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A systematic review of empirical studies: Outcomes from programs informed by STEM reforms and policies

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Abstract

The study aims to identify trends in STEM education policies and reforms during the last twenty-three years to understand how STEM education has developed and explain the paradox between suggested policies and outcomes in STEM education. A total of 1,493 articles were identified from the database search. After the initial analysis, 27 articles were included in the review and analyzed using qualitative content analysis and open coding. First, the need to approach STEM education as an interdisciplinary, integrated approach, focusing on problem solving by the students emerged. Furthermore, the reforms described in the published papers are happening either outside of the formal school time, or on a small scale and are not systematic efforts to address STEM education concerns at local, national or international level. The gap is identified on putting in practice, on a large scale, integrated STEM education. Implications and suggestions for action are discussed.

Keywords: STEM education, STEM policies, STEM reforms

INTRODUCTION

STEM education has been emphasized in different educational systems worldwide (Achieve, 2013; National STEM School Education Strategy, 2015; EU STEM Coalition, 2016), with countries announcing initiatives to further support its development. The acronym STEM refers to the four separate and distinct fields known as science, technology, engineering, and mathematics. STEM education is sometimes referred to as the broad education category involving any of the four disciplines; thus, teaching any of the four disciplines is sometimes referred to as STEM education (Cotabish et al., 2013; Watt et al., 2013). More recent definitions, which are endorsed in this paper, consider STEM education as an interdisciplinary or transdisciplinary approach which focuses on teaching the four different subjects or disciplines in an integrated way using a problem-based approach, based on real world applications (Takeuchi et al., 2020). Therefore, STEM education focuses on developing students' competences linked with critical thinking, problem-solving, and inquiry-based learning, and supports them in understanding the connection between STEM and the real world (Breiner et al., 2012; Labov et al., 2010). STEM education seeks to develop and provide innovative solutions to global issues, with an emphasis on the 2030 sustainable development goals, and should be based on a curriculum that can 'prepare young people with required competences to live sustainable, fulfilled and healthy lives in the rapidly changing world of the 21st century' (Organization for Economic Co-operation and Development [OECD], 2019, p. 3).

The emphasis on STEM education in policy is linked to the need for more people in the STEM workforce, and more citizens with STEM related skills (EU STEM Coalition, 2016) to support the growing economies (Hoeg & Bencze, 2017). Various reports (Achieve, 2013; EU STEM Coalition, 2016; EU, 2019; OECD, 2019) highlight the demand for STEM competences, especially in young people. However, students' attitudes towards STEM subjects continue to decline (i.e., EU, 2019; Osborne & Dillon, 2008) and their knowledge and skills in STEM subjects, such as mathematics and science is deteriorating based on results from international studies (i.e., PISA 2018).

The paradox here is the following: policy has long recognized the need for STEM education as a way to improve the skills and employability of future citizens

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Contribution to the literature

- This study systematically identifies gaps in STEM education reform and policy.
- This study systematically addresses the practical barriers and opportunities in achieving integrated STEM education.
- This study examines the alignment between policies, reforms, and their implementation in the context of integrated STEM education.

(Hoeg & Bencze, 2017) and many reports have been published about the need to implement STEM education in schools (Achieve, 2013; EU STEM Coalition, 2016). Despite the efforts on policy level, there is limited observed improvement on students' STEM related outcomes (i.e., skills, attitudes, knowledge) according to international studies and policy reports (Evagorou et al., 2024). To explore this paradox, the purpose of this paper is to identify empirical outcomes from the implementation of STEM policies and reforms during the last 23 years. Specifically, this systematic literature review aims to identify the themes that emerge in the studies examining STEM policies and reforms since 2000.

STEM Education Policies and Reforms

The idea to explore findings of empirical studies about the outcomes of STEM policies and reforms was an outcome from an analysis the authors did (Evagorou & Konstantinidou, 2023) for the purposes of a bigger project, the ICSE STEM Academy. The analysis focused on the policy needs of 13 European countries and based on the findings it was observed that all countries state that they engage students in STEM education; none of the countries shares our definition of integrated and interdisciplinary STEM; and none of the countries have STEM curricula as part of formal school learning. To understand this discrepancy between the emphasis on STEM education in reports and policies, students' continuing decline in attitudes and knowledge in STEM, and what is actually reported in different countries, we decided to explore outcomes of STEM policies and reforms as reported in research papers since 2000.

A question that came across as we started exploring policies and reforms was what exactly we mean by the two terms. According to Patrinos et al. (2013) education policy refers to policy actions, specific programs, and systemic changes that are linked to the suggested change or innovation. Reforms on the other hand refer to changes in educational policy and practice. The main aim of any reform in education is 'to improve educational programs and practices which will, in turn, assist to meet overall objectives of education in more effective ways' (Irez & Han, 2011, p. 252). The driving force behind all educational policies and reforms is the improvement of the quality of education (Patrinos et al., 2013), and quality of education is measured in different ways, with the most usual being student achievement.

Current STEM education reforms focus on building a strong foundation for scientific and STEM literacy (Johnson et al., 2020) by moving from an understanding of basic STEM subjects (Crawford et al., 2021) to the acquisition of those 21st century skills which have been claimed to have a significant place on every country's agenda (Hernandez et al., 2014). In the US the most important reform related to STEM education is the next generation science standards (NGSS) which was first set up in 2013 (Achieve, 2013) and focuses on the integration of the STEM disciplines, knowledge, and skills for future citizens (Rennie et al., 2012). Additionally, the US has also implemented reforms (e.g., PCAST 2012) to increase the recruitment of diverse populations to STEM studies. During the last decade the number of STEM schools in the US has grown significantly (Johnson & Sondergeld, 2020) with the aim of closing the STEM pipeline (Carnevale et al., 2011; Dickman et al., 2009).

In China the Ministry of Education proposed in 2016 the implementation of STEAM as an educational approach and a STEAM school alliance was formulated with schools teaching STEAM from early childhood until the end of formal schooling (Li & Chiang, 2019). In Australia the government focused the reforms on promoting problem solving, critical thinking and creative skills as part of STEM education and on student's engagement, participation and aspiration and increasing teacher quality in teaching STEM (National STEM School Education Strategy, 2015).

