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Challenges and potential in implementing STE(A)M in teachers' practices: a systematic review

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ABSTRACT

The potential of STE(A)M has been widely recognised in recent years; however, challenges have also been identified in the implementation of this approach, making it important to deepen research into teachers' practices. In this study, we conducted a systematic review focused on teaching practices within a STE(A)M approach, to understand what challenges and limitations teachers encounter, as well as the possibilities authors suggest to overcome them. The research question is: What are the challenges and potentialities of implementing the STE(A)M approach in teachers' practices? This review analysed articles indexed in the Web of Science and Scopus databases over the last eight years, following the PRISMA scheme. The 26 articles examined highlight challenges such as time management, lack of resources and funding, limited guidance, gaps in teacher training, difficulty integrating subject areas, issues implementing new technologies and obstacles imposed by school structures. In light of these, the following proposals were suggested: placing greater emphasis on STE(A)M in initial and continuing teacher education, increasing support from schools and government bodies, encouraging collaborative work between teachers from different areas, adopting innovative strategies and methodologies and offering a clearer conceptualisation of STE(A)M.

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KEYWORDS
STEAM; systematic review; teachers; teaching practices

1. Introduction

At a time when education is facing numerous challenges, it is essential to meet the teachers´ needs by creating an environment that fosters both their professional development and the implementation of innovative approaches, such as the STE(A)M (Science, Technology, Engineering, Arts and Mathematics) approach. The focus on STEM has evolved over time to include the Arts, recognising the growing importance of creativity and artistic thinking as key elements of a well-rounded education. This integration of the Arts into STEM is seen as 'a way to foster creativity and gain new perspectives' (Teixeira et al., 2022). Integrating STE(A)M into teaching not only enriches the educational process, but also contributes to teacher motivation, which is directly reflected in student engagement and performance

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(Çiftçi & Topçu, 2022; Quigley & Herro, 2016). These approaches allow teachers to explore new ways of teaching, promoting a more creative and effective learning environment.

The STE(A)M approach emphasises the integration/articulation of areas in order to develop skills such as communication, problem-solving, reasoning and scientific and technological knowledge. Although the development of these skills seems to be more or less consensual in the understanding of STE(A)M, it is possible to find different conceptualizations in the literature. Teixeira et al. (2022) analyzed five conceptual and/or empirical and pedagogical STE(A)M models derived from different interpretations and conceptions of STE(A)M disciplinary integration/articulation: a Framework for Education (Yakman, 2011); STEM literacy framework (Falloon et al., 2020); a temporal model (Tytler et al., 2021); conceptual model (Quigley et al., 2020); pedagogical model (Lin & Tsai, 2021). Of the models analyzed, with regard to articulation, Yakman (2011) points to multidisciplinarity. Quigley et al. (2020) advocate a transdisciplinary model. The others adopt interdisciplinarity. However, there is a common assumption: the development of skills, abilities and competences in students and the promotion of collaborative work between teachers when inter- and transdisciplinary modalities are adopted. In this sense, the STE(A)M approach is seen as having the potential to change the educational paradigm.

The STE(A)M approach has been described in the literature as 'reporting a wide range of positive outcomes, with many scholars arguing STE(A)M-based curricula to be more suitable in fostering creative and higher-order thinking abilities necessary for dealing with (global) challenges in the context of the twenty-first century' (Hodl et al., 2022, p. 180). Several empirical studies have shown that teaching practices focused on the STE(A)M approach have beneficial impacts on student motivation and commitment, engagement in relation to STE(A)M subject areas and the overall development of attitudes and values (Li et al., 2022; Wu et al., 2021). Even with the potential of the STE(A)M approach, there are also numerous challenges and gaps that can be found in its development in practice (Çiftçi & Topçu, 2022). Currently, most teachers specialise in specific subjects and are only experts in their own areas, lacking a comprehensive understanding of all the content knowledge needed for STE(A)M education (Li et al., 2022). In the remaining years of schooling, from elementary school to higher education, researchers reveal that many of the difficulties presented are related to the lack of experience of teachers, the limitation of using pre-made scripts and curricular delimitations, as well as the difficulty of collaboration between teachers from different subject areas (Alkhateeb, 2018; Harris & De Bruin, 2018; Sulaeman et al., 2022).

This study aims to identify and analyze the potential, challenges and proposals for improvement to the challenges encountered in implementing the STE(A)M approach over the last 8 years. In this way, it is possible to provide suggestions that contribute to a more effective implementation of STE(A)M practices, based on the existing literature.

2. Methodology

This study is qualitative and bibliographical in nature. It is a systematic literature review that used two databases: Web of Science (WOS) and SCOPUS, based on key words in published articles that addressed teaching practices and teachers' perceptions of the STE(A)M approach.

This study was conducted in four key stages: (1) initial study question, (2) search and selection of relevant studies applying the inclusion and exclusion filters or criteria, (3) data extraction, and (4) analysis and synthesis of the studies.

The study's initial question is: What are the challenges and potential of implementing the STE(A)M approach in teachers' teaching practices?

