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SURVEY PAPER

Mathematics and interdisciplinary STEM education: recent developments and future directions

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Abstract
This special issue introduces recent research on mathematics in interdisciplinary STEM education. STEM education is widely promoted by governments around the world as a way of boosting students' interest and achievement in science, technology, engineering, and mathematics and preparing STEM-qualified workers for twenty-first century careers. However, the role of mathematics in STEM education often appears to be marginal, and we do not understand well enough how mathematics contributes to STEM-based problem-solving or how STEM education experiences enhance students' learning of mathematics. In this survey paper, we present a narrative review of empirical and conceptual research literature, published between 2017 and 2022. These literature sources are organised by a framework comprising five thematic clusters: (1) interdisciplinary curriculum models and approaches; (2) student outcomes and experiences; (3) teacher preparation and professional development; (4) classroom implementation and task design; and (5) policy, structures, and leadership. We use the framework to provide an overview of the papers in this issue and to propose directions for future research. These include: investigating methods and rationales for connecting the constituent STEM disciplines so as to preserve the disciplinary integrity of mathematics; clarifying what is meant by student "success" in interdisciplinary STEM programs, projects, and other educational approaches; moving beyond classroom practices that position mathematics as just a tool for solving problems in other disciplines; understanding what makes a STEM task mathematically rich; and asking how STEM education research can productively shape STEM education policy.

Keywords Mathematics in STEM · Interdisciplinary STEM education · Mathematics education · Mathematical modelling · Computational thinking

1 Introduction

Around the world, STEM education is promoted by governments as a means of addressing social and economic challenges and creating a scientifically, mathematically, and technologically literate citizenry. In many countries, formal policies and reports by governments and business groups aim to incorporate STEM into the school curriculum, encourage young people to engage in STEM education, and advocate for STEM careers (e.g., Department of Education and Skills, Ireland, 2017; Education Bureau of Government of HKSAR, 2016; European Schoolnet, 2017; Honey et al., 2014; Office of the Chief Scientist, 2014). However, as STEM education research is still in an embryonic state, the field is lacking a scientific evidence base that can inform the development of theory, policy and practice (Maass et al., 2019). In addition, although it is common to claim that mathematics is the discipline that underpins STEM, it is not clear how mathematical concepts and practices contribute to a better understanding of the other STEM disciplines; nor do we understand well enough how STEM education experiences enhance students' learning of mathematics (English, 2016; Fitzallen, 2015).

Therefore, in this special issue of *ZDM*, we are interested in *interdisciplinary approaches that connect mathematics to at least one of the other STEM disciplines*. This theme is timely in light of recent interest in interdisciplinary

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mathematics education and the role of mathematics in STEM education. For example, a Topic Study Group on interdisciplinary mathematics education was introduced at ICME-13, the 13th International Congresses on Mathematical Education held in 2016 (see Doig et al., 2019) and this group continued to meet in subsequent ICMEs. In addition, a new Thematic Working Group on mathematics in the context of STEM education was established at CERME-11, the 11th Congress of the European Society for Research in Mathematics Education in 2019 (Ubuz et al., 2019) and continued to meet at CERME-12 (Ubuz et al., 2022) and CERME-13. This current special issue of *ZDM* also complements and builds on the research reported in *ZDM 51*(6) on twenty-first century skills and STEM teaching and learning. As interest in interdisciplinary STEM education is growing, it is appropriate to identify, synthesise, and critically evaluate current research that focuses on mathematics education within this context.

In this survey paper, we begin with a brief overview of the state of research in integrated STEM education and then present a more detailed survey of research literature on the role of mathematics in integrated STEM education, based on works published from 2017 to 2022. To structure the discussion of this literature, we modified the framework of Honey et al. (2014) to create five thematic clusters that were identified by examining the studies' goals and approaches. Finally, we use our modified framework to introduce the papers in this issue and their contribution to the field, and to propose directions for future research.