In Europe, an integrated STEM education strategy is not observed on national and European level (European Schoolnet and Texas Instrument, 2018). Europe highlighted the demand for STEM competencies, especially in young people, such as problem solving and communication skills. STEM skills and improving women participation in STEM are the main objectives of the European year of skills 2023. Through this initiative, Europe targets the development of skills for jobs related to STEM that help tackle new challenges for European economies by funding EU research programs.

STEM Education and Teachers

One of the driving forces behind any change in education are teachers, and multiple studies are reporting efforts to design innovative courses for pre- and in-service teachers to prepare them to implement integrated STEM education in their practice (e.g., Berlin & White, 2012; Koirala & Bowman 2003). The main emphasis in such integrated approaches is on connected, interdisciplinary, multidisciplinary, or transdisciplinary approaches (Evagorou, 2024; Ryu et al., 2018). An important element of teaching and learning however is identifying those instructional practices that can potentially enhance STEM learning to include them in the teacher development courses (Thibaut et al., 2018).

Self-efficacy (e.g., Kelley et al., 2020; Konstantinidou & Scherer, 2022) in teaching STEM was one of the key factors identified as affecting STEM teaching (i.e., Evagorou & Nisiforou, 2020). For example, when teachers teach conceptually challenging content associated with many STEM themes, but they do not feel comfortable, they tend to avoid teaching the topic, or teaching the subject thoroughly (Bursal & Paznokas, 2006; National Research Council [NRC], 2007). Consequently, it is supported that high-quality teacher professional development (PD) must support and reinforce the growth in teacher skills and self-efficacy (Bray-Clark & Bates, 2003).

Furthermore, research has examined the relationship between teachers' content knowledge and student achievement (e.g., Keller et al., 2017; Metzler & Woessmann, 2012) and it is supported that effective PD should provide also opportunities for educators to increase their knowledge and understanding of STEM content (NRC, 2007).

At the same time, teachers may also require instructional support beyond PD (Scherer et al., 2021), as STEM integrated approach requires profound restructuring of the curriculum and lessons (Nadelson & Seifert, 2017). This support can be facilitated via teacher collaboration, PD, or school leadership. In particular, the support the school provided in the teaching of STEM is an important element for the successful and everyday implementation of STEM in the classrooms by ensuring the proper resources (Lamberg & Trzynadlowski, 2015) and the guidance for teachers as they implement integrated STEM curricula (Dare et al., 2018).

STEM Education and Students

Many countries are concerned with the decreased numbers of students that are recruited in STEM fields, even though worldwide educational policy reports warn about the need for this type of professionals in the immediate future (Trilles & Granell, 2020). Furthermore, organizations and research committees, for example, the OECD (2019) are advocating for the notions of critical thinking skills, problem solving skills, and creativity as some major components of the 21st century skills that need to be possessed by 21st century students. Based on a recent report by OECD (2019), those skills 'prepare young people with required competences to live sustainable, fulfilled and healthy lives in the rapidly changing world of the 21st century' (p. 3). For instance, having students engage in hands-on activities that allow them to discover new concepts and develop new understandings (Satchwell & Loepp, 2002) by providing students a real-life context-based academic learning and problem-solving skills (Cunningham et al., 2020; Hernandez et al., 2014), enriching higher-level thinking skills (Kelley & Knowles, 2016), improving conceptual understanding and academic performance (National Academy of Engineering and National Research Council [NAE/NRC], 2014; Nite et al., 2017).

Research claims that the interdisciplinary STEM approach promotes those identified skills as it starts with a real-world problem or issue and at its core is the engagement of students in the critical thinking and problem solving, and the building of dispositions towards STEM subjects, that will prepare students for productive futures, rather than subject-specific content and skills (Revák et al., 2024; Thibaut et al., 2018).

Purpose of the Study

The purpose of the study is to identify empirical outcomes from the implementation of STEM policies and reforms since 2000. The importance of this study lies in the fact that by understanding the outcomes of the implementation of these policies and reforms in different countries can potentially support us in planning the next steps in STEM education based on lessons learned.

Specifically, the research questions guiding this study are, as follows:

RQ1. What characterizes the articles examining STEM policies and reforms in terms of their

(a) aim,

(b) research approaches, and

(c) the country each study took place in?

RQ2. What themes emerge from the articles focusing on the implementation of STEM reforms and policies in the last 23 years?

METHODOLOGY

The present study followed the procedures of systematic review by the preferred reporting items for systematic reviews and meta-analyses model (Moher et al., 2009).

The process was specific and included the following steps (Kitchenham, 2004): Specifying research questions; search on databases; inclusion/exclusion criteria; selection of studies; analysis and extraction of data; summary and interpretation of findings; and writing the review report.

Journal Research Methodology

A systematic literature search was conducted using three databases relevant for educational research articles: Education Research Complete, Web of Science, and Scopus. The search gathered all articles where the search criteria were present in the article's title, abstract or keywords. In searching the articles, two main key terms were used: 'STEM' OR 'STEM Education' OR 'Science, Technology, Engineering, Mathematics' and 'Policy*' OR 'Reform*' OR 'Educational Policy*' OR 'Educational Reform*'. The database search was restricted to only peer-reviewed journal articles published in English from 2000 onwards. The acronym STEM did not exist until the early 2000s (Li et al., 2020), thus we decided to select articles starting from that year until 2023. The initial search created a database of 1,493 papers.

Inclusion Criteria

As indicated by the search criteria, not all STEM related papers were included, but only STEM papers that fit the following inclusion criteria:

1. Only articles published in English in peer-reviewed journals were included. Book chapters, book reviews, conference papers, national or international reports, magazines articles, working papers, theses, and other publication types were excluded.
2. As the current study is not an analysis of policy or reform documents, such documents were excluded.
3. Papers included were concerned with the outcomes of the implementation of a STEM policy, or a specific STEM reform or program which can potentially facilitate the development of STEM education.
4. Papers in which their rationale is based on the need to introduce STEM education and made explicit references to reforms were included.
5. Papers which considered STEM education as the integration of at least two STEM disciplines.