To answer the problem question, the following questions were outlined:

Q1: What are the potentialities found in implementing the STE(A)M approach?
Q2: What challenges have been encountered in implementing the STE(A)M approach?
Q3: How can the challenges encountered in implementing the STE(A)M approach be overcome?

The ERIC database in Thesaurus was used to select the key words, starting with the terms that had already been selected in accordance with the research question, and the following key words were defined: 'teacher', 'teaching practices' and 'STEAM'.

The articles were selected using the inclusion and exclusion criteria of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart, and a total of 745 articles were initially obtained, as shown in Flow diagram (Figure 1).

The selection process initially resulted in 752 articles. The 'duplicates' criterion allowed the exclusion of 6 articles that were present in both WoS and Scopus databases. Next, 368 articles were removed because they were not 'open access'. Of the remaining 378, 90 were excluded because they did not fall into the 'Social Sciences' category. We only kept the publications that were accessible in the final evaluation phase (282) and that were published in the last 8 years, with the oldest article dating from 2016, as no articles published before that year met the criteria for inclusion in this review. Articles without 'STEAM' or 'STEM' in the title and/or abstract were also excluded 130 articles. Subsequently, we eliminated literature reviews (systematic and bibliometric) and studies focused only on students. After this screening, 124 articles were selected for in-depth reading and evaluation, with the aim of identifying those that really addressed the study's initial question. After thorough reading, 26 articles remained.

Analysis of these 26 articles made it possible to identify categories and subcategories, as shown in Table 1.

The categories were defined in advance, based on the main areas of interest related to the implementation of the STE(A)M approach in the educational context. The subcategories, in turn, emerged during the systematic analysis of the selected articles, representing recurring or specific themes that detail and complement the main categories. These categories reflect different dimensions of the implementation of the STE(A)M approach in the educational context.

3. Results and analysis

Given the current panorama and the expansion of STEM to STE(A)M in recent years, it is important to note how this inclusion of the arts translates into the selected studies. Of the 26 studies, 15 are about the STEM approach, 9 already include the arts (STE(A)M) and 2 are about both. This data demonstrates a change in the view of educators and teachers regarding the importance of the arts in students' education, although there is still some

