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Subject integration and theme evolution of STEM education in K-12 and higher education research

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Over the past two decades, the field of STEM education has produced a wealth of research findings. This study systematically reviewed the published literature from the perspective of subject integration and theme evolution, considering both K-12 and higher education. It was found that STEM education originated from higher education, but the main emphasis is gradually shifting to the K-12 stage. There were mainly sixteen subjects involved in STEM education, showing the gradual in-depth integration of science, engineering, technology, math, humanities, and social sciences, in which humanism is increasingly emphasized. Culture is a new perspective for understanding the diversity of participants, which also gives STEM education a distinctive regional character. In addition, in the K-12 stage, research related to computer science and art stands out alongside the four main subjects, demonstrating relatively even distribution across research themes. Conversely, in higher education, engineering, and chemistry garner considerable attention, with research themes predominantly concentrated on learning outcomes and social relevance. On a holistic scale, researchers exhibit a pronounced interest in learning outcomes, yet relatively less emphasis is placed on pedagogical aspects. Regarding prospective trends, there should be a heightened focus on the cultivation of students' thinking competencies, students' career development, and pedagogy.

Introduction

In response to the global challenges, the promotion of economic development, and the need to meet modern society's demands for knowledge and skills within the realms of STEM, the emergence of STEM education aimed to develop employment opportunities in STEM fields while bolstering national competitiveness. The acronym STEM education originated from the four subjects (i.e., science, mathematics, engineering, and technology) that were proposed in the report "*Undergraduate Science, Mathematics, and Engineering Education*" (National Science Board 1986). Essentially, STEM education stands as an innovation-oriented education that prevailed in Western countries, spearheaded by the United States.

Subsequently, Yakman (2008) introduced the addition of the "A" element, representing arts, to STEM education, thereby incorporating humanities subjects such as history, philosophy, and religion. The fundamental objective of STEM education is to amalgamate multiple subjects into a cohesive framework (Morrison 2006). According to the National Science Foundation (2014),

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STEM entails a comprehensive integration of various disciplines, encompassing not only the subjects of natural sciences (e.g., computers and information, engineering, and mathematics), but also the subjects of social sciences (e.g., psychology, economics, sociology, and political science). With an increasing number of disciplines becoming intertwined in STEM education, its interdisciplinary essence has become progressively prominent. As a result, STEM education is increasingly acknowledged as interdisciplinary education with a focus on engineering, where subject integration plays a central role.

In the past two decades, STEM education has witnessed a large number of research achievements, and many scholars have conducted comprehensive reviews on the topic. These studies have focused either on curriculum reform (Uskoković 2023), teaching methods (Li and Wong 2023), or technology applications (Salas-Pilco et al. 2022; Conde et al. 2021). At the research level, especially in teaching and learning, many researchers have recognized the interdisciplinary nature of STEM education, but almost no research has focused on the development of STEM education from the perspective of subject integration (Perignat and Katz-Buonincontro 2019). The evolution of STEM disciplines and the development of their themes are closely interrelated, but the underlying coupling relationships and reasons for their formation remain unexplored.

Moreover, there exist significant differences in the disciplinary systems of K-12 education and higher education, including teaching objectives, methods, breadth, and depth. As a result, STEM education at different educational levels exhibits distinct characteristics, making it necessary to conduct a segmented analysis. Although some researchers have analyzed the development trends in STEM education from a macro perspective and recognized differences between educational stages, this has not been the primary focus of their work, and there has also been a lack of emphasis on specific disciplines (Zhan et al. 2022a).

Based on these considerations, this study attempts to examine and explore the developmental trajectories and trends of STEM education at various educational stages from the perspective of disciplinary evolution. Specifically, the following questions will be addressed:

RQ1: How were subjects integrated into STEM education in K-12 and higher education?

RQ2: What is the distribution of the subject themes involved in STEM education at the K-12 and higher education levels?

Methods

Keyword search. Papers related to STEM education were searched on 10 July 2023 from the Science Web Core Collection. The query started with the search statement TI = (STEM education) OR TI = (STEAM education) OR AK = (STEM education) OR AK = (STEAM education) OR AK = (STEAM education) OR KP= (STEM education) OR KP = (STEAM education), which yielded a total of 3668 publications. The search results were further refined according to the research area, while duplicates, poorly indexed documents, and documents inconsistent with STEM Education/STEAM Education research were removed, leaving a final total of 2188 publications.

Research process. WOS (Web of Science) was selected as the data source for this study. This database covers a wide range of journals, has a high impact, and can provide a complete sample for this study (Martín-Páez et al. 2019). Then, the following steps were used to analyze the data.

Step 1: Data classification (education stage classification). It has been shown that K-12 and higher education systems have different focuses on STEM education (Zhan et al. 2022a). To clarify the characteristics of the different stages, the data was divided into K-12 and higher education levels based on field information such as title, keywords (including author keywords and keywords plus), journal, and abstract. After discarding the data that could not be categorized, 903 valid data were obtained for the K-12 stage, with the time range from 2009 to 2023, and 873 valid data for the higher education stage, with the time range from 2004 to 2023.

Step 2: Keywords cleaning. In the collected data, some keywords have the same meaning but may be analyzed as different words, such as math, mathematics; model, models, etc., and some words have similar semantics, which may also lead to inaccurate analysis results when analyzed separately, so it was necessary to build a synonym database for synonym replacement so that they could be more accurately counted and visualized.

Step 3: Data classification (time and theme classification). The data at different stages were sub-categorized by time and theme respectively. Time division according to a time slice for a year. The keywords with the top 10 frequency in each subject were screened as alternative theme terms, and the alternative subject terms of each subject were integrated, then the remaining keywords were used as subject terms to participate in the final statistics.

Step 4: Data statistics and visualization. The categorized subject time and subject themes of different sections were counted separately, and the statistical results were visualized and described using heat maps. The heat map used in this study is a kind of statistical chart that shows the frequency of a certain word by the relative shades of color blocks, with dark colors representing the high frequency of occurrence and light colors representing the low frequency of occurrence. Finally, four maps were created to depict the time distribution and theme distribution at the K-12 and higher education levels. The research process is shown in Fig. 1.

Research findings

Analysis of the temporal evolution of the subject. STEM education originated from higher education, but in recent years, there has been rapid development in the K-12 stage. Both levels show a similar trend of overall integration, starting with a focus on science, technology, engineering, and mathematics, and later, an increasing involvement of humanities and social sciences. Interdisciplinary integration has become prominent, particularly in higher education. As shown in Fig. 2.

Subject integration of STEM in K-12 Education. Subject integration refers to the methods and processes of cross-fertilization of different subjects, which is specifically expressed as the mutual integration of a subject with one or more subjects through knowledge, concepts, skills, methods, etc. at a certain time node, so time node is one important element of subject integration path analysis. Figure 2(1) illustrates the integration of different subjects at different time points at the K12 level. In the early stages (2009 to 2014), the subjects of science, technology, engineering, and mathematics played a dominant role, and these subjects were considered to be the core of STEM education. Over time, science subjects such as computer science, arts, physics, and environmental science were gradually incorporated into the STEM education integration pathway. In the post-2019 period, more and more research has emerged in the humanities and social sciences.

Different subjects played different roles in STEM education at the K-12 level. Science and technology provided a rich foundation of knowledge and practice for students involved in STEM education. Engineering developed students' design thinking and problem-solving skills, while mathematics provided the foundation for quantitative and logical thinking. Early STEM education

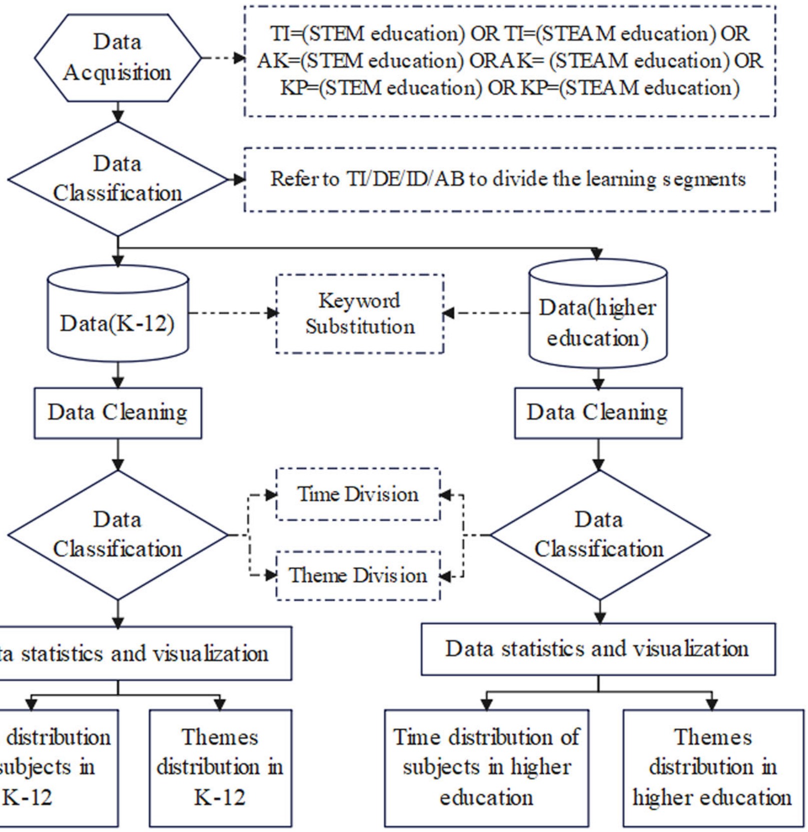

Fig. 1 Research process. The entire research process went through five stages: data acquisition, data classification (education stage classification), keyword cleaning, data classification (time and theme classification), and data statistics and visualization.

has not yet shown a clear trend of cross-fertilization of disciplines. Science courses, such as physics, chemistry, and biology, were considered the main foci of STEM education, with students exploring basic science concepts through participation in experiments and educational games.