2 A brief overview of research in integrated STEM education

To characterise then-existing approaches to integrated STEM education, Honey et al. (2014) developed a framework with four high-level features: (1) the *goals* of integrated STEM education; (2) the *nature and scope* of integration; (3) *implementation* of integrated STEM education; and (4) the *outcomes* of integrated STEM education. While these features are clearly interconnected, representing them separately in the framework facilitates a systematic approach to analysis and discussion of key aspects of the broad research landscape.

2.1 Goals

In the context of mathematics and interdisciplinary STEM education, Anderson et al. (2020) warned that there is no sound evidence base to support the ambitious goals outlined in policy documents—for example, increasing students' engagement and participation in STEM subjects and careers; or developing teachers' capacities to design and deliver inquiry-based, integrated STEM curricula. This observation suggests that research addressing the nature and scope, implementation, and outcomes of integrated STEM education should inform policy development, and that such policies need to be carefully scrutinised to evaluate their feasibility and implications.

2.2 Nature and scope of integration

Although it is widely understood that the STEM acronym refers to the disciplines of science, technology, engineering and mathematics, there are different views on the nature and scope of integration between disciplines and how STEM should be represented in the school curriculum. Researchers have proposed various ways of classifying STEM connections and disciplinary emphasis. For example, Vasquez et al. (2013) described a continuum connecting disciplinary, multidisciplinary, interdisciplinary, and transdisciplinary approaches to integrated STEM education, as summarised in Table 1.

In contrast, Kelley and Knowles (2016) defined integration in terms of authentic application of STEM knowledge and practices in real-world situations. Their conceptual framework for integrated STEM education represents the STEM practices of science inquiry, technological literacy, engineering design, and mathematical thinking as interconnected pulleys working together in a block and tackle system. However, they acknowledged that it is neither possible nor desirable to teach all the content of the constituent STEM disciplines in an integrated fashion. Hobbs et al. (2018) captured the variability in STEM integration in

Table 1 Forms of STEM integration (Vasquez et al., 2013)

Form of integration	Features
1. Disciplinary	Concepts and skills are learned separately in each discipline
2. Multidisciplinary	Concepts and skills are learned separately in each discipline but within a common theme
3. Interdisciplinary	Closely linked concepts and skills are learned from two or more disciplines with the aim of deepening knowledge and skills
4. Transdisciplinary	Knowledge and skills learned from two or more disciplines are applied to real-word problems and projects, thus helping to shape the learning experience

practice by identifying five models of STEM teaching used in Australian schools that differed in terms of the degree and type of integration of the separate disciplines. Ranging from no integration (represented as S-T-E-M) to full integration of all four disciplines (represented as STEM), this classification also illustrated intermediate forms that bear some resemblance to the multidisciplinary and interdisciplinary connections described by Vasquez et al. (2013) (see Fig. 1).

Despite the variety of models and frameworks for integrated STEM education that have been proposed, it is often the case that one discipline has a dominant role. Other concerns have been expressed about the need to maintain the integrity of the constituent STEM disciplines, especially mathematics (English, 2016).

2.3 Implementation

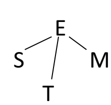
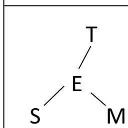
Honey et al. (2014) identify teacher expertise as possibly the most important factor in effective implementation of integrated STEM education. Little is known about how to create initial teacher education programs that prepare teachers who have either content knowledge in multiple STEM disciplines or the capacities and dispositions to work collaboratively with colleagues across individual STEM disciplines. Nevertheless, some promising initiatives have been reported in the literature on interdisciplinary collaborations between university STEM and education academics to build STEM teacher education programs (e.g., Evans et al., 2019; Goos & Bennison, 2018). Other research has reported on literature reviews (Margot & Kettler, 2019) or needs assessments (Shernoff et al., 2017) that identify challenges faced by teachers and the supports they need for implementing integrated STEM education. These reviews found that teachers experienced challenges in shifting towards more student-centred pedagogical approaches, in accommodating an integrated STEM curriculum within existing discipline-specific curricula, in negotiating structural barriers such as class scheduling, and in assessing student learning in an integrated STEM curriculum. Suggested supports identified by these reviews include more time for collaboration between teachers of different disciplines, well-organised professional learning opportunities, and a quality STEM curriculum together with resources that are explicitly linked to the goals of the constituent STEM disciplines.