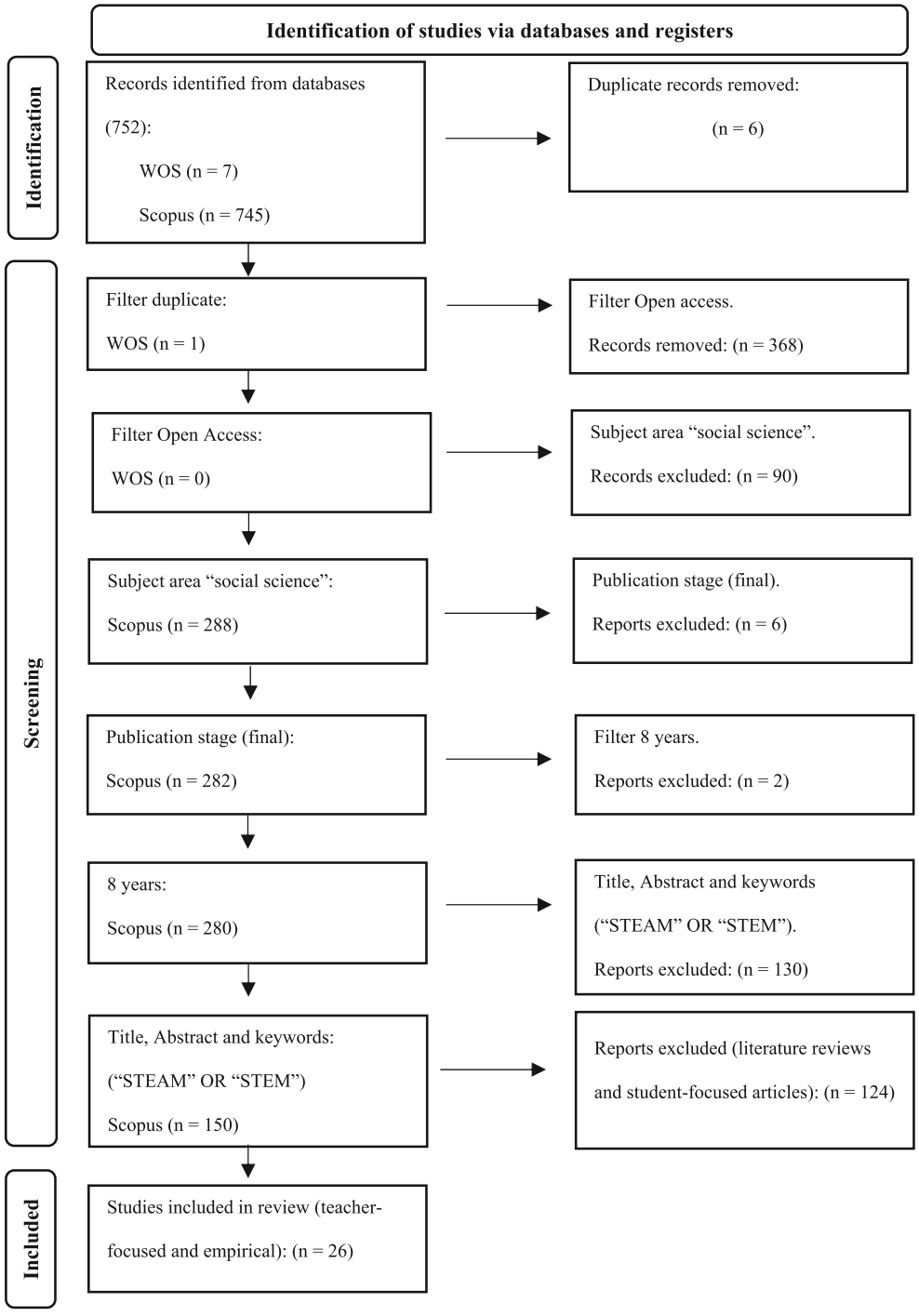

Figure 1. Flow diagram of the selection of papers analyzed.
Note: It was filled in using the PRISMA model (Page et al., 2021).

Table 1. Categories and subcategories of analysis for the systematic literature review.

Theme:	
Categories	Subcategories
Potential of implementing the STE(A)M approach	Holistic development of the student Technological and curricular adaptation Development of teacher practice
Challenges of implementing the STE(A)M approach	Teaching practices Teacher training and capacity building Lack of guidance and school policies
Proposals for addressing the challenges of implementing the STE(A)M approach	Teachers' Professional Development Integrated STE(A)M curriculum Support from public and school institutions

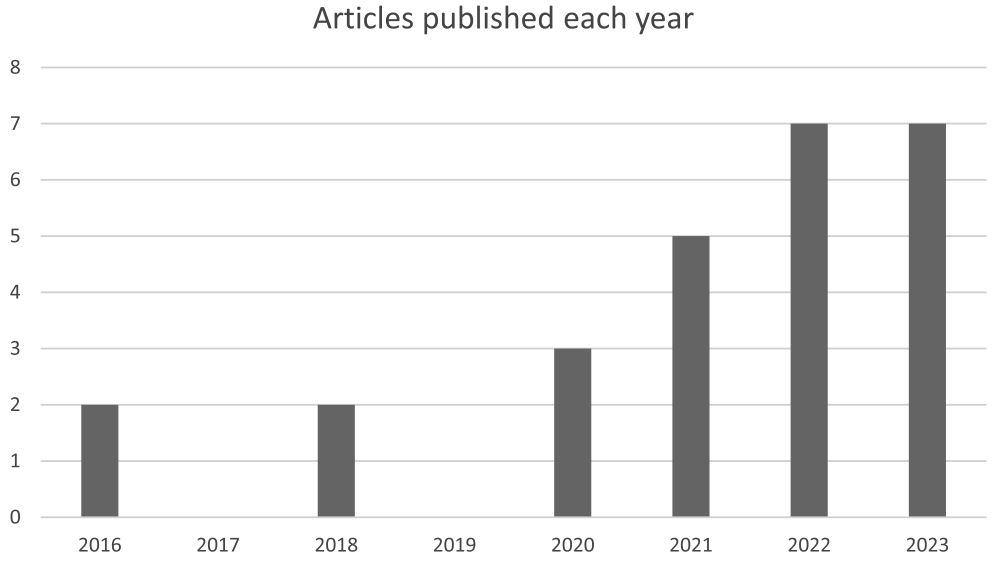

Figure 2. Articles published each year.

reluctance for this inclusion to take place. In this study we use the term STE(A)M encompasses both the STEM, and its extension to include the Arts. The studies are distributed as follows in terms of time: two from 2016, two from 2018, three from 2020, five from 2021, seven from 2022 and seven from 2023 (Figure 2).

Regarding the years of schooling covered in these studies, five are early childhood educators, nine are elementary school teachers, eight secondary school teachers, one vocational teacher and four in in-service teacher training. Several studies (Boice et al., 2021; Dokumaci et al., 2023; Harris & De Bruin, 2018; Jho et al., 2016; Nguyen et al., 2020) encompass more than one cycle of education, for example, studies that include both elementary and middle school teachers. It is observed that the most frequently studied contexts are elementary and middle school education. In terms of areas, some studies include teachers from different areas, for example in the study by Olivato and Silva (2023), generalist teachers, art teachers and English teachers participated. Quigley and Herro (2016) included science and math teachers. In this way, there is a diversity in both the levels of education and the

areas in which the teachers involved work, highlighting the breadth of the studies and the multiplicity of educational contexts analyzed.