As time went on, computer science and environmental science became important subjects for STEM education, and they facilitated the development of computational thinking and environmental awareness in students at the basic education level (Zhan et al. 2022b). In 2013, Grover and Pea (2013) published a study entitled "Computational Thinking in K-12: A Review of the State of the Field", which explored the importance of including computational thinking as a content and goal of STEM education and had a profound impact on subsequent research regarding the integration of computing into STEM education. In 2022, the U.S. Department of Education proposed "*Science, Technology, Engineering, and Math, including Computer Science*", also hinting at the importance of computer science in STEM (Department of Education, 2022).

Environmental issues have always been important social topics and are closely related to the development of engineering and technology. The integration of environmental science emphasized the importance of environmental awareness and sustainable development, making students conscious of environmental problems and proposing solutions through scientific and technological means. At the K-12 level, researchers have focused on green skills elements in STEM curricula and the integration of STEM educational approaches in environmental curricula (Sümen and Çalisici 2016).

After 2019, the integration of humanities and social sciences brought more dimensions and diversity to STEM education. At this stage, STEM education showed a clear interdisciplinary character. Compared to science courses that are involved in STEM education in the form of teaching content, humanities, and social sciences are integrated in a way that is more on the level of research methods and educational philosophy.

Psychological research explored the impact of spatial thinking, spatial skills, and spatial abilities on STEM learning, recognizing the importance of students' mental states and cognitive abilities for learning (Buckley et al. 2018; Gilligan et al. 2017; Taylor and Hutton 2013). The inclusion of arts enhanced students' understanding of creativity and encouraged them to use their imagination and creative abilities in the practice of science and engineering (Yakman 2010). The inclusion of political science primarily conducted a comparative study of STEM education across different regions from the perspective of policies (Sharma and Yarlagadda 2018).

Philosophy created a framework for analyzing and synthesizing STEM education goals and discourses, encouraging students to think deeply about the value and impact of science and technology (Ortiz-Revilla et al. 2020). The incorporation of history offered students diverse learning objectives that enabled them to understand the context and social impact of the development of science and technology (Park and Cho 2022). The inclusion of linguistics promoted the engagement of culturally and linguistically diverse students in STEM education, encouraging cross-cultural communication and collaboration across linguistic and cultural boundaries (Mallinson and Hudley 2018).

In the K-12 stage, there is a significant concentration of disciplines in STEM education, with computer science and arts receiving the most attention alongside the four main subjects. Additionally, interdisciplinary teaching in this stage is guided by conceptual instruction. In 2013, the United States released the

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	*sum*
stem	0	0	0	0	0	3	2	2	2	10	14	17	27	42	56	68	85	172	170	106	776
steam	0	0	0	0	0	0	0	0	0	0	0	1	4	3	2	3	11	29	31	13	97
science	0	0	0	0	0	2	2	0	2	10	10	9	27	23	39	47	66	110	111	60	518
math	0	0	0	0	0	0	1	0	1	6	3	7	8	8	14	26	12	36	43	22	187
technology	0	0	0	0	0	1	0	0	1	5	5	1	8	10	10	12	17	40	44	29	183
engineering	0	0	0	0	0	0	1	0	2	4	6	2	4	10	9	9	11	37	35	12	142
computer	0	0	0	0	0	1	0	0	0	1	0	0	1	2	1	1	4	14	9	5	39
arts	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	9	14	10	37
physics	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	3	2	10	8	6	33
environment	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	2	2	8	7	5	26
biology	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	3	7	7	20
chemistry	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	1	0	0	8	4	16
political science	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	5	7
psychology	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	1	2	6
linguistics	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	3	1	6
philosophy	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	1	0	4
economics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	4
history	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
sum	0	0	0	0	0	7	6	2	8	37	39	42	81	101	135	178	214	468	495	289	2102 2102

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	*sum*
stem	1	1	1	1	3	1	6	3	10	9	13	31	22	44	48	49	89	162	219	70	783
steam	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	4	5	16	13	6	47
science	0	0	0	1	0	0	4	1	6	4	8	18	10	25	31	26	55	66	93	40	388
engineering	0	1	0	1	1	2	1	1	2	1	5	1	3	6	7	9	16	42	39	9	147
math	0	0	0	1	0	0	1	1	1	4	4	4	5	9	14	13	17	22	32	10	138
technology	0	0	0	0	0	0	2	1	3	1	6	0	1	4	7	10	18	23	40	12	128
chemistry	0	0	0	0	0	0	0	0	0	0	3	1	1	2	0	3	5	10	9	3	37
arts	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	3	0	6	11	8	29
computer	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	1	2	9	10	1	27
biology	0	0	0	0	1	0	0	0	1	0	1	2	2	1	2	0	2	1	7	4	24
physics	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	1	1	4	11	2	22
environment	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	3	5	4	14
psychology	0	0	0	0	0	0	0	0	0	0	0	0	2	1	2	0	0	0	2	0	7
philosophy	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	5	0	7
economics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4	1	6
history	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	3	0	6
linguistics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	2	0	6
political science	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	4
sum	1	2	1	4	6	3	14	9	24	20	41	58	50	94	114	121	212	369	506	171	1820 1820

Fig. 2 Time distribution of subjects. (1) Time distribution of subjects in K-12 education. (2) Time distribution of subjects in higher education. The first column displays the subjects involved in STEM education, and the first row is the timeline. This figure illustrates the time and subject distribution of STEM-related literature. Darker colors indicate a greater number of documents related to the corresponding time node and subject.

milestone document "*K-12 Science Education Framework*", initiating a major reform in science education. This document became the blueprint for the formal launch of the new era of science education reform known as the "*Next Generation Science Standards*" (NGSS). NGSS proposed a paradigm for science education in the U.S., integrating three dimensions: practices, cross-cutting concepts, and disciplinary core ideas. Seven powerful cross-cutting concepts were selected from these dimensions to bridge the boundaries between different subjects. These concepts include patterns, cause and effect relationships, systems and system models, matter and energy, structure and function, stability and change, and scale, proportion, and quantity (National Research Council 2013). The document brought new guidance and direction to STEM education in the United States, emphasizing comprehensive and interdisciplinary educational principles.

Subject integration of STEM in higher education. Figure 2(2) illustrates the time distribution of subjects at the higher education level. Since 2004, a total of 16 subjects have been involved in STEM studies at the higher education level. Similar to the K-12 level, the integration in higher education also shows an intersection of science, technology, engineering, humanities, and social sciences.

STEM subjects (science, technology, engineering, and mathematics) continued to play an important role at the higher education level, covering a wide range of fields of study. Unlike at the K-12 level, STEM education in higher education has exhibited a blend of disciplines at the beginning because of the strong interdisciplinary nature of the courses offered at universities themselves (for example, biochemistry). Students were exposed to more specialized and in-depth knowledge of science, technology, engineering, and mathematics disciplines in their areas of specialization. The focus of disciplinary integration was on combining theories and methods from different disciplines for cross-disciplinary research and innovation. For example, researchers in the multidisciplinary education (ME) course selected undergraduate students in engineering, pre-nursing, and pre-occupational health to collaborate in a maker space to solve health problems and create practical solutions to health-related problems facing the community through their backgrounds and competencies (Ludwig et al. 2017).

The development and disciplinary integration of STEM education was influenced by educational reform and societal needs. With the continuous advancement of technology and globalization, there was an increasing demand for comprehensive ability and interdisciplinary thinking. Traditional science and engineering education could no longer meet the current social and professional needs. Therefore, the integration of humanities and social science disciplines has become an important trend in the development of STEM education. For example, art subjects have promoted the integration of innovation and esthetics by providing creative expression and the development of design thinking. The prominence of gender, race, and economic issues, cultural background conflict in higher education has called for the inclusion of social science disciplines such as psychology, economics, and philosophy, linguistics, political science.

In higher education, the distribution of subjects was relatively diverse, with engineering receiving significant attention among the four main subjects. Additionally, chemistry has also been highly regarded, while comparatively, computer science's involvement is not as prominent.

Comparing the temporal evolution of subjects at different educational levels. In summary, the concept of STEM education was gradually evolving from an initial bias toward engineering education to a more integrated and diverse educational paradigm. Since 2004, there have been 16 subjects involved in STEM (i.e., science, technology, engineering, mathematics, art, physics, chemistry, biology, psychology, computer science, environmental science, linguistics, economics, political science, philosophy, and history). In the analysis of subject integration, the overall integration trend was similar between the K-12 stage and the higher education stage. However, there were still some differences between K-12 education and higher education.

First, STEM education arose in higher education, but there seems to be a trend of research focus shifting from higher education to K-12 education. From 2004 to 2009, STEM research was focused on higher education, and after 2016, the number of papers in K-12 surpassed higher education. The reason for this phenomenon may be that the rise of STEM education sprung from the lack of talent in STEM careers, and higher education was directly oriented to society, so it was reasonable for research and reform to start from higher education, while government policies lead and funding investment largely promoted the rapid development of STEM education in K-12 education stage. Higher education points to the current talent needs of society, while K-12 education points to the future talent needs of society. The inclusion of STEM education in the education strategy of several countries also indicates that STEM talents are an important component of future national competitiveness, so it is very necessary to emphasize the K-12 stage.

Second, at the level of pedagogy and practice, disciplinary integration in STEM education at the K-12 level was often achieved through interdisciplinary projects and activities, such as engineering design challenges, science experiments, and mathematical modeling. These activities were usually classroom-cantered, with teachers guiding students through practice and inquiry. In contrast, in STEM education at the higher education level, disciplinary integration was focused more on the integration of research and practice. Students explored and applied integrated disciplinary knowledge in depth through participation in research projects, hands-on internships, and interdisciplinary courses.