2.4 Outcomes

Outcomes of integrated STEM education are linked to goals and may include outcomes for both students and teachers. Gao et al. (2020) report that there has been little research on assessing students' interdisciplinary understanding in STEM education, and likewise it is rare to find studies that show how STEM education helps students to develop understanding of mathematical concepts. A few studies have explored how the integration of computer science technologies enhance students' thinking about abstract mathematics concepts (e.g., Namukasa et al., 2022; Pei et al., 2018; Sinclair & Patterson, 2018). More progress seems to have been made in designing integrated STEM professional development programs for teachers and investigating changes in their knowledge and practice (e.g., Anderson et al., 2017; Hobbs et al., 2019).

Given the rapidly growing interest in STEM at all levels of education, and in both formal and out-of-school settings,

Fig. 1 Five models of STEM teaching in Australian schools (adapted from Hobbs et al., 2018)

Representation	Description
S-T-E-M	Each discipline is taught separately
SteM	All four disciplines are taught but more emphasis is on one or two (S and M in this example).
	One discipline is integrated into the other three, which are taught separately.
STEM	All four disciplines are integrated into a subject taught by one teacher.
	A STEM curriculum is divided into separate subjects so that each teacher teaches a subject-specific component of a combined unit.

there is an urgent need for research into interdisciplinary STEM education that builds deep connections between mathematics and the other STEM disciplines. We now turn to our survey of empirical and conceptual research literature on the role of mathematics in integrated STEM education, with the aim of highlighting both recent advances and persistent gaps to situate the special issue papers within this research landscape.

3 Survey methodology

The time period for our survey aims to capture the current state of research on the role of mathematics in integrated STEM education. We chose 2017 as our starting point to acknowledge the shift towards the latter research focus that was recommended by English (2016) in her highly cited commentary paper published in the *International Journal of STEM Education*.

STEM education research has a short history and there are few general literature reviews that can provide an overview of the field before the time period covered by our survey. The most comprehensive is the review conducted by Li et al. (2020), which analysed 798 articles published in 36 STEM education, discipline-based education, and general education journals from 2000 to 2018. Their review documented the rapid rise in publications, from fewer than 10 per year before 2010 to more than 100 per year since 2016 and the consistently high proportion (around 75%) of authors from the USA. Although authors from all continents except Africa contributed articles during this time period, Australia and Canada were the only other countries to contribute more than 2% of the total published articles. Li and colleagues also analysed the research topics addressed by these articles, using categories developed in an earlier review of articles published in the *International Journal of STEM Education* (Li et al., 2019). Almost half of publications (375, 47%) were in the category of goals, policy, curriculum, evaluation, and assessment, with an additional one-quarter of publications (200, 25.1%) addressing teaching and learning in K-12 education. Smaller numbers of publications dealt with post-secondary STEM teaching and learning, culture and social and gender issues in STEM education, and epistemological perspectives on STEM and STEM education. However, these categories are too broad to shed any light on the prior status of research into the role of mathematics in interdisciplinary STEM education—the theme of our own literature survey.

A focused literature review more closely aligned with our own survey theme was conducted by Baldinger et al. (2020). These researchers analysed mathematically rich implementation of integrated STEM education at the secondary school level in research published between 2013 and 2018. From an initial pool of 4072 articles, only 32 were identified that focused specifically on teaching and learning secondary mathematics integrated with other STEM disciplines. The selected articles addressed teaching of a wide range of mathematical content as well as valued mathematics practices such as communication, representation, generalisation, conceptual understanding, and proof/justification. Mathematical communication and representation were identified as significant themes across the literature analysed in this study, as was the need to engage students in authentic, integrative, real-world tasks. Nevertheless, the very small number of articles that gave attention to mathematics within integrated STEM reinforced a view that mathematics was used mainly as a tool for supporting learning in the other disciplines.