In the research by Sulaeman et al. (2022), most teachers in the study stated that it makes sense and is important to implement the STE(A)M approach in all school years. After this initial analysis of the studies, the review of the categories and subcategories found follows:

3.1. Potential of implementing the STE(A)M approach

3.1.1. Holistic student development

The literature analyzed points to different potentials of the STE(A)M approach in the holistic development of students. In the context of primary education, the participants in the study by Lupión-Cobos et al. (2023) revealed that their students developed the ability to learn autonomously and with peers through the implementation of a STE(A)M project, which, in the view of another teacher in the same study, led to an improvement in knowledge acquisition. Thus, the authors highlighted the importance of scientific-technological literacy to prepare students for everyday situations. Similarly, in secondary education, Quigley and Herro (2016) argue that young people need skills such as innovation, creativity and critical thinking to face complex challenges. The teachers in the study reported the students' enthusiasm for sharing information about their discoveries and solutions, as well as the students' recognition of the importance of mathematics, which they previously did not understand.

Empirical studies corroborate this perspective. For example, participants in the study by Quigley et al. (2020) identified that STE(A)M can promote curiosity and problem-solving skills, those in the study by Mafugu et al. (2022) concluded that the interdisciplinary approach favours the exchange of values and knowledge between disciplines.

However, there are variations depending on the educational context and teachers' knowledge of the conceptualisation of STE(A)M (Alkhateeb, 2018). Quigley et al. (2020) point out that, despite the challenges, the inclusion of the arts allows for greater student involvement in formulating solutions and integrating knowledge. On the other hand, Akkoyun and Topalsan (2022) point out that the STEM approach (without the addition of the arts) increases students' creativity and gives them a different perspective. These studies show that the impact of the approach depends on the curriculum structure and the support given to teachers.

3.1.2. Technological and curricular adaptation

A constantly evolving society requires schools and curricula to be constantly adapted, so integrating technology into teaching, especially in the STE(A)M context, has proved fundamental to promoting more effective and innovative learning. Empirical studies highlight this importance. For example, Quigley and Herro (2016), who carried out their study in secondary schools in the United States, found that the effective incorporation of new technologies resulted in a measurable increase in teacher motivation, who felt inspired by the innovations implemented.

Similarly, Correia and Baptista (2021) carried out research into initial teacher training. Their data showed that the use of Information and Communication Technologies (ICT), in conjunction with active methodologies, not only increased trainees' motivation, but also helped them overcome conceptual difficulties in teaching STEM subjects. Mafugu et al.

(2022) carried out a study in Natural Sciences and Technology classrooms, covering primary and secondary schools, where, through systematic observations and the application of questionnaires to teachers and students, they found that learning improved significantly when students had opportunities for hands-on interaction with educational materials.

In the field of robotics, Budiyanto et al. (2022) carried out a case study in technical schools. The results showed that learning based on this technology facilitated the development of skills in programming, problem-solving and computational thinking, contributing to a more systematic integration of technology into the curriculum. In addition, Çoban et al. (2022) investigated the application of Virtual Reality (VR) in secondary schools in the context of STEM subjects. They demonstrated that VR provides an immersive experience that facilitates the understanding of abstract and complex concepts, increasing student engagement.

With regard to educational reforms, Alghamdi (2023) analyzed the Tatweer programme, implemented in Saudi primary and secondary schools, adopting a mixed approach that combined analysis of student performance, evaluation of technological infrastructure and interviews with teachers. This research revealed that investment in infrastructure and teacher qualifications has contributed to more dynamic teaching in line with the demands of the twenty-first century.

In addition to the empirical data, teachers' opinions and experiences underline the relevance of technological integration. Teachers' reports indicate that incorporating these tools fosters motivation and creates an environment conducive to pedagogical innovation, as evidenced in the studies by Quigley and Herro (2016) and Correia and Baptista (2021). Similarly, teachers emphasise that strategies that promote experimentation and hands-on manipulation of materials- as demonstrated by Mafugu et al. (2022) – are essential for effective learning.

In short, the analysis of the studies presented shows that technology plays a central role in the implementation of STE(A)M teaching. Thus, the effectiveness of technological integration depends not only on the availability of resources, but also on ongoing training and planned implementation, allowing the benefits of technological innovations to be maximised in the educational context.

3.1.3. Development of teacher practice

The literature analyzed shows that implementing the STE(A)M approach has a significant impact on teachers' professional development, especially when active methodologies and interdisciplinary collaboration are used. For example, Boice et al. (2021) show that participation in training programmes strengthens the common pedagogical base and reduces resistance to change, allowing for a more equitable integration of STE(A)M areas. In higher education, Wawan et al. (2022) observed that the use of methodologies such as project-based learning in initial teacher training promotes the development of scientific and reflective skills, encouraging trainees to construct knowledge in a progressive way that is adapted to contemporary challenges.

In addition, Quigley and Herro (2016) point out that the active involvement of teachers in curriculum development, through the application of active methodologies – namely Problem-Based Learning, Design Thinking, Project-Based Learning and research activities – not only stimulates critical reflection on one's own teaching practice, but also fosters teacher creativity. This perspective is reinforced by the findings of Amran et al.