In addition, the concept of STEAM education was more popular at the K-12 stage. "STEAM" was more frequently used in the K-12 stage, which could be said to a certain extent that the STEAM education concept was more popular in the K-12 stage, but may not necessarily indicate a deeper level of interdisciplinary integration in this stage.

Analysis of the evolution of subject themes. Research hotspots are reflected, to some extent, by the frequency of scientific theme terms. In this study, 32 keywords were selected as subject themes at the K-12 level and 33 keywords were selected at the higher education level. To facilitate the analysis, these keywords were grouped into "learning outcomes", "teachers' professional development", "technology empowerment", "social relevance", and "pedagogy". As shown in Fig. 3.

Subject theme evolution in K-12 education. Overall, STEM research topics at the K-12 level predominantly emphasize "learning outcomes", while maintaining a relatively balanced distribution across "teachers' professional development", "technology empowerment", "social relevance", and "pedagogy". The dimension of "learning outcomes" primarily encompassed keywords such as students' academic performance, thinking skills, and associated influencing factors. "Teachers' professional development" involved aspects related to teachers' preparedness for STEM education and collaborative efforts among educators. "Technology empowerment" focused on the impact of various technologies such as modeling, robotics, programming, and augmented reality on both the teaching environment and instructional content. "Pedagogy" primarily revolved around inquiry based and game based learning. Furthermore, research related to social themes primarily aimed to foster educational equity from multiple dimensions, including aspects like gender, culture, and policy.

At the K-12 level, the theme of "learning outcomes" account for the largest proportion with 37.69%, under which the theme words included "achievement", "self-efficacy", "performance", "attitudes", "computational thinking", "knowledge", "creativity", "beliefs", "design thinking" and "cognitive-load". In 2009, Obama proposed the "*Competing for Excellence*" initiative, which aimed to improve students' achievement in STEM. This initiative has led to more researchers exploring different teaching models, activities, and tools to improve student achievement and performance. Also, students' attitudes, knowledge, beliefs, self-efficacy, and cognitive-load were important factors influencing STEM performance and interest and have received close attention from researchers. Self-efficacy refers to one's perceived ability to perform specific behaviors that may contain difficulties and stress (Bandura et al. 1999). Cognitive load is a multidimensional structure that represents the burden placed on a learner's cognitive system when processing specific tasks, often appearing alongside keywords like motivation, performance, etc., in educational research with technical support (Kao and Ruan 2022).

Computational thinking, creativity (Zhan et al. 2023), and design thinking were goals of STEM education and were closely related to the disciplines. Computational thinking (CT) could be seen as a thinking pattern for solving problems with computational tools, and it is a fundamental skill required in everyday life (Wing 2006). It has the most direct relationship with computers, and the "*Next Generation Science Standards*" emphasized its significance by considering computational thinking as a core scientific practice. In China, computational thinking is recognized as a core competency in the curriculum standards for information technology. In addition, there is also increasing research focusing

K-12 Stage Subject Topic Distribution Map

Topic Categories	Keywords	stem	steam	science	math	technology	engineering	computer	arts	physics	environment	biology	chemistry	political science	psychology	linguistics	philosophy	economics	history	Percentage	
Learning Outcomes	achievement	108	3	79	48	25	15	4	2	8	2	1	0	1	0	2	0	2	0	9.58%	37.69%
	self-efficacy	64	8	44	26	23	9	4	6	2	7	2	1	0	0	0	0	0	0	6.26%	
	performance	53	7	37	17	13	10	3	5	2	4	1	0	1	1	1	0	2	0	5.01%	
	attitudes of students	48	3	46	6	8	4	2	1	6	2	0	0	0	0	0	0	0	0	4.02%	
	computational thinking	39	6	19	17	11	7	15	1	2	3	3	1	0	0	0	0	0	0	3.96%	
	knowledge of students	44	4	37	5	2	7	2	1	2	3	0	1	0	1	0	0	0	0	3.48%	
	creativity	16	10	13	1	3	1	0	5	0	1	3	1	1	0	0	0	0	0	1.76%	
	beliefs of students	21	0	22	4	3	0	1	0	1	0	0	0	0	0	0	0	0	0	1.66%	
	design thinking	14	4	5	0	0	7	0	1	0	0	0	0	0	0	0	0	0	0	0.99%	
	cognitive-load	10	1	8	0	2	2	1	2	0	3	0	0	0	0	1	0	0	0	0.96%	
Technology Empowerment	modelling	97	16	55	24	28	15	4	5	4	4	0	4	0	1	0	0	1	0	8.24%	18.91%
	robotics	56	6	19	8	14	14	4	3	1	4	1	1	0	0	1	0	0	0	4.22%	
	programming	53	5	22	13	7	6	7	7	2	4	4	0	0	0	1	0	0	0	4.18%	
	augmented reality	22	8	12	5	8	1	0	3	2	4	0	0	0	0	1	0	0	0	2.11%	
	scratch	3	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.16%	
Social Relevance	gender	143	7	101	47	27	17	11	3	12	2	0	1	0	0	0	0	3	0	11.95%	17.53%
	equity	23	1	14	10	4	2	1	3	0	3	1	1	0	0	0	0	0	1	2.04%	
	culture	24	0	13	5	1	2	1	1	0	0	0	0	1	0	2	1	0	0	1.63%	
	policy	15	2	9	5	0	0	0	0	0	0	1	0	3	0	0	0	0	0	1.12%	
	justice	7	0	3	2	0	1	0	0	0	2	0	1	3	0	0	0	0	0	0.61%	
	patriotism	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0.19%	
Teachers' Professional Development	knowledge of teachers	50	2	43	7	7	6	3	0	1	1	0	1	0	0	0	0	0	0	3.86%	15.62%
	professional developmen	52	3	31	12	7	6	2	2	1	1	1	0	0	0	0	1	0	1	3.83%	
	attitudes of teachers	33	4	31	10	9	4	0	4	0	3	0	0	0	0	0	0	1	0	3.16%	
	conceptions of teachers	20	0	24	7	2	5	0	0	2	0	0	0	0	0	0	1	0	0	1.95%	
	beliefs of teachers	26	2	21	4	1	3	0	0	0	0	0	1	0	0	0	0	0	0	1.85%	
	teacher preparation	6	0	5	1	3	3	1	0	0	0	1	0	0	0	1	0	0	0	0.67%	
	teacher collaboration	1	2	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0.29%	
pedagogy	inquiry based learning	50	3	42	10	11	15	5	6	4	0	0	4	0	0	1	1	0	0	4.85%	10.25%
	game based learning	43	2	23	10	12	1	8	0	3	2	3	0	0	0	1	0	0	0	3.45%	
	project based learning	15	9	7	5	7	2	2	1	1	1	0	0	0	0	0	0	0	0	1.60%	
	self-regulated learning	4	0	2	0	0	1	1	0	0	0	2	0	0	1	0	0	0	0	0.35%	

Higher Education Stage Subject Topic Distribution Map

Topic Categories	Keywords	stem	steam	science	engineering	math	technology	chemistry	arts	computer	biology	physics	environment	psychology	philosophy	economics	history	linguistics	political science	Percentage	
Learning Outcomes	achievement	82	2	55	15	5	33	1	2	9	2	3	2	2	1	2	1	2	1	7.35%	30.47%
	performance	69	3	31	6	10	17	0	0	12	4	1	5	1	0	3	0	3	2	5.58%	
	self-efficacy	59	1	39	10	13	15	0	1	3	2	0	3	0	0	2	0	2	3	5.11%	
	motivation	44	0	25	5	12	13	0	1	5	1	2	0	0	0	2	0	2	2	3.81%	
	persistence	44	0	27	6	5	10	1	1	2	2	1	1	0	1	0	1	0	1	3.44%	
	innovation	18	4	7	7	2	4	0	1	0	1	0	3	1	0	1	0	2	2	1.77%	
	critical thinking	20	5	10	2	4	0	1	0	0	1	0	0	0	0	0	0	0	0	1.44%	
	computational thinking	10	4	4	5	1	0	0	0	2	0	2	1	0	0	0	0	0	0	0.97%	
	creativity	8	3	1	2	0	1	0	2	1	0	0	2	1	0	0	0	1	1	0.77%	
	digital skills	3	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0.23%	
Technology Empowerment	programming	55	1	29	16	11	11	7	7	6	3	1	1	0	1	0	0	1	1	5.05%	11.53%
	modelling	29	2	14	6	7	8	3	4	1	0	1	1	0	0	1	0	1	1	2.64%	
	robotics	22	3	5	14	0	4	2	4	2	2	1	2	0	0	0	0	1	1	2.10%	
	augmented reality	14	0	4	4	3	3	0	1	1	0	0	0	0	0	0	0	0	0	1.00%	
	virtual reality	9	3	2	1	0	1	0	1	1	0	0	4	0	0	0	0	0	0	0.74%	
Social Relevance	gender	214	4	131	29	18	64	3	5	6	5	8	4	1	2	0	2	0	2	16.64%	47.31%
	career	75	0	51	15	13	23	0	1	4	0	2	1	0	0	0	0	0	2	6.25%	
	choice	65	0	43	13	6	20	0	0	6	2	2	1	0	3	0	3	0	2	5.55%	
	identity	54	0	41	7	3	15	1	0	2	7	2	1	0	0	0	0	0	5	4.61%	
	stereotype threat	42	0	35	11	4	19	0	1	5	3	2	2	0	0	0	0	0	3	4.24%	
	race	50	0	29	3	5	11	1	1	1	4	0	0	2	0	1	0	1	0	3.64%	
	culture	34	0	13	4	4	3	0	2	1	1	0	0	3	2	1	2	1	0	2.37%	
	equity	28	0	12	3	4	2	1	5	1	0	0	1	0	0	0	0	1	1	1.97%	
	minority	18	0	9	3	4	3	0	3	1	0	2	3	2	0	0	0	1	1	1.67%	
	marginalized populations	3	0	1	0	0	0	1	2	0	0	0	0	0	2	0	2	0	0	0.37%	
Teachers' Professional Development	faculty training	52	0	32	5	7	7	1	7	0	0	0	1	1	0	0	0	1	1	3.84%	6.11%
	professional development	13	2	9	1	4	5	2	0	0	0	0	0	0	0	0	0	0	0	1.20%	
	educational innovation	17	4	2	5	2	1	0	1	0	0	0	0	0	0	0	0	0	0	1.07%	
pedagogy	collaborative learning	13	1	8	3	2	4	6	1	1	1	0	0	0	2	2	0	1	1	1.54%	4.58%
	active learning	19	1	11	3	1	3	1	2	0	2	1	0	1	0	0	0	0	0	1.50%	
	experiential learning	10	0	4	1	0	2	0	2	3	0	0	0	0	0	0	0	1	1	0.80%	
	game based learning	7	1	2	1	1	2	0	0	2	0	0	0	0	0	0	0	1	1	0.60%	
	positive education	1	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0.13%	