Quality Assessment of the Studies

In a systematic review, there is a considerable variation in the actions during the quality assessment of the studies (Gough et al., 2017). We assessed the studies' quality throughout the search and screening process by comparing the data to the research questions. Other methodological aspects, such as research approaches, could play a decisive role in the judgment of the quality. In this review, we chose to include them in the coding categories in order to describe their variations across studies.

Coding and Extraction of Data

The final 27 articles were coded to extract the relevant data and develop a narrative synthesis of the studies. A codebook was created in a spreadsheet with four overarching themes (see **Table A1** in **Appendix A** for a more detailed explanation of the coding categories):

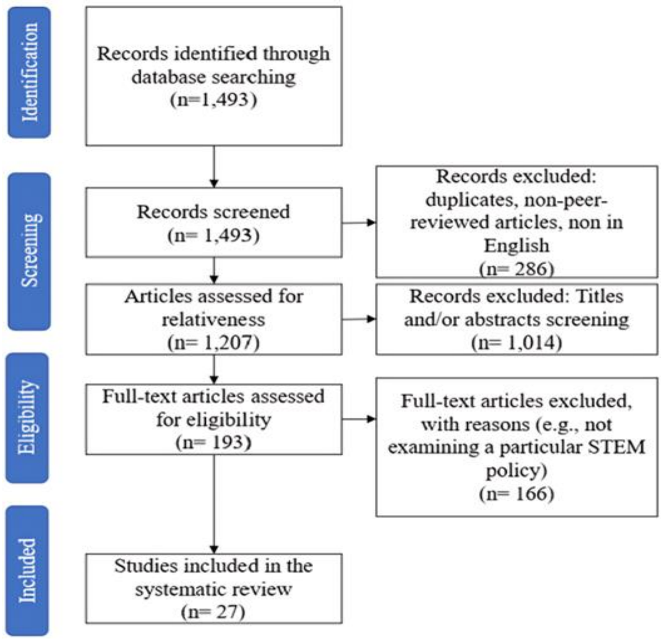

Figure 1. Flowchart of the review process (Source: Authors' own elaboration)

1. *Article info*, including author(s), year of publication, and name of the journal.
2. *Sample*, including the country each study took place, the stage of formal education (1 = primary education, 2 = secondary education, and 3 = tertiary education) and the professional status of a teacher (1 = pre-service and 2 = in-service).
3. *Aim of the studies*, focusing on the main aim of each study.
4. *Research approach* (1 = qualitative approach, 2 = quantitative approach, and 3 = mixed approach)

The codebook was developed by the first author. The second author tested the coding categories for a small number of articles. All articles included in the review were coded by both authors. The first author went through the articles and oversaw the data extraction. Any coding disagreements were resolved through a discussion.

Review Process

Figure 1 shows an overview of the review process. A total of 1,493 articles were identified from the database search. After removing the duplicates and the non-peer reviewed articles which were not written in English, 1,207 articles were checked using the inclusion criteria by reading the titles and the abstracts. Many articles were excluded mainly because they did not focus on the implementation of a specific program that promoted STEM education, or defined STEM education as focusing only on one of the STEM disciplines. After this stage the number of the articles was significantly reduced. Therefore, 193 articles that met the inclusion criteria were selected for full-text review. In this stage, 166

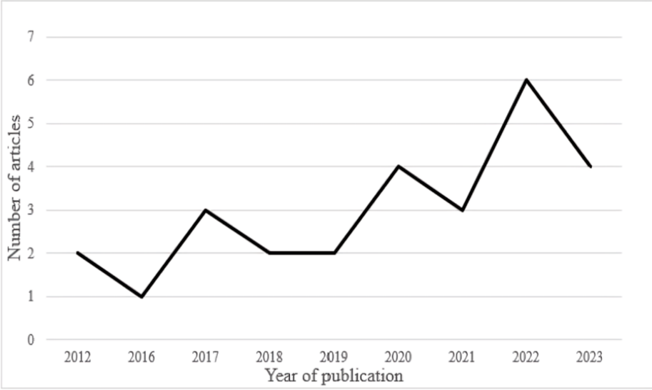

Figure 2. Frequency of peer-reviewed journal articles over time (Source: Authors' own elaboration)

articles were excluded after reading the full-text articles based on the inclusion criteria. Finally, 27 articles were included in the review.

Data Analysis

The final 27 articles were sorted to extract the relevant data and develop a narrative synthesis of the studies. Those articles were sorted using the following categories:

(1) article information, including author(s), year of publication, and name of the journal,

(2) sample and the country the study took place, and

(3) research approach that was followed (i.e., qualitative, quantitative, or mixed approach).

Then, all 27 papers were read and analyzed in line with the two research questions of this study. For the first research question the

(a) aim,

(b) research approaches, and

(c) the country in which each study took place were recorded.

For the second research question the papers were open coded in terms of the themes that emerged from the findings of the empirical studies. For the second research question, the first author read all the articles and created an initial list of themes related to findings of the articles. Then the second author read 25% of the articles independently and created a list of themes. The two authors discussed the list of themes and merged specific themes to create five themes. Then the first author read all the articles again using the five themes as guides for the analysis. The second author reviewed 75% of the analysis with 90% agreement. Both authors reviewed the papers again until full agreement was reached.

RESULTS

As **Figure 2** shows, the number of publications considering the topic of our study tended to be lower during 2012 to 2019. However, from 2019 onwards there is an increase regarding the number of publications with some fluctuations and a noticeable peak in 2022.