(2021), who indicate that professional development is an essential need, as demonstrated by the demands of pre-school teachers. Additionally, Boice et al. (2021) point out that participation in training programmes positively impacts teachers' collaboration, pedagogy, self-efficacy and arts integration practices, underlining the importance of training strategies that promote collaborative and innovative practice.

The studies analyzed suggest that the effectiveness of STE(A)M implementation is closely linked to the level of teacher training and support received. Active involvement in creating and adapting the curriculum, coupled with participation in professional development programmes that promote collaboration and the use of innovative methodologies, is essential.

3.2. Challenges of implementing the STE(A)M approach

3.2.1. Teaching practices

Several studies have highlighted the challenges faced in implementing the STE(A)M approach, with the main difficulties being related to time management, a lack of material resources, a shortage of financial support, insufficient training (initial and ongoing), and a lack of adequate guidance for teachers. In addition, the difficulty of working with an interdisciplinary curriculum and the challenge of promoting collaborative work were also widely mentioned. Studies such as those by Boice et al. (2021) reveal that the lack of time to plan and collaborate with colleagues is a significant barrier to the implementation of the STE(A)M approach. Complementarily, Quigley et al. (2020) emphasise that teachers need dedicated periods for interaction with their peers to develop relevant problems, which would facilitate the exchange of feedback. Jho et al. (2016) further reinforce that the scarcity of time and the lack of confidence among teachers, often resulting from inadequate training in STE(A)M, are additional obstacles to the implementation of this approach. These perceptions reflect the necessity of time and a work environment that fosters collaboration and sharing.

Akkoyun and Topalsan (2022) analyzed the impact of anxiety and stress on teachers who implement the STEM approach without previous experience. The results indicated that teachers with less experience or who apply the approach without adequate training have high levels of anxiety. This study reinforces the need to invest more in training and empowering teachers to reduce the stress related to implementing STE(A)M practices and improve their teaching effectiveness. The analysis of the studies reveals that the challenges to implementing the STE(A)M approach are multifaceted, ranging from training limitations to resistance from teachers and students themselves. These results highlight the need for greater institutional support, continuous professional development, and curriculum adaptation to ensure more effective adoption of the STE(A)M approach in schools.

3.2.2. Teacher training and capacity building

The studies analyzed reveal several challenges associated with the effective implementation of the STE(A)M approach, with an emphasis on inadequate training and lack of support for teachers. Quigley and Herro (2016) point out that research into the effectiveness of STE(A)M practices is still limited, leading to a fragmented understanding of how to structure and implement this approach in schools. The study, which involved 21 teachers collaborating on the implementation of STE(A)M, pointed to a lack of knowledge about

the inclusion of the arts as a significant barrier, reflecting a narrow view of the integration of these disciplines. In addition, difficulties were identified such as the lack of institutional support, the absence of a clear and structured definition for STE(A)M, the lack of guiding documents and the lack of continuous and specific training. These factors, coupled with resistance to change, compromise teachers' ability to adopt the approach effectively (Amran et al., 2021; Nguyen et al., 2020; Wu et al., 2021).

Similarly, Jho et al. (2016) address the practical challenges faced by teachers, such as the shortage of time and material resources, as well as teachers' lack of confidence, which is directly linked to the absence of specific training. Alkhateeb (2018) also highlights teachers' dependence on pre-defined scripts and materials; when these resources are not available, teachers find it difficult to develop alternatives, which negatively affects the quality of teaching and, consequently, student performance.

The difficulty of teaching areas outside the teachers' specialisation is another obstacle identified. Nguyen et al. (2020) report that many teachers face challenges when trying to teach in an interdisciplinary way, due to the traditional segmentation between STEM subjects, which prevents the effective integration of these areas in teaching (Correia & Baptista, 2021; Wu et al., 2021). Amran et al. (2021) reinforces this view, pointing out that the incorporation of creativity into STEM teaching is hampered by a lack of specific training, time constraints and financial limitations, resulting in a shortage of adequate support and guidance.

Overall, the analysis of the studies shows that the challenges for teacher education and training, both initial and ongoing, are broad and multifaceted, and directly affect the successful implementation of the STE(A)M approach. This suggests the need for substantial investment in training programmes, greater curricular clarity, and institutional support to strengthen teachers' confidence and effectiveness in this area.

3.2.3. Lack of guidance and school policies

The studies analyzed highlight significant challenges related to the lack of clear guidelines and institutional support for the implementation of the STE(A)M approach. Although the positive results of non-traditional assessment practices, such as formative assessments based on the STE(A)M approach, are well documented, the study by Quigley and Herro (2016) revealed that many teachers are forced to apply traditional assessments due to the bureaucratic demands of school institutions. This scenario highlights a conflict between pedagogical innovations and the rigidity of assessment policies, which often do not reflect ongoing methodological changes.

Harris and De Bruin (2018) also identify the limitations imposed by schools' organisational structures, pointing out that although interdisciplinarity is recognised as crucial, its implementation is hampered by the constraints of the education system. The lack of adequate guidance documents contributes to the difficulty in effectively applying interdisciplinary approaches, as indicated by Nguyen et al. (2020). This gap in guidance can result in problems such as those observed in the study by Quigley et al. (2020), where the lack of the lack of relevance of the problems addressed negatively impacted the development of lessons.