Fig. 3 Themes distribution of subjects. (1) Themes distribution of subjects in K-12 education. (2) Themes distribution of subjects in higher education. The first column represents topic categories, the second column contains relevant keywords, and the third row displays the subjects involved in STEM education. This figure illustrates the theme and subject distribution of STEM-related literature. Darker colors indicate a greater number of documents related to the corresponding subject and theme.

on the connection between CT and mathematics (Lv et al. 2023). Weintrop et al. defined computational thinking in mathematical and scientific practices using a taxonomy that includes four main categories: data practices, modeling and simulation practices, computational problem-solving practices, and systems thinking practices, which had a broad impact on K-12 education (Weintrop et al. 2016).

Furthermore, there was a clear association between creativity and the arts, as well as between design thinking and engineering disciplines. Some scholars argued that creativity plays one of three roles that arts assume in STEM education, with the other two being arts/esthetic learning and contextual understanding (Liu et al. 2021). Design is a prerequisite for making and the first step in the formation of STEM work, often found in studies of engineering subjects (Hernandez et al. 2014), and design thinking also plays an important role in engineering education, especially in high school (Li and Zhan 2022).

"Technology empowerment" (18.91%) was the second most popular theme, with the following themes: "modeling", "robotics", "programming", "augmented reality", and "scratch". "Technology empowerment" emphasized the development of student literacy such as information awareness and computational thinking on the one hand, and laid the foundation for students' STEM education practices on the other. Researchers have explored that robotics education has the potential to cultivate transferable skills in the STEM field (Nelson 2014) and narrow the gender gap in STEM, particularly by promoting girls' learning (Zhong et al. 2023). The use of modeling tools can help students visualize abstract scientific and mathematical concepts or objects, which has a positive impact on learners' academic and personal growth.

In addition, programming is a fundamental requirement for learning computer subjects, and the development of skills related to computer programming and robotics, as well as the introduction of computational thinking principles in STEM education, were considered by researchers as trends in today's world (Bermúdez et al. 2019). AR (Augmented Reality) is the technology that allows virtual objects to be overlaid on real images, enriching students' learning experiences. AR-STEM research was primarily conducted among K-12 students and typically relies on marker-based AR. However, location-based AR has significant advantages in supporting student learning beyond the classroom and facilitating scientific inquiry-based learning (Sırakaya and Alsancak Sırakaya 2022). Scratch is a graphical programming tool. In the K-12 stage, the abstract nature of programming concepts and languages makes it challenging for students to grasp them directly. Graphical programming significantly reduces the complexity of programming, making Scratch widely adopted (Kao and Ruan 2022).

The theme of "social relevance" ranked third with 17.53%, with the main themes related to "gender", "equity", "culture", "policy", "justice" and "patriotism". Equality has always been an important topic in education, ensuring that individuals of different genders and races can participate in STEM education without discrimination. The Obama administration launched "*the Teach for Innovation program*" in 2009, which aimed to increase access to STEM education and employment opportunities for disadvantaged groups, and has contributed in part to researchers' attention to gender. The topic of justice was multifaceted, with environmental justice being particularly prominent. Its purpose was to encourage readers to reframe societal and environmental issues as an ethical responsibility, fostering the construction of this responsibility through care, recognition, openness, and responsiveness to both human and non-human vitality (Kayumova et al. 2019).

Furthermore, since STEM education was a national priority, many researchers have analyzed the development of STEM education through policy analysis (Zhong et al. 2022), particularly focusing on different countries and regions such as South Korea (Park et al. 2016), the United States, Europe (Subotnik et al. 2017), India, Australia (Sharma and Yarlagadda 2018), etc. In South Korea, researchers have combined history education with traditional STEM education to inspire students' patriotism (Park and Cho, 2022).

STEM education originated in the United States, and its evolution is determined by a variety of factors, including national economy, politics, and culture (Zhong et al. 2022). As STEM education was increasingly promoted worldwide, it faced challenges of cultural conflicts and international exchanges. "Culture" was a broadly encompassing term, and research about culture could be divided into two categories. First, it served as a research methodology, such as sociocultural theory, exploring social issues like gender and race and aiming at promoting educational equity for students of diverse cultures and languages (Eisenhart and Allen 2020).

Second, culture served as the background and content carrier for STEM activities. In China, researchers have developed C-STEAM, or culturally oriented disciplinary integration education, based on STEM education and considering the reality and needs of China's development. This concept emphasized exploring and creating cultural concepts using related disciplines in the context of traditional Chinese culture, cultivating students' humanistic spirit, and enhancing their cultural identity and understanding. At the same time, C-STEAM embodied the nurturing value of cultivating students' core literacy, the carrying value of passing on excellent traditional culture, and the social value of creating a culture with regional characteristics. On this basis, the researcher proposed the ETIC curriculum classification framework and 6 C implementation model, which provided a reference for promoting the construction and development of the regional C-STEAM curriculum. (Zhan et al. 2020, 2021; Huo et al. 2020).

"Professional development" ranked fourth with 15.62%. The theme words related were "knowledge", "professional development", "attitudes", "conceptions", "beliefs", "teacher preparation", and "teacher collaboration". Researchers have indicated that changing teachers to interdisciplinary teaching requires first developing the skills and attitudes of interdisciplinary teaching, and professional development (PD) was considered a key component to helping teachers through this transition process (Al Salami et al. 2017). The link between teacher preparation to teach STEM and student STEM achievement has motivated researchers to develop professional development programs to address teacher confidence, attitudes, knowledge, pedagogy, and other preparation issues (Nadelson et al. 2013). Understanding the beliefs held by educators was central to influencing change and improving instruction, so researchers needed to be able to design educational programs that address teachers' beliefs and work to change them when appropriate (Nathan et al. 2010; Vossen et al. 2020).

Furthermore, there was still considerable uncertainty about "what STEM education is" and "what it means" in terms of curriculum and student achievement, research and discussion on the concept of STEM aimed to create a shared concept of STEM education to facilitate dialog between different stakeholders (Dare et al. 2019; Holmes et al. 2018). The above topics can all be categorized as preparations for STEM education, primarily referring to pre-service and in-service STEM teacher training. In addition to the mentioned content, this also included language training, relevant technical learning, and teaching methods. Furthermore, due to the interdisciplinary nature of STEM education, collaboration among teachers from multiple disciplines was necessary, especially when humanities and social sciences were involved (Park and Cho 2022). Therefore, teacher cooperation was also an important way for teachers' professional development.

"Pedagogy" received the least attention (10.25%). The theme words related were "inquiry based learning", "game based learning", "project based learning", and "self-regulated learning". Game based learning demonstrated a close association with technology and computers. Nowadays, students are generally passionate about electronic games, however, they often lack sufficient computer programming knowledge and skills, which limits their development in the computer and technology fields. To address this issue, game based learning has received significant attention in the K-12 stage. The purpose of inquiry based learning was to cultivate students' inquiry skills, which was also at the core of the science curriculum. In STEM education, this method was considered to have three components: data analysis, interpretive reflection, and critical reflection. Using inquiry based learning could integrate various disciplines, enhance educators' attitudes, and it's also suitable for the special needs of gifted students (Abdurrahman et al. 2019).

STEM PBL (STEM Project-Based Learning) is a student-centered teaching approach based on constructivism, characterized by clear outcomes and vaguely defined tasks (Capraro and Slough 2013). STEM PBL activities are fundamentally interdisciplinary, encouraging students to construct knowledge, identify problems independently, and collaborate to solve them (Han et al. 2015). Self-regulated learning (SRL) refers to an active, iterative process in which learners achieve their goals by controlling, monitoring, and adjusting their cognitive/metacognitive processes and learning behaviors. This approach was effective in activating and monitoring learners' behaviors, cognitions, and emotions, which is crucial for task performance in the STEM field (Li et al. 2020).

Through the above analysis, it is evident that research topics in different disciplines have varying emphases. "Achievement" and "gender" were highly popular topics in the scientific community. Additionally, in the fields of math, physics, chemistry, and biology, there was a greater emphasis on "technological empowerment" and "pedagogy". Technology placed the most emphasis on "modeling", while computer science was concerned with "computational thinking". Engineering exhibited a relatively even distribution of research topics. In contrast, the focus areas within humanities and social sciences were relatively scattered.

Subject theme evolution in higher education. In comparison to the K-12 level, research theme distribution in higher education appeared to be more concentrated. This was primarily manifested in the prevalence of research related to "learning outcomes" and "social relevance", which collectively account for over three-quarters of the total research. Conversely, research areas focusing on "teachers' professional development", "technology empowerment", and "pedagogy" were relatively scarce. However, from a disciplinary perspective, research topics in the humanities and social sciences at the higher education level exhibited greater diversity and richness.