Also relevant to our special issue theme is a recent systematic review of the role of mathematics in STEM education conducted by Just and Siller (2022). Their search considered STEM tasks or STEM teaching at secondary school level and targeted peer-reviewed publications from 2018 to 2022. Following screening and removal of records that did not meet their inclusion criteria, only 14 studies remained from the initial pool of 2766 identified through database searching. Their analysis of the role of mathematics in secondary STEM classrooms, based on this rigorously selected sample of manuscripts, revealed that only one or two of the constituent STEM disciplines were emphasised in STEM implementation, with mathematics tending to be used as a tool for solving scientific problems. Thus, mathematical concepts and processes remained largely invisible, even in tasks that involved mathematical modelling of real-world phenomena.

To provide a more expansive overview of recent trends in research on the role of mathematics in integrated STEM education—including, but not limited to, secondary school education as was the case for the reviews of Baldinger et al. (2020) and Just and Siller (2022)—we decided to conduct a narrative literature review rather than a systematic review. Systematic reviews are defined by their use of comprehensive search strategies and explicit inclusion/exclusion criteria to identify all relevant research literature on a topic (Sutton et al, 2019). In contrast, narrative reviews use purposive sampling of literature to present a critical analysis of significant literature on a topic. Still, a narrative review is expected to follow thorough and careful methodological steps, despite the differences it presents from a systematic review (Furley & Goldschmied, 2021). In conducting a narrative review our goal is to offer an interpretative understanding from a selected sample of studies, through critical reflection on specific elements of that bulk of research. Thus we do not claim to have considered all possible sources: instead, we aim to present a critical appraisal of what we judged to be significant literature on interdisciplinary or integrated STEM education, at all educational levels, that connects mathematics to at least one of the other STEM disciplines. Altogether, we seek an elucidatory view of the topic, its latest developments, and existing critical points, using a selected sample of studies.

Using combinations of search terms such as (mathematics or math*) and (STEM education or STEAM education), we searched the Web of Science and ProQuest databases for journal articles, conference papers, and edited books published between 2017 and 2022. We supplemented the database search with a hand search of STEM education journals (*Journal for STEM Education Research*, *International Journal of STEM Education*, *Frontiers of Education: STEM Education*, *Journal of STEM Education: Innovation and Research*) and conference proceedings (annual meeting of the International Group for the Psychology of Mathematics Education [PME]; biennial Congress of the European Society for Research in Mathematics Education [CERME]; biennial international STEM in Education conference). Responsibility for searching all of these sources was divided between the three authors. This initial search yielded 72 publications.

Using an Excel spreadsheet, we recorded the studies' citation details, abstracts, research goals or questions, the theoretical frameworks or concepts used by the researchers, the number and type of participants, methodological approaches used, disciplines integrated with mathematics in the STEM context, and findings. The first author began classifying the publications according to their goals and the issues they addressed, using the four features of the framework devised by Honey et al. (2014). However, it became apparent that the framework needed to be modified to better capture the issues that were especially relevant to our topic—which specifically examines the role of *mathematics* in integrated STEM education. Through discussion, the three authors agreed on the following thematic clusters:

(1) interdisciplinary curriculum models and approaches;
(2) student outcomes and experiences;
(3) teacher preparation and professional development;
(4) classroom implementation and task design;
(5) policy, structures, and leadership.

These clusters are related to those of Honey et al. (2014), but they distinguish between student and teacher learning in terms of both outcomes and experiences, as well as drawing attention to the policy environment and institutional structures and leadership needed for effective implementation.

The first author then completed the reclassification and screening of publications, removing those that treated the STEM disciplines as separate entities, rather than integrated, or did not refer to the role of mathematics in STEM education. This process left 53 publications that were included in our survey analysis.

Figure 2 shows our thematic framework and identifies the number of publications in each cluster. The collection of 53 literature sources comprises 10 book chapters, 27 journal articles, and 16 conference papers. (Note that the total number of publications shown in Fig. 2 exceeds 53 because a publication could be assigned to more than one thematic cluster.).