Table 1. The distribution of the 27 studies in 20 journals

Journal	n
International Journal of Science and Mathematics Education	3
International Journal of STEM Education	2
Journal of Science Education and Technology	2
Journal of STEM Education	2
Teachers College Record	2
Education Sciences	2
Urban Education	1
Journal of Research in Science Teaching	1
Journal of Pre-College Engineering Education Research	1
International Journal of Technology and Design Education	1
Journal of Science Teacher Education	1
Frontiers in Education	1
Journal of Mathematics and Science Education	1
Computer Applications in Engineering Education	1
British Educational of Educational Technology	1
Science Studies and Science Education	1
School Science and Mathematics	1
Australian Journal of Education	1
Interdisciplinary Journal of Problem-Based Learning	1
Sustainability	1

Note. n: Number of publications included

Table 1 shows the distribution of the 27 studies in 20 journals. It is observed that there is a variety of journals from which the studies emerged. Li et al. (2020) also showed that STEM education articles have been published in many different journals, especially with the limited journal choices available in STEM education. This can be attributed to the fact that articles related to STEM can be published in journals that are concerned with one of the four disciplines (i.e., science, technology, engineering and mathematics) but also to the fact that STEM education is a wide topic with many different issues that need to be examined (e.g., PD, diversity and inclusion, STEM career) and consequently many journals are concerned with.

RQ1. The Main Characteristics of the Articles Examining STEM Reforms

Aim of the studies

The 27 articles included in this review present empirical evidence regarding STEM reforms that were implemented worldwide. The implementation of an initiative or a program based on particular regulations concerned with STEM education a country followed was the common characteristic of those articles. However, the aims of the articles were diverse. The majority of the articles concentrated on the integration of STEM disciplines, while some of them focused on understanding the impact of STEM curricula on students' performance. Furthermore, some articles focused on the preparation and development of pre-service and early career teachers, particularly in enhancing their ability to teach STEM subjects in an integrated manner. A number of articles aimed to investigate how various programs, courses, or teaching methods impact students' interest in pursuing careers in STEM fields, but also some looked at how teachers' practices and awareness, such as integrating 3D printing, influence students' STEM career aspirations. Finally, many of the articles focused on various aspects of STEM education improvement, for example teacher PD, program and reform evaluation, factors that influence STEM curriculum implementation in schools.

Research approaches

A variety of research approaches has been observed across the 27 studies with most of them following a qualitative research approach (12), 10 followed a quantitative research approach and the rest of the studies followed a mixed method approach (5) by utilizing both qualitative and quantitative data. Regarding the qualitative studies, most of the studies included a type of an interview (e.g., semi-structured interviews), but also other types of qualitative approaches were used such as the case study approach, content analysis and survey data. Regarding the quantitative studies, four of them followed an experimental and quasi-experimental design, respectively to explore the effectiveness of an integrated STEM approach. Furthermore, other quantitative approaches were conducted such as logistic regression analyses, cluster analysis and multiple regression. Regarding the articles which followed a mixed-method approach, all used quantitative data through questionnaires or assessments accompanied with additional qualitative data through interviews, observations or reflections.

Sample

Of the 27 studies reviewed, 18 were conducted in the US, focusing on different aspects of STEM education. For example, the implementation of an integrated STEM approach was investigated, whilst the STEM shortage was elaborated too. Furthermore, research in the US concerned the PD of mainly the pre-service teachers on STEM integration and pedagogical practices. Furthermore, two studies have been conducted in Kosovo and Australia, respectively while one study in each of the rest of the countries (i.e., China, Spain, Qatar, and Egypt). The two studies conducted in Australia emphasize the importance of recognizing factors influencing STEM curriculum and the challenges in integrating STEM into formal schooling. While the studies from Kosovo focus on the PD of pre-service teachers and the use of STEM practices. Eighteen studies conducted in secondary schools, two studies in primary schools and tertiary education, respectively. There were studies that considered two levels of education in their sample. Four studies considered classes from primary and secondary education and one study focused on secondary and tertiary levels. Furthermore, twenty studies considered in-service teachers while six studies that focused on the PD of teachers included pre-service teachers in their samples. Only one study used different school stakeholders in its sample as its aim was to build a regional STEM partnership. Therefore, most of the studies included in-service teachers that teach in secondary education.

RQ2. Themes Emerged from the Articles Focusing on the Implementation of STEM Policies and Reforms

From the content analysis of all 27 papers, four themes emerged which describe how the policies and reforms have been implemented in STEM education since 2000. The four themes are described separately in the section below, with some themes including sub-themes.

Theme 1–Integrated STEM curriculum

The research papers under the theme *Integrated STEM curriculum* present diverse perspectives on the integration of STEM education into the curriculum. In **Table 2**, the six studies of this theme are presented. Their common characteristic is the emphasis on integration of STEM education, and in particular the inclusion of engineering design challenges in K-12 science classrooms to enhance student learning and achievement.

All the six studies have been conducted between 2016-2023, five of which took place in the US and one in Qatar. In US, there is an interest to measure the impact of integrated STEM on students' performance but also to understand the level of teacher's ability for implementing STEM integration. Based on the findings of those studies, it was claimed that despite the level of education, students who were taught through integrated STEM approaches performed significantly better than those who were taught the traditional way. The study that took place in Qatar tries to enhance students' attitudes on the development of STEM skills in students. Three sub-themes emerged from the analysis of this category:

(a) Integrated STEM and student learning outcomes

Johnson and Sondergeld (2020) used the I-STEM model with the intent of closing the achievement gap for students from underserved communities.

The I-STEM model differs from traditional STEM in schools and aims to integrate the different practices by using problem-based learning (PBL) as a methodology and additionally engaging the local community and industry as partners and mentors in the process. They found that the attendance rate of students that

Table 2. Summary of the studies of theme 1 (n = 6)