"Social relevance" was the most popular theme in higher education research (47.31%). The research content could be broadly categorized into three types. The first category was educational equity and justice, including keywords "gender", "identity", "stereotype threat", "race", "equity", "minority", and "marginalized populations". STEM identity is an expressed connection between one's self and STEM, which depends on the individual's beliefs about their abilities and their conceptual and practical knowledge of their particular STEM subject (Charleston et al. 2014). Enhancing the self-identity of minority groups and optimizing the experience of marginalized populations, especially females, contributed to their more active participation in STEM education. Stereotype threat is a risk experienced by individuals in which individuals fear that they will validate negative stereotypes of the group to which they belong (Spencer et al. 1999). Stereotype threat has been shown to have a significant impact on the likelihood of women, minorities, and white men leaving STEM professions (Beasley and Fischer 2012).

The second category was students' career development, including the keywords "career" and "choice". Career orientation was more prominent at the higher education level than at the K-12 level, with researchers focusing on career goals, career preparation, the position of STEM talent in the labor market, major selection, and attrition.

The third category was culture-related research, which, in higher education, connected with various humanities and social sciences disciplines such as psychology, philosophy, history, linguistics, and more. Research in this category focused on promoting educational equity and students' full participation in STEM education by addressing the fair treatment of students from different sociocultural backgrounds and using "culturally responsive pedagogy". This approach involved leveraging the cultural characteristics, experiences, and perspectives of ethnically diverse students to teach them more effectively, fostering educational equity and comprehensive engagement in STEM education (Gay 2003).

"Learning outcomes" was also a theme that received a lot of attention in higher education, with 30.47%. The related themes included "achievement", "performance", "self-efficacy", "motivation", "persistence", "innovation", "critical thinking", "computational thinking", "creativity", and "digital skills". It was evident from this that higher education was not only concerned with issues such as students' achievement, performance, and computational thinking but also paid attention to influencing factors such as students' self-efficacy and motivation. How to sustain students in STEM majors and reduce attrition of STEM majors, especially among minority and female populations, was a concern in studies related to "persistence" (Burt et al. 2019; Ong et al. 2018).

Compared to the K-12 stage, higher education placed less emphasis on computational thinking and creativity but focused more on innovation and critical thinking. Creativity refers to "the generation of novel and useful ideas by an individual or a small group of individuals" while innovation is "the successful implementation of creative ideas within an organization" (Amabile 1988). The distinction between creativity and innovation lies in the emphasis on products and outcomes in innovation. Higher education demands that students not only have creative ideas but also successfully transform these ideas into scalable products. In contrast, K-12 education placed more emphasis on encouraging students to generate new ideas. Besides, Critical thinking was another important developmental goal at the higher education level. It served as a method and tool for problem-solving, conceptualized as purposeful, self-regulated judgment involving various thinking skills such as analysis, evaluation, and reasoning (Gadot and Tsybulsky 2023).

Digital skill is a concept encompassing skills and specific techniques that are necessary for the use of effective digital technology (van Laar et al. 2019). In research, various terms were used to describe the ability to use digital technology effectively in learning activities, such as digital skills, technical skills, digital literacy, digital competence, digital tools, 21st-century skills, ICT literacy, and ICT skills. Studies have shown a positive correlation between students' digital skills and their creative self-efficacy, and higher levels of digital skills were often predictive of higher levels of actual performance (Chonsalasin and Khampirat 2022).

"Technology empowerment" was ranked third with 11.53%, and the related themes were "modeling", "robotics", "programming", "augmented reality" and "virtual reality". Modeling is a useful tool to identify current problem situations, predict future societal changes, and identify possible solutions (Suh and Han 2019). Programming was considered to be related to problem-solving and the main pedagogical challenge was the lack of appropriate methods and tools as well as scaled and personalized instruction (Medeiros et al. 2019). Robots were often used in the classroom to develop students' human-machine collaboration skills (Mathers et al. 2012).

Augmented Reality (AR) refers to the technology that enhances virtual information in the real environment through ongoing activities and user input, while "Virtual Reality (VR)" is the technology that immerses users in a purely virtual environment. The learning environments created by VR and AR technologies contributed to the formation of collaborative, interactive, and highly immersive learning experiences, thereby enhancing the efficiency of learning for learners (Zhong et al. 2021). Additionally, they demonstrated the potential to help students improve their cross-cultural communication skills (Akdere et al. 2021).

"Teachers' Professional Development" was ranked fourth with 6.11% of the total, and related terms were "faculty training", "professional development", and "educational innovation". Faculty training and professional development were broadly defined terms, and there was a significant degree of overlap in their research content. They encompassed research related to teacher development (such as teacher reflection and active learning), diversity and equity issues among the teaching staff, curriculum design, teaching methodologies, and pedagogical knowledge. Research related to educational innovation encompassed the introduction of new educational technologies, teaching methods, curriculum designs, and assessment approaches to address evolving learning needs and societal challenges.

"Pedagogy" was the least studied topic (4.58%), with related themes including "collaborative learning", "active learning", "experiential learning", "game based learning", and "positive learning". Collaborative learning played a significant role in enhancing the likelihood of successful problem-solving.

Additionally, collaborative skills are crucial for individuals pursuing STEM careers. Active learning is a method characterized by students taking control of their learning to some extent through metacognition, self-assessment, and reflection, within student-centered and inquiry based learning approaches (National Research Council et al. 2000; Kuh 2008). The American Association for the Advancement of Science encouraged university science educators to shift their teaching from traditional lectures to active learning (American Association for the Advancement of Science 2011).

Experiential Learning is an educational approach that emphasizes acquiring knowledge and skills through first-hand experiences, practice, and reflection, often in forms such as teaching, research, and internships. Experiential learning can facilitate the transfer of classroom learning to real-world practice and has the potential to enhance students' learning, motivation, skill development, and graduation rates (Gong et al. 2022). Game based learning was not very common in higher education, and research in this area was quite scattered, covering topics such as computer-based learning and the creation of diverse and inclusive learning environments. The origins of positive learning can be traced back to the early days of the positive psychology movement, to promote students' overall well-being, not just the imparting of knowledge and skills, but also the cultivation of their positive psychological traits and qualities (White 2016).

Undoubtedly, in higher education, almost all disciplines focused their research on "learning outcomes" and "social relevance". Among these, the most emphasized areas included students' performance, diversity, equity, and career development. Furthermore, engineering placed a significant emphasis on programming and robotics technology; mathematics and technology prioritized students' self-efficacy, motivation, persistence, and programming skills. Chemistry, on the other hand, exhibited a unique pattern by showing less focus on learning outcomes but a greater emphasis on technology integration and pedagogy. The arts concentrated more on technology integration and social relevance. However, many other disciplines lacked a substantial focus on teacher professional development.

Comparing the evolution of subject themes at different educational levels. From the above analysis, it can be found that the distribution of research topics in K-12 education was relatively balanced, while in higher education, it was more concentrated. However, in higher education, research in the humanities and social sciences was more in-depth, and the distribution of themes was more extensive. The research hotspots at the two levels have shown the following differences.

Overall, in the K-12 stage, "learning outcomes" received the most attention, while career education for students was lacking. In higher education, "learning outcomes" and "social relevance" were the most emphasized aspects, while "teachers' professional development" and "pedagogy" were relatively neglected.

Specifically, concerning "learning outcomes", achievement, performance, and self-efficacy were common topics across different educational levels. K-12 education placed more emphasis on computational thinking, creativity, and design thinking, while higher education focused more on innovation and critical thinking. Regarding "teachers' professional development", higher education paid relatively less attention to teachers and their development, lacking a systematic body of research. In "technology empowerment", technologies in the research were highly similar, but there was a greater volume of publications in K-12 education. The knowledge or tools learned were also more foundational and straightforward at this level. In the realm of "social relevance" research, gender, equity, and culture were common topics of interest, but higher education delved into students' career choices and development, an area that lacked emphasis in K-12 education. In terms of "pedagogy" research, K-12 education primarily focused on inquiry based learning and game based learning, while higher education emphasized collaborative learning and active learning.

Discussion

This study analyzed and compared the development of the STEM research field in two aspects: subject integration and subject themes distribution, to clarify the STEM subject orientation and the ecological map of subject integration in the STEM field.

Referring to RQ1, the subject time distribution maps were used to find out how subjects integrated into STEM education at the K-12 and higher education levels. From the above analysis, it is clear that subject integration followed the evolutionary path of science, technology, engineering, and mathematics to the addition of social sciences and humanities. The addition of the latter has qualitatively improved the connotation of STEM education and fundamentally changed the subject integration path. In other words, the field of STEM studies has expanded from science education to the whole education field, and the cross-fertilization of subjects has become its most fundamental feature. This conclusion has been corroborated by existing research and policies (Perignat and Katz-Buonincontro 2019; Zhan et al. 2022a).

Referring to RQ2, the subject themes distribution maps at the K-12 and higher education levels reflected the main research content of STEM education. Research themes were not evenly distributed, especially since the research on "learning outcomes" was much more than the research on "teachers' professional development" and "pedagogy", which implied that the current attention to STEM teachers was insufficient. Previous research indicated that teacher education programs lack content related to interdisciplinary integration across different subject areas and do not provide suitable activities for integrating STEM education (Türk et al. 2018). In addition, although K-12 education started late, it has developed rapidly due to the promotion of policies and the future needs of society, but there is still much room for expansion of its research scope, especially career issues. In recent years, with the further development of globalization, student diversity has become evident not only in higher education but also in K-12 education. Research has shown that multicultural education and culturally supportive teaching contribute to addressing the persistent inequalities in the field of STEM education (Charity Hudley and Mallinson 2017).