In broader contexts, the study by Lupión-Cobos et al. (2023) highlights the growing interest of the Spanish education system and UNESCO in including the STE(A)M

approach in the curriculum, recognising it to improve the teaching and learning process. Similarly, in Ireland, there has been a significant increase in government support for the STEM approach over the last 10 years, as noted by O'Neill et al. (2023). However, in Brazil, despite national objectives to promote interdisciplinary integration, the STE(A)M approach is not specifically mentioned. The study by Olivato and Silva (2023) reveals that Brazilian teachers still have a limited understanding of these concepts, which indicates that implementation depends not only on explicit policies, but also on an ongoing effort to train and empower teachers.

The studies indicate that although there is an increased focus on STE(A)M subjects in the curricula of several countries, the lack of clear educational policies and insufficient professional development of teachers remain significant barriers. To ensure effective implementation of the STE(A)M approach, it is crucial to invest in teacher training and professional development, as well as ensuring clear guidance and institutional support.

3.3. Proposals for addressing the challenges of implementing the STE(A)M approach

To overcome the challenges, the authors of the different articles in this systematic literature review propose several conclusions.

3.3.1. Teachers' professional development

The STE(A)M approach has been recognised as a significant change in teachers' pedagogical practice, as highlighted by Quigley and Herro (2016). The integration of active methodologies, such as Problem-Based Learning, Design Thinking, Project-Based Learning, inquiry activities and the use of technological resources, is considered essential to motivate teachers to face conceptual challenges (Correia & Baptista, 2021). Correia and Baptista (2021) stress the importance of continuous investment in the professional development of practicing teachers, so that they can overcome erroneous and outdated scientific mental models.

In the study by Amran et al. (2021), teachers' needs are described, including the need for specialised training courses, expert guidance, and adequate financial resources to support the effective integration of creativity into STEM teaching.

Several authors reinforce the need to invest in teachers' continuous professional development as a key solution for the successful implementation of the STE(A)M approach (Alghamdi, 2023; Sellami et al., 2022; Sulaeman et al., 2022; Wijaya et al., 2022). The study by Romero-Ariza et al. (2021) highlights the importance of continuous professional development and support for changes in teachers' beliefs to effectively promote the STE(A)M approach in education.

3.3.2. Integrated STE(A)M curriculum

The effective integration of subject areas in the development of STE(A)M activities faces several challenges. One suggested approach is to start from scientific and social issues, which allows the teacher to address problems more broadly, beyond the traditional boundaries of STE(A)M subjects (Nguyen et al., 2020). This approach can facilitate a more fluid integration between different areas of knowledge.

Sharing experiences and challenges between teachers is considered an important strategy to support pedagogical practice (Wu et al., 2021). Amran et al. (2021) highlights the need to establish collaborative partnerships to combine the strengths and skills of different domains, as a solution to the limitations of traditional subject teaching. These partnerships can help overcome teachers' difficulty in approaching subjects in an interdisciplinary way, promoting a more integrated and cohesive approach.

Correia and Baptista (2021) state that implementing STEM practices can make it easier to approach complex topics in specific areas where teachers may have difficulties. The study reveals that teachers were able to overcome their conceptual difficulties about certain scientific content by using interdisciplinary methods and resources, which also contributed to their motivation.

In addition, Boice et al. (2021) emphasise the need for more research on STE(A)M programmes so that teachers have a deeper understanding of the activities and methodologies involved. This greater understanding is essential for effective implementation and for addressing the challenges associated with STE(A)M curriculum integration.

These approaches suggest that to overcome the challenges of STE(A)M curriculum integration, it is crucial to foster collaboration between teachers, promote interdisciplinary practices and invest in scientific research that helps clarify and improve pedagogical practices within the STE(A)M curriculum.

3.3.3. Support from public and school institutions

Effective implementation of the STE(A)M approach requires collaborative partnerships that integrate knowledge and skills from different areas. It is essential that teachers from different disciplines work together to build STE(A)M lessons (Harris & De Bruin, 2018). This collaborative work is supported by the support of school principals and political institutions, especially in acquiring the necessary physical and material resources.

Quigley et al. (2020) point out that schools should provide ongoing support and professional development to teachers, helping them to design relevant and integrated problems in STE(A)M activities. Sellami et al. (2022) reinforce the need to train teachers through STE(A)M-focused professional development programmes and the provision of adequate resources. The importance of support from school management is also highlighted by Nurtanto et al. (2020), who emphasise the need for institutional support in distributing material resources and facilitating the implementation of STE(A)M practices.

In addition, Quigley et al. (2020) report that it is crucial to offer time flexibility to teachers, allowing them to plan STE(A)M lessons collaboratively with their colleagues. This flexibility is important for creating coherent problems, generating ideas and providing feedback, which contributes to a more effective implementation of the STE(A)M approach.