Reference	Title	Journal	Country	Sample	Research approach
Johnson and Sondergeld (2023)	Outcomes of an integrated STEM high school: Enabling access and achievement for all students	Urban Education	USA	1,835 students' comparison schools & 62 students from STEM school	Quantitative approach
Anwar et al. (2022)	The effectiveness of an integrated STEM curriculum unit on middle school students' life science learning	Journal of Research in Science Teaching	USA	1,305 sixth-grade students	Quantitative approach
Ali et al. (2021)	A STEM model to engage students in sustainable science education through sports: A case study in Qatar	Sustainability	Qatar	248 students from 15 different government-operated (public) secondary schools	Mixed-method approach
Dare et al. (2018)	Understanding science teachers' implementations of integrated STEM curricular units through a phenomenological multiple case study	International Journal of STEM Education	USA	Nine middle school physical science teachers	Qualitative approach
Selcen Guzey et al. (2017)	The impact of design-based STEM integration curricula on student achievement in engineering, science, and mathematics	Journal of Science Education and Technology	USA	42 treatment teachers, 17 control teachers and 4,450 students in grades 4-8	Quantitative approach
Selcen Guzey et al. (2016)	Building up STEM: An analysis of teacher-developed engineering design-based STEM integration curricular materials	Journal of Pre-College Engineering Education Research	USA	48 science teachers	Mixed-method approach

participated in I-STEM had a significantly higher level compared with the remainder of the district's high school student population and based on the authors, this can be attributed to the fact that student educational engagement was increased promoting eagerness to attend school. Furthermore, I-STEM students attain significantly greater levels of college readiness, something that is critical especially for students from urban schools who are educationally disadvantaged compared to their suburban peers.

Conversely, Selcen Guzey et al. (2016) explore the varying effects of engineering design-based STEM integration curricula on student achievement across different demographics, emphasizing the need for ongoing research to understand integrated science and engineering experiences. While Johnson and Sondergeld (2023) present a positive outlook on the impact of integrated STEM education, Selcen Guzey et al. (2017) suggest that the impact may vary based on teacher-level factors such as teacher gender and experience.

Anwar et al. (2022) followed a quasi-experimental design and measured the relative effectiveness of the integrated life science and engineering curriculum unit on students' science learning outcomes and knowledge retention. Although the intervention focused on the integration of two STEM disciplines, findings revealed that the integrated STEM curriculum helped students enhance their science learning and retention of the content knowledge.

(b) Challenges in implementing integrated STEM curriculum

Dare et al. (2018) and Anwar et al. (2022) delve into the experiences of science teachers and the effectiveness of integrated STEM curriculum units. Both studies highlight the challenges faced by teachers in implementing integrated STEM initiatives, particularly in terms of curriculum materials, student engagement, and balancing the coverage of science content with engineering design challenges. Both papers underscore the importance of supporting teachers in curriculum design.

A specific challenge that was reported by Dare et al. (2018) is teachers' support while they implement integrated STEM curricula. The teachers designed their own integrated STEM curricula as part of the teacher PD. During the implementation they were supported throughout the process by the researchers, and despite this support they faced multiple challenges that were connected to the different topics taught, their own knowledge and skills, their effort to balance between the concepts in the formal curricula and the skills provided in what they were implementing, and the innovative aspect of the curriculum. Dare et al. (2018) support the idea that during the implementation of an integrated

Table 3. Summary of the studies of theme 2 (n = 5)

Reference	Title	Journal	Country	Sample	Research approach
Berisha and Vula (2023)	Introduction of integrated STEM education to pre-service teachers through collaborative action research practices	International Journal of Science and Mathematics Education	Kosovo	51 pre-service mathematics and chemistry teachers	Qualitative approach
Berisha and Vula (2021)	Developing pre-service teachers conceptualization of STEM and STEM pedagogical practices	Frontiers in Education	Kosovo	40 pre-service teachers (22 mathematics and 18 chemistry) from University of Prishtina	Qualitative approach
Bartels et al. (2019)	Shaping preservice teachers' understandings of STEM: A collaborative math and science methods approach	Journal of Science Teacher Education	USA	13 pre-service teachers	Qualitative approach
Ryu et al. (2019)	Preservice teachers' experiences of STEM integration: Challenges and implications for integrated STEM teacher preparation	International Journal of Technology and Design Education	USA	6 pre-service teachers	Qualitative approach
Eriksen Brown and Bogiages (2017)	Professional development through STEM integration: How early career math and science teachers respond to experiencing integrated STEM Tasks	Journal of Mathematics and Science Education	USA	46 beginning secondary (9th through 12th grade) math and science teachers	Qualitative approach

STEM curriculum teachers are not usually supported as much, and therefore policy should address the issue of PD and preparing teachers. One suggestion on this topic could be to involve teachers in communities of practice to support each other during the implementation.

(c) Integrated STEM in real-world contexts

Ali et al. (2021) and Anwar et al. (2022) highlight the effectiveness of integrating STEM education with real-world contexts, specifically through sports-based learning and engineering design challenges. Both studies demonstrate the positive impact of integrating sports-driven engineering design challenges and inquiry-driven learning approaches in enhancing students' interest and attitudes towards STEM fields, improving their cognitive skills, and fostering their scientific knowledge. Similarly, Johnson and Sondergeld (2023) who studied the effectiveness of I-STEM school, explain that the curriculum of this type of school gives emphasis on problem- and project-based learning to apply students' learning in real-world formats.

Theme 2–Pre-service and early career teachers' professional development in STEM education

Five studies were included in this theme, three of which took place in the US and the rest in Kosovo. In **Table 3** those studies are presented.

Most of the studies focused on teachers in secondary education with an emphasis on the integration of mathematics and science disciplines. Based on those articles, it is acknowledged that there is a call for an integrated STEM teaching approach or at least the combination of two disciplines (e.g., science and math) during instruction.

However, it is supported that few teachers have the background to authentically teach STEM in an integrated way. Teachers' engagement in integrated STEM was highlighted in almost all the articles. The engagement can be achieved through the collaboration of the teachers coming from different disciplines or through their active participation in the PD workshops. The two sub-themes that emerged in this theme are presented below:

(a) Development of lesson-planning activities by teachers

Lesson preparation is one of the core components of the teachers, although they face difficulties in planning and implementing integrated STEM teaching in their classrooms (Rinke et al., 2016). Ryu et al. (2019) supported the significance of pre-service teachers to develop STEM integration lessons and teach them. Similarly, Bartels et al. (2019) supported that it is vital for pre-service teachers not only to experience but also to have the opportunities to plan, teach, and reflect on their own integrated lessons. Berisha and Vula (2023) claimed that a collaborative STEM classroom teaching environment during the PD for pre-service teachers helped them to develop their lesson plans. Those lesson plans did not only focus on the necessary knowledge but also promoted the learning of different 21st century skills (e.g., collaboration, problem-solving, use of technology).