STEM education has obvious interdisciplinary characteristics, in which different subjects play different roles, as shown in Table 1. The essence of science subjects is to understand the objective laws of the world, and science education aims to help students understand the world through inquiry methods, knowledge is the key to its teaching. The essence of technology is the application of knowledge scenarios, and technology achieves the purpose of transforming the world by manipulating and optimizing the variables that affect the results (products), the key to its teaching is the acquisition of skills. Engineering is the integrated application of technology, and its purpose is also to transform the world, but unlike technology, engineering places more emphasis on the coordination of all elements within the system to find the optimal solution to the problem, and engineering operates and optimizes the variables that affect the system to achieve the purpose of system optimization. The essence of mathematics is measurement and calculation, which develops itself through abstract, non-empirical mathematical operations and heuristic logical deduction, and can provide the

Table 1 STEM subject orientation.

	S	T	E	M	A
Subjects	Science subjects (e.g., physics, chemistry, biology)	Technical subjects (e.g., computer)	Engineering subjects (e.g., computer, environment)	Mathematics	Humanities and Social Sciences (e.g., art, psychology, language, philosophy, political science, economics, history)
Essence	Recognize objective laws of the world	Scenario application of knowledge	Integrated application of technology	Measurement, computation	Perception, interpretation, and creation of the man-made world
Purpose	Knowing the world	Transforming the world	Transforming the world	Providing a logical and computational basis	Promoting all-round development, enhancing moral values and cultural identity, developing creative and innovative thinking
Methodology	Methods of inquiry	Manipulating and optimizing variables that affect outcomes (products)	Manipulates and optimizes variables that affect the system	Abstract, non-empirical mathematical operations, and heuristic logical-deductive proofs based on	Epistemology, performance theory, value-emotion theory
Keys to teaching and learning	Acquisition of knowledge	Acquisition of skills	Optimization of systems	Arithmetic, measurement, logical deduction	Appreciation, designing, and creating

logical and calculative basis for other subjects, and the key to its teaching is calculation, measurement, and logical deduction.

Unlike the above subjects, the essence of humanities and social sciences is to feel, interpret, and create the man-made world. It contributes to the all-around development of human beings, the enhancement of moral values and cultural identity, and the development of creative and innovative thinking through the unity of awareness, expression, values, and emotions, the key to teaching is tasting, designing, and creating. In addition, there is a slight difference between the humanities and social sciences. The social sciences involved in STEM fields mainly reflect on the social issues that exist or are raised in STEM education from the perspective of research, but are less reflected in the teaching of the subjects, such as psychology. The involvement of the humanities is mainly reflected in the teaching of the subjects, and the educational goals are achieved through teaching students to appreciate the appeal and value of the arts.

The STEM education research ecosystem comprises two parts. The upper elliptical portion reveals the distribution of disciplines and research topics, while the lower timeline illustrates the timeline of interdisciplinary integration. The central part of the ellipse indicates the disciplinary composition of STEM education. Science, oriented towards exploration, forms the foundation of STEM education. Engineering, driven by creativity and innovation, plays a crucial role in fostering students' creativity and innovation. Science and engineering mutually reinforce each other and progress together. Technology provides the tools and support for STEM education, while mathematics serves as the computational foundation, collectively facilitating STEM education activities.

STEM education, through interdisciplinary teaching, emphasizes the cultivation of students' higher-order thinking skills, such as scientific thinking, design thinking, engineering thinking, and computational thinking. The outermost circle includes other disciplines involved in STEM education, such as arts, economics, history, political science, linguistics, psychology, philosophy, physics, biology, computer science, environmental studies, chemistry, and more. This demonstrates the trend in STEM education shifting from STEM to STEAM (Science, Technology, Engineering, Arts, and Mathematics) and the integration of science, technology, engineering, mathematics, and social sciences in education. The pink and blue sections represent the distribution of research topics in the K-12 and higher education stages.

From the above analysis, we could outline the ecological map of STEM subject integration in terms of subject integration and subject themes distribution, as shown in Fig. 4, which demonstrates the subject integration and main research contents of STEM education.

Conclusion and future research

Based on the literature related to STEM education in the WOS database from 2004 to 2023, covering 903 papers at the K-12 level and 873 papers at the higher education level, this study conducted a bibliometric analysis from the perspective of subject evolution, including subject timeline evolution analysis and subject theme evolution analysis, to reveal the subject evolution trends and research hotspots in STEM education. The following conclusions were reached.

First, regarding subject integration, the interdisciplinary and cross-subject collaboration in STEM education was constantly expanding and deepening, forming a new situation in which science, engineering, humanities, and social sciences are integrated. Since 2004, a total of 16 subjects have been involved, among them, arts, physics, chemistry, biology, computer science, and environmental science were the main integrated subjects. Interdisciplinary integration promoted the innovation and development of STEM education research.

Second, regarding the research themes, humanism was more and more emphasized in STEM education. In the temporal evolution of subjects in STEM education, it was found that the research outputs of humanities and social science subjects such as arts, psychology, and philosophy kept increasing. The cultural themes have enriched the diversity of participants and the uniqueness of regions in STEM education research, viewed from perspectives such as theory, teaching methods, and regional development. "Social relevance" has garnered significant attention across different educational levels. In K-12 education, research topics were relatively balanced, but there was a lack of research on students' career choices and development. In higher education, research topics in the humanities and social sciences were more diverse in their distribution.

To sum up, this study analyzed the developmental lineage of STEM education, focusing on the subject roles, and hot topics of research, and summing up potential guidance for subsequent subject integration research. Future work should prioritize the articulation of STEM subject integration between K-12 education and higher education. At the K-12 level, it is necessary to enhance vocational education appropriately, while in higher education, reducing the attrition rate of STEM majors may become a crucial issue. Additionally, attention to multi-discipline teacher collaboration and professional development, high-quality curricula

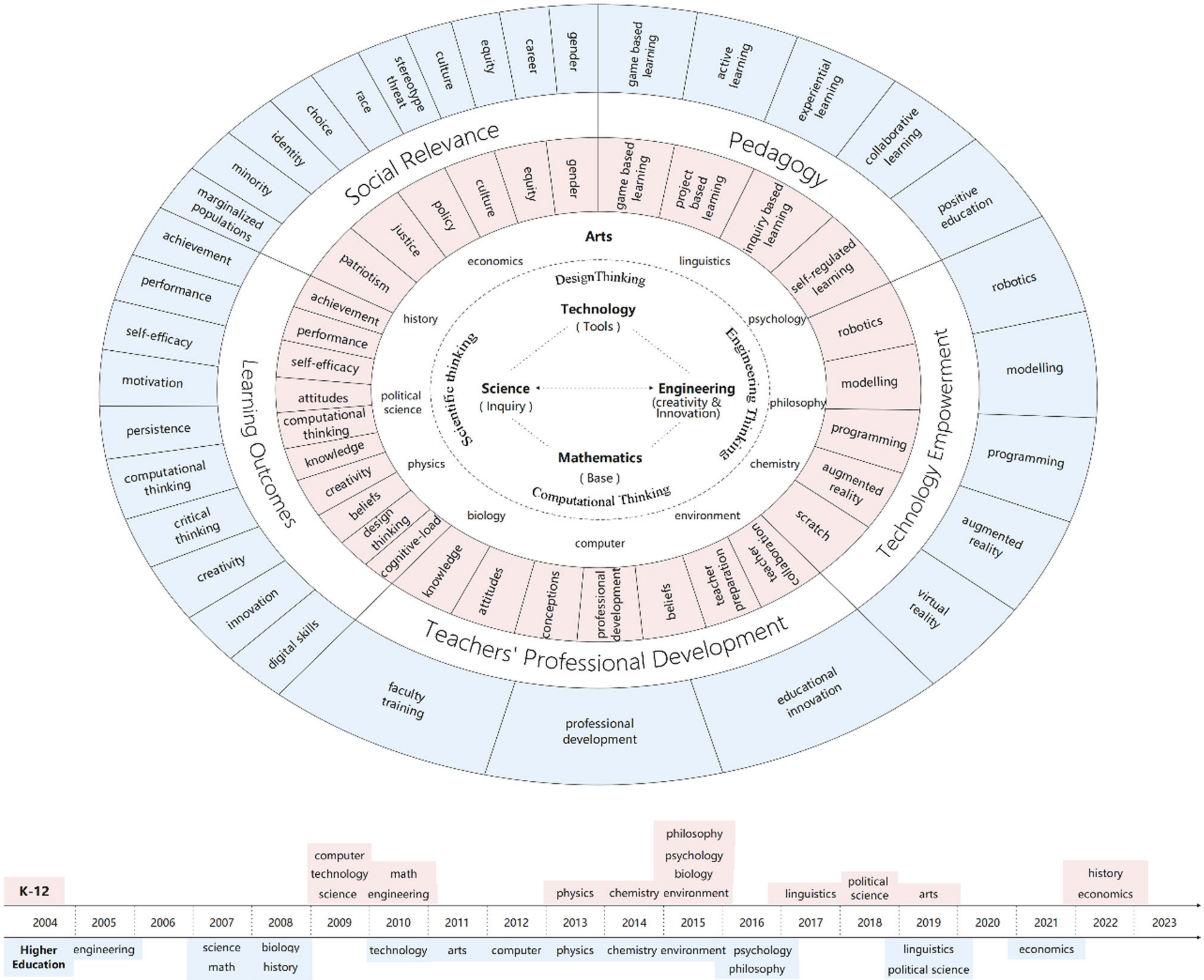

Fig. 4 Ecological map of subject integration in STEM. This figure is composed of two parts, with the upper part representing the content dimension, and the lower part representing the time dimension. The pink area within the ellipse illustrates the most prominent research themes in the K-12 stage, while the blue area illustrates the most prominent research themes in higher education.

design, and regional policy support should continue to be emphasized. Moreover, different countries present different characteristics in the development of STEM education due to their different cultural, political, and economic backgrounds. In future studies, we aim to conduct a comparative study on the development of STEM education on a country-by-country basis.