The geographical distribution of corresponding authors in our 2017–2022 literature sample is shown in Fig. 3. Despite the obvious dominance of US authors in our

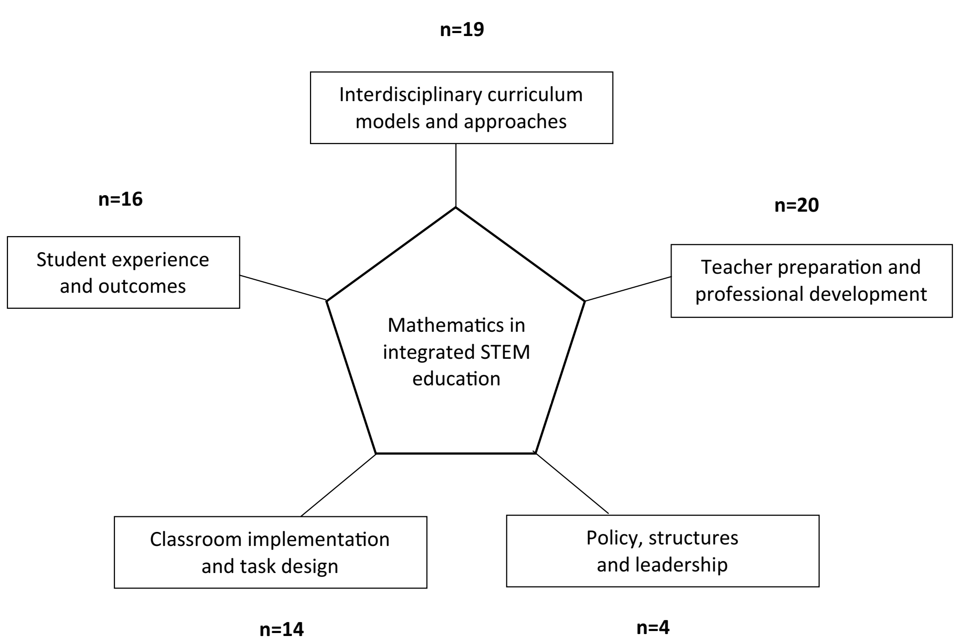


Fig. 2 Thematic framework for classifying publications with numbers of publications in each cluster

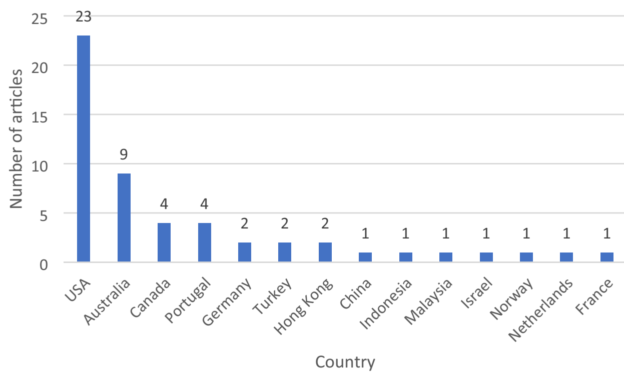


Fig. 3 Publication distribution by country of corresponding author

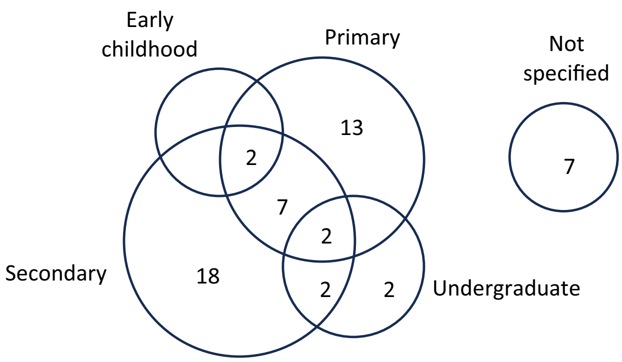


Fig. 4 Publication distribution by educational level

literature sample, more than half of the corresponding authors came from other countries—a higher proportion of non-US authors than reported in previous literature surveys of STEM education research (e.g., Li, 2022; Li et al., 2020).