(b) School support during the implementation of STEM education

Berisha and Vula (2021) claimed that teachers encountered challenges in their attempt to implement STEM education in their classrooms. The authors reported that school culture in Kosovo is not

Table 4. Summary of the studies of theme 3 (n = 7)

Reference	Title	Journal	Country	Sample	Research approach
Kitchen et al. (2022)	The impact of participating in college-run STEM clubs and programs on students' STEM career aspirations	Teachers College Record	USA	15,847 students from 27 colleges and universities nationwide	Quantitative approach
Cheng et al. (2021)	Exploring the role of 3D printing and STEM integration levels in students' STEM career interest	British Journal of Educational Technology	USA	26 teachers and their 1,455 students in primary and secondary classrooms	Quantitative approach
Corin et al. (2020)	The role of dual enrollment STEM coursework in increasing STEM career interest among American high school students	Teachers College Record	USA	14,144 college students nationwide	Quantitative approach
Tan-Wilson et al. (2020)	An undergraduate STEM interdisciplinary research program: Factors predictive of students' plans for careers in STEM	Journal of STEM Education	USA	92 educators from different academic majors in higher education	Quantitative approach
Trilles and Granell (2020)	Advancing preuniversity students' computational thinking skills through an educational project based on tangible elements and virtual block-based programming	Computer Applications in Engineering Education	Spain	256 high-school students	Mixed method approach
Geoff Knowles et al. (2018)	Increasing teacher awareness of STEM careers	Journal of STEM Education	USA	22 high school science and engineering technology education teachers	Quantitative approach
Kitchen et al. (2018)	The impact of college- and university-run high school summer programs on students' end of high school STEM career aspirations	Science Studies and Science Education	USA	845 program participants and 15,002 controls	Quantitative approach

characterized as collaborative and the communication among teachers is limited.

Ryu et al. (2019) stated that after the STEM teaching methods course, pre-service teachers successfully developed STEM integration lessons and taught them; however, they also faced challenges attributable to current school practices. For example, the time that was required to develop and implement integrated STEM lessons and the limited interdisciplinary understandings by teachers. Furthermore, it was claimed that teachers need support during the implementation of integrated STEM lessons. Role models who have experience of integrated STEM should share their experiences and teaching examples with other teachers, whilst model curricula could provide the necessary support to teachers for STEM integration. Berisha and Vula (2023) also highlighted the importance of providing to pre-service teachers teaching practice examples in STEM education.

Theme 3–Career related to STEM

Seven studies constituted this theme, six of which come from the US and one from Spain. All the articles provide evidence of how to attract students to a STEM career addressing the global shortage of STEM graduates (Johnson et al., 2020, p. 389). However, one of them gives emphasis on the role of secondary teachers in career guidance of their students in STEM. In **Table 4** the seven studies of the theme are summarized.

The studies of this theme mainly investigated what strives especially high school students to pursue a STEM career or graduates to remain in a STEM profession. Many studies claimed that high school students that are exposed to additional programs related to STEM domains are more likely to pursue a STEM university degree. For example, Corin et al. (2020) investigated changes in students' reported interest in STEM careers after taking a dual enrolment STEM course. They found that the odds of a STEM career intention were 1.3 times ($p < .05$) greater for those taking a dual enrolment course compared with peers who did not.

Furthermore, Kitchen et al. (2022) also reported that participation in university- or college-run STEM club or program activities had a significant impact on the odds that college-going students would express STEM career aspirations relative to students who did not participate. Similarly, Kitchen et al. (2017) revealed that high school STEM summer program participation boosted end of high school STEM career aspirations. Students who participated in a high school STEM summer program had 1.4 times the odds of indicating end of high school STEM career aspirations relative to those who did not participate in a summer program. An observational study was conducted by Crawford et al. (2021) to evaluate the effectiveness of an established outreach event, which took place numerous times over the past five years. The study reported that 70% of students reported that their understanding of science careers had improved, and more than 21% of students said their interest in a science career had increased.

Trilles and Granell (2020) were concerned with the declined numbers of university students enrolled in STEM related studies such as computer science. After a three-year intervention in high schools, their study supported those students who interacted with tangible resources (e.g., sensors) accompanied with social interaction in groups that increased students' motivation in computational thinking and programming. The research program by Tan-Wilson et al. (2020) involved pairing life science majors with majors in other STEM disciplines to work on interdisciplinary projects. Of the participants, 74% planned to remain in STEM, and 26% intended to move to non-STEM careers. They also reported that students who interacted mainly within their own discipline, tended to pursue non-STEM careers, while those interacted almost equally with mentors from both disciplines (e.g., life sciences with computer science or engineering) tended to pursue STEM careers.

Finally, the study by Cheng et al. (2021) focused on the influence of 3D printing integrated STEM education on students' interest in STEM careers. The results indicated that while the integration of 3D printing in science classrooms did not significantly predict students' interest in STEM careers, teachers' STEM integration level positively predicted students' interest in both analytic and empathetic STEM careers. On the contrary, Knowles et al., 2018 supported that 3D scanning could facilitate teachers' STEM career pathways.

Theme 4–Factors for the advancement of STEM education

This theme constitutes nine papers which underscore the importance of systemic reforms, PD, and collaborative efforts in advancing STEM education across diverse regions and contexts. In **Table 5**, the studies of the theme are presented.

Two of the studies are from Australia, one from China and the rest from the US. The studies offer insights into overcoming the multifaceted challenges and barriers educators face emphasizing the pivotal role of strategic vision, leadership, and community engagement in driving effective STEM education.