Data availability

The datasets generated during and/or analyzed during the current study are available in the supplementary file.

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References

Abdurrahman A, Nurulsari N, Maulina H, Ariyani F (2019) Design and validation of inquiry-based STEM learning strategy as a powerful alternative solution to facilitate gift students facing 21st century challenging. J Educ Gifted Young Sci 7(1):33–56. https://doi.org/10.17478/jegys.513308

Akdere M, Acheson K, Jiang Y (2021) An examination of the effectiveness of virtual reality technology for intercultural competence development. Int J Intercult Relat 82:109–120. https://doi.org/10.1016/j.ijintrel.2021.03.009

Al Salami MK, Makela CJ, de Miranda MA (2017) Assessing changes in teachers' attitudes toward interdisciplinary STEM teaching. Int J Technol Des Educ 27(1):63–88. https://doi.org/10.1007/s10798-015-9341-0

Amabile TM (1988) A model of creativity and innovation in organizations. Res Organ Behav 10(1):123–167. https://web.mit.edu/curhan/www/docs/Articles/15341_Readings/Group_Performance/Amabile_A_Model_of_CreativityOrg.Beh_v10_pp123-167.pdf

American Association for the Advancement of Science (2011) Vision and change in undergraduate biology education: a call to action. Washington, DC. https://www.aaas.org/sites/default/files/content_files/VC_report.pdf

Bandura A, Freeman WH, Lightsey R (1999) Self-efficacy: the exercise of control. J Cognit Psychother 13(2):158–166. https://doi.org/10.1891/0889-8391.13.2.158

Beasley MA, Fischer MJ (2012) Why they leave: the impact of stereotype threat on the attrition of women and minorities from science, math and engineering majors. Soc Psychol Educ 15(4):427–448. https://doi.org/10.1007/s11218-012-9185-3

Bermúdez A, Casado R, Fernández G, Guijarro M, Olivas P (2019) Drone challenge: a platform for promoting programming and robotics skills in K-12 education. Int J Adv Robot Syst 16(1):172988141882042. https://doi.org/10.1177/1729881418820425

Buckley J, Seery N, Canty D (2018) A heuristic framework of spatial ability: a review and synthesis of spatial factor literature to support its translation into STEM education. Educ Psychol Rev 30(3):947–972. https://doi.org/10.1007/s10648-018-9432-z

Burt BA, Williams KL, Palmer GJM (2019) It takes a village: the role of emic and etic adaptive strengths in the persistence of black men in engineering graduate programs. Am Educ Res J 56(1):39–74. https://doi.org/10.3102/0002831218789595

Capraro RM, Slough SW (2013) Why PBL? Why STEM? Why now? An introduction to STEM project-based learning: an integrated science, technology, engineering, and mathematics (STEM) approach. In STEM project-based learning. Brill, Rotterdam, p 1–5
Charity Hudley AH, Mallinson C (2017) "It's worth our time": a model of culturally and linguistically supportive professional development for K-12 STEM educators. Cult Stud Sci Educ 12:637–660. https://doi.org/10.1007/s11422-016-9743-7
Charleston LJ, George PL, Jackson JFL, Berhanu J, Amechi MH (2014) Navigating underrepresented STEM spaces: experiences of Black women in U.S. computing science higher education programs who actualize success. J Diversity Higher Educ 7(3):166–176. https://doi.org/10.1037/a0036632
Chonsalasin D, Khampirat B (2022) The impact of achievement goal orientation, learning strategies, and digital skill on engineering skill self-efficacy in Thailand. IEEE Access 10:11858–11870. https://doi.org/10.1109/ACCESS.2022.3146128
Conde MÁ, Rodríguez-Sedano FJ, Fernández-Llamas C, Gonçalves J, Lima J, García-Peñalvo FJ (2021) Fostering STEAM through challenge-based learning, robotics, and physical devices: a systematic mapping literature review. Comput Appl Eng Educ 29(1):46–65. https://doi.org/10.1002/cae.22354
Dare EA, Ring-Whalen EA, Roehrig GH (2019) Creating a continuum of STEM models: exploring how K-12 science teachers conceptualize STEM education. Int. J. Sci. Educ. 41(12):1701–1720. https://doi.org/10.1080/09500693.2019.1638531
Department of Education (2022) Science, Technology, Engineering, and Math, including Computer Science. https://www.ed.gov/stem
Eisenhart M, Allen CD (2020) Addressing underrepresentation of young women of color in engineering and computing through the lens of sociocultural theory. Cult Stud Sci Educ 15:793–824. https://doi.org/10.1007/s11422-020-09976-6
Gadot R, Tsybulsky D (2023) Digital curation as a pedagogical approach to promote critical thinking. J Sci Educ Technol. https://doi.org/10.1007/s10956-022-10016-x
Gay G (2003) Becoming multicultural educators: personal journey toward professional agency. Jossey-Bass Publishers, San Francisco, CA
Gilligan KA, Flouri E, Farran EK (2017) The contribution of spatial ability to mathematics achievement in middle childhood. J Exp Child Psychol 163:107–125. https://doi.org/10.1016/j.jecp.2017.04.016
Gong HJ, Kwon J, Brock M (2022) Experiential learning through a peer learning assistant model in STEM. Educ Res 64(3):317–333. https://doi.org/10.1080/00131881.2022.2096092
Grover S, Pea R (2013) Computational thinking in K–12: a review of the state of the field. Educ Res 42(1):38–43. https://doi.org/10.3102/0013189X12463051
Han S, Yalvac B, Capraro MM, Capraro RM (2015) In-service teachers' implementation and understanding of STEM project based learning. Eur J Math Sci Technol Educ 11(1):63–76. https://doi.org/10.12973/eurasia.2015.1306a
Hernandez PR, Bodin R, Elliott JW, Ibrahim B, Rambo-Hernandez KE, Chen TW, de Miranda MA (2014) Connecting the STEM dots: measuring the effect of an integrated engineering design intervention. Int J Technol Des Educ 24:107–120. https://doi.org/10.1007/s10798-013-9241-0
Holmes K, Gore J, Smith M, Lloyd A (2018) An integrated analysis of school students' aspirations for STEM careers: which student and school factors are most predictive? Int J Sci Math Educ 16(4):655–675. https://doi.org/10.1007/s10763-016-9793-z
Huo L, Zhan Z, Mai Z, Yao X, Zheng Y (2020) A case study on C-STEAM education: Investigating the effects of students' STEAM literacy and cultural inheritance literacy. In Technology in Education. Innovations for Online Teaching and Learning: 5th International Conference, ICTE 2020, Macau, China, August 19-22, 2020, Revised Selected Papers 5 (pp. 3–12). Springer Singapore, https://doi.org/10.1007/978-981-33-4594-2_1
Kao GYM, Ruan CA (2022) Designing and evaluating a high interactive augmented reality system for programming learning. Comput Hum Behav 132:107245. https://doi.org/10.1016/j.chb.2022.107245
Kayumova S, McGuire CJ, Cardello S (2019) From empowerment to response-ability: Rethinking socio-spatial, environmental justice, and nature-culture binaries in the context of STEM education. Cult Stud Sci Educ 14:205–229. https://doi.org/10.1007/s11422-018-9861-5
Kuh GD (2008) Excerpt from high-impact educational practices: what they are, who has access to them, and why they matter. Assoc Am Coll Univ, 14(3), 28–29. file:///C:/Users/lenovo/Downloads/High-Impact_Educational_Practices_What_They_Are_Who_Has_Access_to_Them_and_Why_They_Matter%20(2).pdf
Li KC, Wong BTM (2023) Personalisation in STE (A) M education: a review of literature from 2011 to 2020. J Comput Higher Educ 35(1):186–201. https://doi.org/10.1007/s12528-022-09341-2
Li S, Chen G, Xing W, Zheng J, Xie C (2020) Longitudinal clustering of students' self-regulated learning behaviors in engineering design. Comput Educ 153:103899. https://doi.org/10.1016/j.compedu.2020.103899
Li T, Zhan Z (2022) A systematic review on design thinking Integrated Learning in K-12 education. Appl Sci 12(16):8077. https://doi.org/10.3390/app12168077
Liu CY, Wu CJ, Chien YH, Tzeng SY, Kuo HC (2021) Examining the quality of art in STEAM learning activities. Psychol Aesthet Creat Arts, https://doi.org/10.1037/aca0000404
Ludwig PM, Nagel JK, Lewis EJ (2017) Student learning outcomes from a pilot medical innovations course with nursing, engineering, and biology undergraduate students. Int J STEM Educ 4(1):1–14. https://doi.org/10.1186/s40594-017-0095-y
Lv L, Zhong B, Liu X (2023) A literature review on the empirical studies of the integration of mathematics and computational thinking. Educ Inform Technol 28(7):8171–8193. https://doi.org/10.1007/s10639-022-11518-2
Mallinson C, Hudley AHC (2018) Balancing the communication equation: An outreach and engagement model for using sociolinguistics to enhance culturally and linguistically sustaining K–12 STEM education. Language 94(3):e191–e215. https://doi.org/10.1353/lan.2018.0048
Martín-Páez T, Aguilera D, Perales-Palacios FJ, Vílchez-González JM (2019) What are we talking about when we talk about STEM education? A review of literature. Sci Educ 103(4):799–822. https://doi.org/10.1002/sce.21522
Mathers N, Goktogen A, Rankin J, Anderson M (2012) Robotic mission to mars: hands-on, minds-on, web-based learning. Acta Astronautica 80:124–131. https://doi.org/10.1016/j.actaastro.2012.06.003
Medeiros RP, Ramalho GL, Falcao TP (2019) A systematic literature review on teaching and learning introductory programming in higher education. IEEE Trans Educ 62(2):77–90. https://doi.org/10.1109/TE.2018.2864133
Morrison J (2006) Attributes of STEM education: the student, the school, the classroom. TIES Teach Inst Excellence STEM) 20:2–7. http://leadingpbl.pbworks.com/f/Jans%20pdf%20Attributes_of_STEM_Education-1.pdf
Nadelson LS, Callahan J, Pyke P, Hay A, Dance M, Pfiester J (2013) Teacher STEM perception and preparation: inquiry-based STEM professional development for elementary teachers. J Educ Res 106(2):157–168. https://doi.org/10.1080/00220671.2012.667014
National Research Council, Division of Behavioral and Social Sciences and Education, Board on Behavioral, Cognitive, and Sensory Sciences, & Committee on Developments in the Science of Learning with additional material from the Committee on Learning Research and Educational Practice (2000) How people learn: Brain, mind, experience, and school: Expanded edition. National Academies Press, Washington, DC
National Research Council (2013) Next Generation Science Standards, https://www.nextgenscience.org/
National Science Board (1986) Undergraduate Science, Mathematics and Engineering Education, https://www.nsf.gov/nsb/publications/1986/nsb0386.pdf
National Science Foundation (2014) NSF approved STEM fields, https://btaa.org/docs/default-source/diversity/nsf-approved-fields-of-studycac2.pdf?sfvrsn=642824bc_2
Nathan MJ, Tran NA, Atwood AK, Prevost A, Phelps LA (2010) Beliefs and expectations about engineering preparation exhibited by high school STEM teachers. J Eng Educ 99(4):409–426. https://doi.org/10.1002/j.2168-9830.2010.tb01071.x
Nelson CA (2014) Generating transferable skills in STEM through educational robotics. In K-12 education: concepts, methodologies, tools, and applications (pp. 433–444). Igi Global, https://doi.org/10.4018/978-1-4666-4502-8.ch026
Ong M, Smith JM, Ko LT (2018) Counterspaces for women of color in STEM higher education: marginal and central spaces for persistence and success: COUNTERSPACES FOR WOMEN OF COLOR IN STEM EDUCATION. J Res Sci Teach 55(2):206–245. https://doi.org/10.1002/tea.21417
Ortiz-Revilla J, Adúriz-Bravo A, Greca IM (2020) A framework for epistemological discussion on integrated STEM education. Sci Educ 29(4):857–880. https://doi.org/10.1007/s11191-020-00131-9
Park H, Byun SY, Sim J, Han HS, Baek YS (2016) Teachers' perceptions and practices of STEAM education in South Korea. Eurasia J Math Sci Technol Educ 12(7):1739–1753. https://doi.org/10.12973/eurasia.2016.1531a
Park W, Cho H (2022) The interaction of history and STEM learning goals in teacher-developed curriculum materials: opportunities and challenges for STEAM education. Asia Pac Educ Rev 23(3):457–474. https://doi.org/10.1007/s12564-022-09741-0
Perignat E, Katz-Buonincontro J (2019) STEAM in practice and research: an integrative literature review. Think Skills Creat 31:31–43. https://doi.org/10.1016/j.tsc.2018.10.002
Salas-Pilco SZ, Xiao K, Oshima J (2022) Artificial intelligence and new technologies in inclusive education for minority students: a systematic review. Sustainability 14(20):13572. https://doi.org/10.3390/su142013572
Sharma J, Yarlagadda PK (2018) Perspectives of 'STEM education and policies' for the development of a skilled workforce in Australia and India. Int J Sci Educ 40(16):1999–2022. https://doi.org/10.1080/09500693.2018.1517239
Sırakaya M, Alsancak Sırakaya D (2022) Augmented reality in STEM education: a systematic review. Interact Learn Environ 30(8):1556–1569. https://doi.org/10.1080/10494820.2020.1722713
Spencer SJ, Steele CM, Quinn DM (1999) Stereotype threat and women's math performance. J Exp Soc Psychol 35(1):4–28. https://doi.org/10.1006/jesp.1998.1373

