher education programs do not have courses or activities to integrate different STEAM fields. In the same study, participants indicated that they learned about STEAM education in their professional context after graduating. This issue makes it difficult to adopt a multidisciplinary approach for STEAM education and sustainability. Indeed, it seems that teacher recruitment is in crisis, at least in the US, and teachers report not having enough training to teach STEAM disciplines (Love & Love, 2023; Montés et al., 2023).

2. Teachers ignore what the STEAM approach is: Although the STEAM education philosophy has been widely disseminated, this approach is not known in all countries and educational contexts. For instance, Wahono and Chang (2019) show how 50% of participant teachers in Indonesia did not know much about STEM education, but they applied several principles of this approach in classrooms without knowing it. Moreover, in this study, 75% of teachers

Table 5. Synthesis of the identified strategies for STEAM teacher education and sustainability

Strategy	Authors	Rationale for the strategy
1. Online flipped classroom	Jeong et al. (2020)	Flipped STEM education can increase academic performance, knowledge, and motivation even more if it is mixed with online formative assessment.
2. Gardens for food production	Turner et al. (2022)	STEM projects involving gardens for food production help to promote design-led innovation, culturally sustaining pedagogy, teacher connectedness and scientific, technological, engineering, and mathematic literacies.
3. Escape rooms	Yllana-Prieto et al. (2021)	Gamification, including the use of escape room games, offers several benefits to teaching and learning in education such as increased engagement and motivation, and enhancement of problem-solving skills.
4. Flipgrid videos, posts, & replies	Merritt et al. (2023)	Flipgrid videos, posts, and replies are useful for sharing different perspectives on energy sources and energy inequalities.
5. Problem-based learning (PBL)	Rico et al. (2021)	PBL can help to deal with knowing the problems the planet and its inhabitants are experiencing, and about being able to collaborate in finding solutions to achieve the SDGs. PBL can connect competencies for sustainability with teaching praxis.
6. Design-based learning	Han et al. (2023)	Design-based learning fosters the creation of communities of practice between local industrial partners, graduate students, and teachers to construct STEM knowledge and skills in an authentic STEM context.
7. Robotics	Turner et al. (2022)	Incorporating robotics into STEM Education has been found to promote student engagement, knowledge, skills, and creativity, and provide a setting for student-centered, project and problem-based learning approaches.
8. Project-based learning (PjBL)	Howley and Roberts (2020)	PjBL provides authentic learning opportunities to integrate sustainability, STEM concepts, and statistics through fun and interactive projects.
9. Inquiry-based learning	Fernández-Martín et al. (2020)	Inquiry-based learning can engage students through oriented questions and authentic activities. Development of these activities can promote initiatives from teachers that change the negative perception of the students toward science, and it can aid in creating teachers' networks to exchange and extend good practices.

are willing to incorporate STEAM principles in their classrooms which could sound contradictory.

3. Inquiry-based learning experiences are not common in teacher education: Inquiry experiences are not common in Spanish primary science teacher training programs, and poor knowledge of inquiry among the programs' students is common (Fernández-Martín et al., 2020). However, as Han et al. (2023) pointed out, scientific inquiry plays a crucial role for students in both mathematical thinking and the development of authentic design tasks, promoting student-centered learning.

4. Reduced number of studies for pre- and in-service teachers: While the number of proposals for STEAM teachers and sustainability continues to increase as **Figure 2** depicts, the overall number of studies in the timeframe of the SLR is reduced. Only 15 proposals were retrieved in ten years. Even as **Figure 2** shows, there is a recent interest in STEAM teacher education and sustainability, starting from 2017, but still, it seems that the interest is put in student-centered proposals and not in teacher-centered ones.

5. The problem in linking STEAM concepts with real-world experiences in sustainability: mathematics and statistics teachers deal with difficulties in integrating subject concepts with sustainability in real-world problems (Alsina & Silva-Hormazábal, 2023; Franco Seguí et al., 2024). This has been the reason because Franco Seguí et al. (2024) and Wiegand and Borromeo Ferri (2023) have proposed an itinerary with activities for statistics, mathematical modeling, and sustainability. Nonetheless, not all teachers are willing to integrate sustainability from an interdisciplinary approach, or they do not want to integrate their own subjects into other ones (Wiegand & Borromeo Ferri, 2023).

6. Lack of studies in cooperation with national ministries or educational agencies and pre-service teachers: Türk et al. (2018) have asserted that there are no studies for STEAM teacher education and national ministries or agencies. Also, studies with promising results claim more systematic support from all actors involved in teacher education programs (Fernández-Martín et al., 2020).

Suggestions and Opportunities for Improvement

Based on the issues identified in the SLR, six suggestions and opportunities for improvement have been elicited.

1. Improve teachers' agency: The teachers' agency can promote initiatives that address sustainability and STEAM education in classrooms. In these, teachers are viewed as social agents and leaders who can contribute through their role to support students' learning of the previous fields in classrooms. Besides, the agency can help educators to cope with the different situations in classrooms. While teachers are not seen as active agents, it is difficult a real transformation in classrooms. In this regard, see studies (Brown et al., 2023; Turner et al., 2022).