Table 5. Summary of the studies of theme 4 (n = 9)

Reference	Title	Journal	Country	Sample	Research approach
Menon et al. (2023)	Preservice elementary teachers conceptions and self-efficacy for integrated STEM	Education Sciences	USA	132 pre-service teachers	Mixed-method approach
Xu et al. (2023)	The relevance of STEM: A case study of an Australian secondary school as an arena of STEM curriculum innovation and enactment	International Journal of Science and Mathematics Education	Australia	5 teachers and school leaders from one secondary school	Qualitative approach
Chiang et al. (2022)	The influence of online STEM education camps on students' self-efficacy, computational thinking, and task value	Journal of Science Education and Technology	China	113 3rd and 4th grade primary school students and six teachers	Mixed-method approach
Colclasure et al. (2022)	The effects of a modeling and computational thinking professional development program on STEM educators' perceptions toward teaching science and engineering practices	Education Sciences	USA	47 participants (middle school, high school, and first- and second-year post-secondary STEM teachers)	Quantitative approach
Falloon et al. (2022)	Shaping science, technology, engineering and mathematics curriculum in Australian schools: An ecological systems analysis	Australian Journal of Education	Australia	449 principals and teachers from primary, secondary, and combined schools	Qualitative approach
Velasco et al. (2022)	Exploring advocacy self-efficacy among K-12 STEM teacher leaders	International Journal of Science and Mathematics Education	USA	11 STEM teacher leaders who were part of the STEM Teacher Ambassadors program	Qualitative approach
El Nagdi and Roehrig (2020)	Identity evolution of STEM teachers in Egyptian STEM schools in a time of transition: A case study	International Journal of STEM education	Egypt	6 STEM teachers and one engineering specialist	Qualitative approach

Table 5 (Continued). Summary of the studies of theme 4 (n = 9)

Reference	Title	Journal	Country	Sample	Research approach
Asghar et al. (2012)	Supporting STEM education in secondary science contexts	Interdisciplinary Journal of Problem-Based Learning	USA	41 teachers from secondary schools	Qualitative approach
Johnson (2012)	Implementation of STEM education policy: Challenges, progress, and lessons learned	School Science and Mathematics	USA	11 leaders from stakeholder organizations that participated in building the regional STEM partnership	Qualitative approach

While some studies focus on the immediate impact of PD programs on participants' confidence and interest in integrated STEM, others delve into the influence of external factors, such as policy and curriculum designs, on STEM teaching and learning. Furthermore, the studies shed light on the complexities of integrating STEM education in diverse contexts, ranging from online camps to regional educational partnerships.

Many of the papers highlighted the lack of resources such as digital infrastructure, or financial support. For instance, Johnson (2012) and El Nagdi et al. (2020) underline the insufficiency of resources and funding as pivotal barriers. Similarly, the study by Chiang et al. (2022) highlights the digital divide and the scarcity of adequate hardware and software especially in rural regions. Four sub-themes emerged and are presented below:

(a) Leadership and vision

The importance of leadership and strategic vision is emphasized by Falloon et al. (2022) and Asghar et al. (2012). Both studies stress the necessity of committed school leadership to mitigate broader systemic constraints. In the former, proactive principals and teachers leveraging community resources facilitated curriculum innovation, while in the latter, a lack of administrative support was deemed a significant barrier.

(b) Training and pedagogical challenges

Some studies (i.e., Colclasure et al., 2022 & Menon et al., 2023) emphasized PD as critical. Insufficient training and low confidence in employing interdisciplinary teaching methods and new pedagogical approaches consistently emerge as obstacles. Furthermore, limited familiarity with interdisciplinary approaches and PBL have been mentioned by Asghar et al. (2012) as challenging factors for integrated STEM education.

(c) Systemic barriers and policy

Systemic barriers including rigid curricular and assessment regimes impede flexible, interdisciplinary STEM education as described from the two studies conducted in Australia by Falloon et al. (2022) and Xu et al. (2023). Both studies call for systemic reform to facilitate coherent and comprehensive STEM strategies across different educational levels.

(d) Cultural and social norms

Cultural perceptions and social norms also present barriers, particularly in contexts with strong traditional educational systems, as discussed from the study that took place in Egypt by El Nagdi et al. (2020). Similarly, the study by Velasco et al. (2022) reveals that resistance and lack of support from peers and administrators can thwart advocacy and STEM reform efforts.

DISCUSSION

This paper introduced a paradox: policy has long recognized the need for STEM education as a means to improve students' skills and make the connection of school subjects to everyday life and the world of work. Despite that, there is limited observed improvement on students' STEM related outcomes (knowledge, skills, and attitudes). What does the review of these studies tell us about this paradox? This systematic review analysis focused on published studies that explicitly made the connection to policies and reforms in STEM as a driving force behind their implementations. The analysis shows a trend in STEM education related studies which increased shortly after the NGSS (Achieve, 2013) was published in the US.

The first important finding according to the review is the need to approach STEM education as an interdisciplinary, integrated approach, focusing on problem solving by the students, which requires the participation of multiple stakeholders and opening up schools to enterprises, scientists, the community and other experts (i.e., Johnson et al., 2020). Furthermore, breaking the boundaries between the different STEM subjects and asking teachers from different disciplines to collaborate provides students with a simulation of real-life situations and the world of work in which experts from different areas need to work together to solve problems.

A second finding is the integration of STEM into the curriculum. Most of the articles that underline this topic focused on the inclusion of engineering design. There is an interest in measuring the impact of integrated STEM curriculum on student's performance. Although the articles investigating this relationship reported a positive impact, it should be acknowledged that they had significant differences regarding their study design (e.g., qualitative vs quantitative measures). Teachers need support in their attempt to implement integrated STEM curricula or to design their own curricula (i.e., Selcen Guzey et al, 2017). Some of the suggestions were the provision of PD and the teachers' involvement in communities of practice to support the inclusion of STEM education in schools (Berisha & Vula, 2023; Eriksen Brown & Bogiages, 2019).

A third important finding is that the reforms described in the published papers are happening either outside of the formal school time and are not systematic efforts to address STEM education concerns at local, national or international level. This identifies a gap between policy and actual practice: policy makers are aware of the importance of STEM education, but they have not been successful in bringing the necessary changes in the schools on a large scale. Some of the findings in the selected papers explain the reasons: most of the curricula around the world are structured around subjects, and each subject is assigned specific time which makes it difficult to have interaction between teachers of different STEM subjects (Ryu et al., 2019); even when teachers are adequately prepared to design and teach integrated STEM courses they face difficulties during the implementation because of school policies related to time constraints, the compartmentalization of subjects (Ryu et al., 2019).