Subotnik RF, Stoeger H, Olszewski-Kubilius P (2017) Talent development research, policy, and practice in Europe and the United States: outcomes from a summit of international researchers. Gifted Child Q 61(3):262–269. https://doi.org/10.1177/0016986217701839

Suh H, Han S (2019) Promoting sustainability in university classrooms using a STEM project with mathematical modeling. Sustainability 11(11):3080. https://doi.org/10.3390/su11113080

Sümen ÖÖ, Çalisici H (2016) Pre-service teachers' mind maps and opinions on STEM education implemented in an environmental literacy course. Educ Sci Theory Pract 16(2):459–476. https://doi.org/10.12738/estp.2016.2.0166

Taylor HA, Hutton A (2013) Think3d!: training spatial thinking fundamental to STEM education. Cognit Instr 31(4):434–455. https://doi.org/10.1080/07370008.2013.828727

Türk N, Kalayci N, Yamak H (2018) New trends in higher education in the globalizing world: STEM in teacher education. Univ J Educ Res 6(6):1286–1304. https://doi.org/10.13189/ujer.2018.060620

Usković V (2023) Natural sciences and chess: a romantic relationship missing from higher education curricula. Heliyon. https://www.cell.com/heliyon/pdf/S2405-8440(23)02222-3.pdf

van Laar E, van Deursen AJ, van Dijk JA, de Haan J (2019) Determinants of 21st-century digital skills: a large-scale survey among working professionals. Comput Hum Behav 100:93–104. https://doi.org/10.1016/j.chb.2019.06.017

Vossen TE, Henze I, De Vries MJ, Van Driel JH (2020) Finding the connection between research and design: the knowledge development of STEM teachers in a professional learning community. Int J Technol Des Educ 30:295–320. https://doi.org/10.1007/s10798-019-09507-7

Weintrop D, Beheshti E, Horn M, Orton K, Jona K, Trouille L, Wilensky U (2016) Defining computational thinking for mathematics and science classrooms. J Sci Educ Technol 25:127–147. https://doi.org/10.1007/s10956-015-9581-5

White MA (2016) Why won't it stick? Positive psychology and positive education. Psychol Well Being 6(1):1–16. https://doi.org/10.1186/s13612-016-0039-1

Wing JM (2006) Computational thinking. Commun ACM 49(3):33–35. https://www.microsoft.com/en-us/research/wp-content/uploads/2012/08/Jeannette_Wing.pdf

Yakman G (2008) STEAM education: an overview of creating a model of integrative education. https://www.researchgate.net/publication/327351326_STEAM_Education_an_overview_of_creating_a_model_of_integrative_education

Yakman G (2010) What is the point of STE@ M?–a brief overview. Steam: a framework for teaching across the disciplines. STEAM Educ 7(9):1–9. https://www.researchgate.net/profile/Georgette-Yakman-2/publication/327449281_What_is_the_point_of_STEAM-A_Brief_Overview/links/5b901b98a6fdcce8a4c2f290/What-is-the-point-of-STEAM-A-Brief-Overview.pdf

Zhan Z, He W, Yi X, Ma S (2022b) Effect of unplugged programming teaching aids on children's computational thinking and classroom interaction: with respect to Piaget's four stages theory. J Educ Comput Res 60(5):1277–1300. https://doi.org/10.1177/07356331211057143

Zhan Z, Ma S, Li W, Shen W, Huo L, Yao X (2021) Effect of "6C" instructional design model on students' STEAM competency and cultural inheritance literacy in a Dragon Boat C-STEAM course. In Proceedings of the 2021 5th International Conference on Education and E-Learning (pp. 229–236). https://doi.org/10.1145/3502434.3502436

Zhan Z, Shen W, Xu Z, Niu S, You G (2022a) A bibliometric analysis of the global landscape on STEM education (2004-2021): towards global distribution, subject integration, and research trends. Asia Pac J Innov Entrepreneurship 16(2):171–203. https://doi.org/10.1108/APJIE-08-2022-0090

Zhan Z, Xiao Y, Li T (2023) Effects of association interventions on students' creative thinking, aptitude, empathy, and design scheme in a STEAM course: considering remote and close association. Int J Technol Des Educ 33(5):1773–1795. https://doi.org/10.1007/s10798-022-09801-x

Zhan Z, Zhong B, Huo L, Huang M (2020) Transdisciplinary education for cultural inheritance (C-STEAM): value orientation and classification framework. China Educ Technol 3:69–76. https://doi.org/10.3969/j.issn.1006-9860.2020.03.010

Zhong B, Liu X, Huang Y (2023) Effects of pair learning on girls' learning performance in robotics education. J Educ Comput Res 61(1):151–177. https://doi.org/10.1177/07356331221092666

Zhong B, Liu X, Zhan Z, Ke Q, Wang F (2022) What should a Chinese top-level design in STEM Education look like? Humanit Soc Sci Commun 9(1):1–8. https://doi.org/10.1057/s41599-022-01279-1

Zhong B, Su S, Liu X, Zhan Z (2021) A literature review on the empirical studies of technology-based embodied learning. Interact Learn Environ, 1–20. https://doi.org/10.1080/10494820.2021.1999274

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Author contributions
ZZ identified the research idea, designed and facilitated the study, wrote the draft, and revised the work extensively. SN was involved in data processing (including collection, refinement, visualization, and analysis), writing, and revising the manuscript.

Competing interests
The authors declare no competing interests.

Ethical approval
This study does not involve human participants. All procedures performed in studies were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent
This article does not contain any studies with human participants performed by any of the authors.

Additional information
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