These studies suggest that support from public and school institutions is essential for the successful implementation of the STE(A)M approach. Collaboration between teachers, institutional support and the provision of adequate resources are key to overcoming challenges and ensuring an integrated and effective pedagogical practice.

4. Conclusion

This systematic literature review highlights the central role of teachers in the successful implementation of the STE(A)M approach, revealing that its success depends above all on

a strong investment in teachers' professional development. Ongoing training, focused on innovative strategies and the promotion of interdisciplinary integration, enables teachers to adopt teaching practices in line with STE(A)M objectives, thus contributing to a notable improvement in educational quality.

In addition to training teachers, the effective implementation of this approach requires profound transformations in various aspects of school practice. Curricula need to be rethought to cohesively integrate the various disciplines, the structure of schools needs to be reorganised to support interdisciplinary practices and training models need to be adapted to meet the emerging needs of teachers. The adequate provision of material and financial resources is also an indispensable element in consolidating these changes.

Despite the potential revealed, significant challenges remain, namely insufficient initial and ongoing training in STE(A)M, resistance to change on the part of some teachers and a lack of resources which sometimes limits the application of interdisciplinary practices. To overcome these barriers, it is imperative to develop more engaging and effective training programmes that promote a culture of innovation and flexibility in schools. The development of curriculum proposals based on research evidence can also serve as a guide for teachers to implement and adjust the STE(A)M model consistently.

The educational transformation enhanced by STE(A)M depends on the strengthening of teachers' professional development, the revision and integration of curricula and robust institutional support, both in terms of funding and resources. This ongoing commitment to capacity building and innovation is the indispensable foundation for overcoming the challenges inherent in implementing this approach and for fully exploiting the opportunities it offers, preparing students for the challenges of the contemporary world.

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Data availability

I, Patrícia Bertolo Teixeira, bearing Citizen Card (Documento Cartão de Cidadão), n° 14845800, as first author of this manuscript, confirm that I make the data available for publication and that I understand the terms of the publicly available data policy.

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Appendix

The articles are organised in chronological order.

Article	Descripton (Focus and method)
Quigley and Herro (2016). Finding the joy in the unknown: implementation of STEAM teaching practices in middle school science and math classrooms.	To analyze the implementation of STE(A)M teaching practices in secondary school classrooms. 21 science and math teachers from 7 schools took part in the study. Data was collected through reflective diaries, artifacts created by teachers and students and observation.
Jho et al. (2016). An analysis of STEM/STEAM teacher education in korea with a case study of two schools from a community of practice perspective.	To investigate STE(A)M teacher training and the conditions for its successful implementation in the classroom. Through participant observation, interviews and document collection, case studies were carried out with 2 research communities of secondary and elementary school teachers.
Harris and De Bruin (2018). Secondary school creativity, teacher practice and steam education: an international study.	To understand how creativity is understood in secondary schools by focusing on creative and critical thinking by teachers and students. Data collection included interviews with participants comprising 24 focus groups. Reflections from 75 secondary school teachers from different countries were analyzed.
Alkhateeb (2018). The degree practices for mathematics teachers STEM education.	To investigate the STEM teaching practices of mathematics teachers. 30 math teachers took part in the study. The methodology is descriptive analytical, by observation.
Nurtanto et al. (2020). Vocational teachers' perceptions and perspectives in the implementation of STEM learning in the twenty-first century.	To analyze teachers' perspectives on the STEM approach. 157 vocational education teachers were surveyed, 10 of whom were interviewed in depth.
Quigley et al. (2020). STEAM designed and enacted: understanding the process of design and implementation of STEAM curriculum in an elementary school.	To understand how teachers can design and implement STE(A)M teaching practices. The planning, reflections, classroom observation and field notes of collaborative groups of kindergarten teachers and elementary school teachers in implementing the STE(A)M approach in the classroom were analyzed.
Nguyen et al. (2020). Measuring teachers' perceptions to sustain STEM education development.	To identify teachers' perceptions of the STEM approach. Data was collected from 186 secondary and higher education teachers.
Amran et al. (2021). Assessing preschool teachers' challenges and needs for creativity in STEM education.	To assess the needs and challenges of promoting creativity in the STEM approach. 22 kindergarten teachers were interviewed.

(*continued*).