2. Cooperation among teachers, institutions, and stakeholders is necessary: Cooperation to disseminate good practices on STEAM education and sustainability is necessary. Also, the creation of CoPs involving teachers, students, and stakeholders can help to empower teachers to maintain integrated STEAM teaching. CoPs are "groups of people who share a concern, a set of problems, or a passion about a topic, and who deepen their knowledge and expertise in this area by interacting on an ongoing basis" (Wenger et al., 2002, p. 4). Concerning this, see the study (Han et al., 2023).

3. Teacher education programs need curricula reformulation: An improvement in PCK about SD and sustainability in STEAM teacher training programs is needed. Similarly, by incorporating educational methodologies such as inquiry-based learning, teachers can design student-centered initiatives, e.g., in science. Subjects addressing real-world challenges through an interdisciplinary approach regarding sustainability and STEAM are needed in the curricula of teacher education programs. About this, see studies (Alsina & Silva-Hormazábal, 2023; Franco Seguí et al., 2024; Rico et al., 2021).

4. STEAM teachers' experiences on sustainability matter: Bringing teachers' experiences (FoK) to classrooms is crucial to identify current issues, inequalities, or breaches in sustainability and STEAM. By integrating these experiences in classrooms through an active learning approach, students could be more engaged in the tasks proposed. Concerning this, see the study Merritt et al. (2023).

5. Integrate active learning methodologies and online formative assessment: Exploring new approaches for teacher education such as escape rooms or flipped classrooms with online formative assessment could be good methods to improve teachers' knowledge about sustainability. Online formative assessment interfaces are appropriate tools for continuous interaction between teachers and students (Jeong et al., 2020). In addition, PBL, PjBL, ICT, or robotic approaches with SDGs have been demonstrated to be effective for teacher pre- and in-service training. Besides, projects involving the head, heart, and hands have led to transformative learning. Regarding this, see studies (Fernández-Martín et al., 2020; Jeong et al., 2020; Rico et al., 2021; Turner et al., 2022; Yllana-Prieto et al., 2021).

6. Rural teachers are important: We only detected one proposal for rural teachers (Howley & Roberts, 2020). Rural education is important for the cultural, social, and economic development and integration of countries. More proposals for rural teachers are needed in the STEAM sphere (Gavari-Starkie et al., 2022).

CONCLUSIONS AND FUTURE DIRECTIONS

In this SLR, we identified and analyzed studies about STEAM TEfS and SD based on 207 studies retrieved from the databases Scopus, WoS, and ERIC. We adopted this approach because many of the current studies in the state-of-art highlight student-centered proposals and not properly teacher-centered ones. Undoubtedly, most of the educational methodologies deployed in educational settings are designed by teachers and the success relies on their pedagogical perspective and the knowledge in their disciplines. However, are STEAM teachers ready to cope with sustainability and SD? Based on the evidence, we partially agreed, because although there are meaningful proposals that we analyzed, it is still tough to sketch a big picture about the current context of STEAM teacher education due to the low number of proposals identified. It seems that sustainability and SD, at least for STEAM teacher education, is more a discourse than a real reflective pedagogical practice influencing the curricula of STEAM programs and helping to cope with the different environmental and social challenges entailed in the SDGs. Even, in the conceptualization of this SLR, we found a plethora of studies promoting, e.g., sustainability in higher education institutions, but few describe the impacts, implications, issues, challenges, flaws, etc., for both teachers and students.

Another elicited problem is regarding the pre-service STEAM teacher education programs. We noticed three overall issues in these:

(1) Pre-service teachers lack knowledge about the STEAM approach.

(2) There are no subjects or courses related to STEAM in the curricula of these programs, and the current ones do not foster an interdisciplinary approach which is needed in sustainability and SD.

(3) Pre-service teachers deal with a lack of basic knowledge in their disciplinary fields, and they can have education formation gaps.

Other detected problems are associated with the creation of CoPs, collaboration between teachers, scarce rural STEAM education initiatives for sustainability, links between theoretical concepts and real-world experiences, and articulation between PCK and CK. These problems require the attention of policymakers, instructional designers, teacher education programs, and of course teachers.

In this way, we encourage researchers and teachers to co-design and deploy effective strategies that sustain sustainability and SD into STEAM teacher education programs based on the results of this SLR or to complement it. We think that with the proper formation of pre- and in-service teachers, their initiatives and agency, and the support of the stakeholders, pedagogical

practices that address environmental and social issues and prepare students to be more socially, culturally, and environmentally responsible can be feasible. Also, the promotion of the reflection on the current educational practices (praxis) can yield a real integration of sustainability and SD that fosters learning and transformation in classrooms.

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APPENDIX A: ORIENTING QUESTIONS FOR THE SCREENING PROCESS IN THE SYSTEMATIC LITERATURE REVIEW

1. Is the article in line with STEM or STEAM education and sustainability?
2. Is the study primary research, e.g., case study, pilot study, or survey, etc., in the scope of STEM or STEAM teacher education and sustainability?
3. Does the study describe an educational context into STEAM education and sustainability, e.g., population, characteristics, type of teacher training education, etc.?
4. Does the study show a research method, e.g., (quantitative, qualitative, or mixed)?
5. Does the study evince any learning outcomes from the levels cognitive, affective, behavioral, or psychomotor?
6. Do the discussion and conclusions supported by the results, and they evince the pros and cons and/or the aspects to improve?
7. Has the study cited by other authors?