A fourth finding is the importance of systemic reforms, PD, and collaborative efforts in advancing STEM education in diverse regions and contexts. The studies highlight the need to address the multifaceted challenges and barriers, including resource constraints, leadership and vision, pedagogical challenges, systemic barriers, and cultural/social norms, to foster effective and sustainable STEM education initiatives.

Furthermore, the review highlighted the need for comprehensive PD programs that address the challenges faced by pre-service and early career teachers in effectively integrating STEM disciplines in their teaching practices. The findings highlight the importance of collaborative environments, lesson-planning activities, and school-level support to foster the successful implementation of STEM education.

The issue of shortage of prepared STEM professionals also emerged from the review (i.e., Xu et al., 2023). The exposure of high-school students to additional STEM-related programs was suggested as this approach increases the likelihood they will pursue STEM degrees in university.

Many of the identified articles of the 4 themes were published in the last 5 years (2019-2023) as significant advancements and policy developments in STEM have occurred. These studies offer diverse insights into the role of STEM education by giving emphasis on the effectiveness of various programs, and the impact on students' interest and performance in STEM-related field. Despite the variation regarding the focus and methodology of those studies, all papers share a common goal of evaluating or promoting effective STEM education strategies. For example, Trilles and Granell (2020) investigated the effectiveness of the Sucre4Kids project in advancing pre-university students' computational thinking skills, while Johnson and Sondergeld (2020) reported significant positive academic and attendance outcomes for students at an integrated STEM high school compared to students at traditional high schools. This shift to the investigation of the effectiveness of STEM-related field and student learning outcomes can be attributed to the fact that some years ago data from international assessments highlighted a concerning trend in the performance of 15-year-olds in science and mathematics across Europe. More than 20% of students are unable to complete basic tasks in these subjects, as indicated by European Commission COM (2020). This finding is further supported by the trends in international mathematics and science study (TIMSS), which reports that over 20% of European students are performing at the lowest levels in mathematics and science, while less than 10% reach the highest proficiency levels (Mullis et al., 2020). These results underscore the need for targeted interventions to improve the foundational skills of students in STEM subjects.

How can we solve the paradox and improve STEM education in terms of student outcomes (knowledge, skills, and attitudes)? The findings from this systematic literature review highlight an important development: researchers and policy makers have identified the need to break the boundaries between the STEM subjects. Researchers are already working on integrated STEM education, one which stops seeing boundaries between the different subjects and disciplines and focuses on developing students' skills and competences across subjects, with an emphasis on 21st century skills. The gap now is on putting in practice, on a large scale, integrated STEM education, but to do so some implications for future STEM policy development are proposed. First, national and regional STEM curricula should be restructured to reduce the strict boundaries between different STEM subjects. Teaching should be based on collaboration between subject specialists, promoting interdisciplinary approaches that reflect real-world problem-solving. Furthermore, teachers need support in developing their pedagogical practices and building confidence in teaching in an integrated STEM environment. Policies should prioritize teachers' PD, as they are the main drivers of STEM education implementation. Continuous support through PD programs is crucial, with a focus on practical teaching applications of STEM knowledge. Studies have emphasized the importance of ongoing teacher support during STEM implementation (Dare et al., 2018), including PD opportunities that enhance practical, interdisciplinary teaching skills (Dan & Gary, 2018).

New assessment methods should be developed that evaluate students' skills and competences beyond content knowledge, focusing on aspects such as interest, engagement, identity, self-efficacy, and competences (Allen & Peterman, 2019; Evagorou et al., 2024). Current assessments in STEM education largely focus on monodisciplinary subject knowledge, as it is easier to evaluate with existing practices (Gao et al., 2020). However, since STEM learning is complex, learning processes and practices should be incorporated into learning objectives to allow for comprehensive assessment (Gao et al., 2020).

The review considered different reforms across various countries without considering the cultural differences of those countries. Different cultures have varying perceptions of STEM education, which can impact policy implementation. For instance, a recent study claimed that Chinese women had higher explicit gender-STEM stereotypes than British women (Liu, 2024). Furthermore, the availability of resources across countries might be different as funding and resources are important for shaping the extent to which students engage in and excel at STEM fields (e.g., Wang 2013). Consequently, we encourage future research to account for cultural differences between countries to gain a better understanding of how STEM policies are perceived and implemented in different educational systems.

CONCLUSION

This systematic review underscores the persistent gap between policy intentions and actual improvements in STEM education outcomes. Despite increasing recognition of the need for STEM education to be interdisciplinary, integrated, and aligned with real-world challenges, implementation remains inconsistent and fragmented. The review highlighted that through the years more articles focused on the implementation of specific STEM programs and their effectiveness. Furthermore, through the review several critical developments emerged regarding the advancement of STEM education: interdisciplinary STEM education; integration of STEM into curriculum; implementation challenges; teacher PD; and assessment reforms.

Overall, addressing the paradox between STEM education policy aspirations and actual student outcomes requires concerted efforts to implement integrated STEM curricula, provide continuous teacher support, and develop assessment methods that capture a broader range of student skills and competencies. The shift towards a more holistic, interdisciplinary STEM education is already underway; however systemic barriers that might be different across educational systems need to be addressed addressed to achieve significant and widespread improvements and potentially improve student learning outcomes.

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APPENDIX A

Table A1. Codebook for data extraction

Type	Variable	Explanation	Coding
1. Article info	Author	Author(s) of the article	Text
	Year	Year of publication	Text
	Journal	Journal name	Text
2. Sample	Country	Country each study took place	Nominal
	Level of education	The level of education each study was addressed to	1 = primary education, 2 = secondary education, & 3 = tertiary education
	Teachers	The professional status of the teachers	1 = pre-service teachers & 2 = in-service teachers
3. Aim	Main aim of each study	A summary or note of the study aim or research question	Text
4. Method	Research approach	The research approach of each study was identified	1 = qualitative approach, 2 = quantitative approach, & 3 = mixed approach