Article	Descripton (Focus and method)
Boice et al. (2021). Supporting teachers on their STEAM journey: a collaborative steam teacher training programme.	To gather information about the experiences of teachers who participated in a STE(A)M training programme. Surveys, focus groups and reflections from 17 elementary-school, middle-school, and high-school teachers were analyzed.
Romero-Ariza et al. (2021). Changing teachers' self-efficacy, beliefs and practices through steam teacher professional development.	To evaluate the impact and self-efficacy of an international teacher professional development programme using the STE(A)M education model. The study was mixed and involved 102 secondary school teachers from different areas. Of these, 78 answered a pre-test questionnaire, 51 a post-test and 43 both.
Shaw et al. (2021). Immersive-learning experiences in real-life contexts: deconstructing and reconstructing vietnamese kindergarten teachers' understanding of steam education.	To analyze teachers' perspectives on the potential and challenges of the STE(A)M approach. The study adopted a qualitative and interpretative methodology and involved 105 kindergarten teachers. Data was collected in a participatory way, using photographic images and surveys.
Wu et al. (2021). Transdisciplinary approach in middle school: a case study of co-teaching practices in steam teams.	Observing and documenting the daily teaching activities of the STE(A)M team. The study included the observation of more than 100 lessons by 8 8th grade teachers from different subjects.
Akkoyun and Topalsan (2022). Science education and STEM applications in primary school: elementary school teachers´anxiety levels.	To analyze the anxiety levels of classroom teachers who have had STEM training, and their opinions on STEM training activities. 250 teachers took part. An anxiety scale was used as the data collection tool and an interview was conducted with 10 elementary school teachers
Budiyanto et al. (2022). Computational thinking development: benefiting from educational robotics in STEM teaching.	Analyze the correlation between computational thinking and the STEM approach in the learning context; verify the role of robotics in implementing the STEM approach. Data was collected from 8 initial training teachers through interviews and observation.
Mafugu et al. (2022). Preservice primary teachers' perceptions of STEM-based teaching in natural sciences and technology classrooms.	To understand the perception of initial training teachers about teaching natural sciences and technology in the classroom based on the STEM approach. Five participants were analyzed, selected from a group of 42 initial training teachers. Lesson plans and reflections were used to analyze the results.
Martínez-Borreguero et al. (2022). Cognitive and emotional development of STEM skills in primary school teacher training trough practical work.	To analyze the cognitive, emotional, and didactic development of STEM skills in trainee elementary school teachers. A quasi-experimental research design was used with a control group, experimental group, pre-test, and post-test. 345 future elementary school teachers in the final year of their course took part.
Sellami et al. (2022). Exploring teacher´s perceptions of the barriers to teaching STEM in high schools in qatar.	To understand the barriers that affect STEM teaching in the country's secondary schools. Questionnaires were administered to 299 secondary school teachers.
Sulaeman et al. (2022). Teacher readiness in STEM education: voices of indonesian physics teachers.	To explore the preparation of physics teachers to implement the STEM approach. The study was based on the responses of 101 secondary school teachers to 6 open-ended questions.
Wijaya et al. (2022). Predicting factors influencing preservice teachers´behavior intention in the implementation of STEM education using partial least squares approach.	To determine the factors that influence the intentions of initial training teachers, as well as the effects of gender and age on the implementation of the STEMapproach. The participants were secondary school teachers in initial training. 30 questionnaires on behavioural were distributed to 201 teachers.
Alghamdi (2023). Exploring early childhood teachers' beliefs about steam education in saudi arabia.	To explore Saudi kindergarten teachers' beliefs about the STEM approach in early childhood settings. 245 early childhood educators were surveyed. The survey was quantitative.
Olivato and Silva (2023). Interdisciplinary teaching practices in steam education in brazil.	To explore elementary school teachers' self-efficacy beliefs about interdisciplinary teaching practices related to the STE(A)M approach and project-based learning. Interviews were conducted with 15 elementary school teachers.
Dokumaci et al. (2023). The effect of STEM basic level education on teachers' STEM practices self-efficacy.	To analyze the impact of the STEM approach on teachers' self-efficacy. To collect teachers' opinions on STEM education. A self-efficacy scale was used, and 31 teachers were interviewed, 17 STEM teachers (mathematics, science, physics and chemistry, biology, computer science) and 14 elementary school teachers.

(*continued*).

Article	Descripton (Focus and method)
Fields and Kafai (2023). Supporting and sustaining equitable STEAM activities in high school classrooms: understanding computer science teachers' needs and practices when implementing an e-textiles curriculum to forge connections across communities.	Understanding teachers' needs and practices in relation to implementing the STE(A)M approach. The reflections of 8 secondary school teachers were analyzed.
Lupión-Cobos et al. (2023). Challenges and opportunities to teaching inquiry approaches by STE(A)M projects in the primary education classroom.	This study analyzes teachers' perceptions of their ability to design and develop ste(a)m projects in a professional development programme. 2 case studies were carried out with 2 elementary school teachers. Data was collected through lesson observation, rubric evaluation, interviews, and questionnaires.
O'Dwyer et al. (2023). 'I have seen STEM in action and it's quite do-able!' the impact of an extended professional development model on teacher efficacy in primary STEM education.	To analyze the impact of a STEM professional development programme on teachers' effectiveness in implementing the STEM approach. The study involved 17 elementary school teachers, 2 head teachers and 1 professional development trainer. Pre- and post-programme interviews and surveys were used.
O'Neill et al. (2023). Hungry for more: early childhood educators' perspectives on STEM education, teaching and professional development.	To analyze the impact of a STEM professional development programme on teachers' effectiveness in implementing the STEMm approach. The study involved 17 elementary school teachers, 2 head teachers and 1 professional development trainer. Pre- and post-programme interviews and surveys were used.