A wider range of educational levels was represented in our literature sample than in the secondary-focused reviews of Baldinger et al. (2020) and Just and Siller (2022). Figure 4 shows the distribution of sources by educational level, from early childhood to undergraduate, showing also that many publications addressed more than one level.

4 Survey findings

A full classification of each literature source by thematic cluster and educational level can be found in the Appendix. In the following sections we discuss the main research trends and gaps identified by the survey by selecting and discussing illustrative studies in each thematic cluster.

4.1 Interdisciplinary curriculum models and approaches

Researchers often addressed the question of "what" types of connections should be made between mathematics and the other STEM disciplines, and less often "how" this process might be achieved. It was rarer still to find studies that asked "why" mathematics should be integrated into STEM education – or not. One example is Raymond's (2018) historical analysis of the positioning of mathematics education in the United States, in which she observed a shift away from valuing of mathematics for informed and democratic citizenship towards a "push for mathematics to maintain technological and economic advantages" (p. 1)—commonly recognised by referring to mathematics as the "M in STEM". She argued that the turn towards STEM has spread a myth about the purpose of mathematics education, now widely believed by the public and policy makers, that has led to a narrowing of the mathematics curriculum and distortion of wider social purposes of mathematics.

Relevant to Raymond's argument is a study from the Netherlands that posed "Why" questions about the value of mathematics in integrated STEM education. In this study, den Braber et al. (2019) asked upper secondary school students and teachers participating in an interdisciplinary course on "Nature, life, and technology" to explain the importance of mathematics for the science disciplines. Although these researchers proposed that mathematics offers a distinctive way of understanding the world and solving real-life scientific problems, their analysis of data from teacher ($n = 84$) and student ($n = 416$) surveys showed that around half the student statements referred to mathematics being useful mainly as a tool for calculation. In addition, most teachers admitted that they rarely spoke to their students about the role of mathematics in science. Den Braber and colleagues suggested that teachers working in integrated STEM programs might need to temporarily set aside their own disciplinary beliefs and attitudes so they can recognise, and explain to students, the value that each discipline—especially mathematics—brings to interdisciplinary problem solving.

Echoing some of the concerns expressed by Raymond (2018) and den Braber et al. (2019), Tytler (2020) acknowledged that, in many countries, advocacy for STEM has been driven by national goals for economic well-being and global competitiveness without adequate attention to the nature of interdisciplinary "STEM skills" and how these ways of thinking across disciplines differ from discipline-based knowledge. He identified two problems for mathematics in integrated STEM. First, mathematics is often seen to play a service role, supporting learning of another of the STEM disciplines without requiring new mathematical learning. Second, the highly structured and sequenced nature of the mathematics curriculum makes it difficult to incorporate interdisciplinary STEM tasks. Tytler proposed that STEM integration could be conceptualised at the level of higher order competencies, drawn from the OECD Learning Framework 2030 (OECD, 2018) and identifying the knowledge, skills, attitudes and values associated with the STEM disciplines. Table 2 presents a segment of Tytler's framework, focusing only on forms of knowledge. This framework allows us to ask questions about "what" knowledge connections could be made between mathematics and the other STEM disciplines.

Connections between the *disciplinary knowledge* and *procedural knowledge* of mathematics and other STEM subjects were explored in some studies in our survey. For example, Zhao and Schuchardt (2021) developed a framework for sensemaking of mathematical equations in science contexts, combining four categories in science sensemaking (e.g., recognising the pattern among variables in the mathematical equation; using a mathematical equation to provide a quantifiable measure of a scientific phenomenon) and five in mathematics sensemaking (e.g., using algorithms for problem-solving; attending to the structure of the equation). However, this approach still positions mathematics as a conceptual and procedural tool for representing science concepts, reinforcing Tytler's (2020) concern about the service role of mathematics in integrated STEM education.

Other studies focused on the distinctive forms of *epistemic knowledge* that characterise the separate STEM disciplines. Working in Hong Kong, Leung (2021) developed a curriculum model that integrates these signature forms of epistemic knowledge. He proposed that inquiry processes in the STEM disciplines share a common epistemic frame that can be represented by Polya's problem-solving cycle of understanding the problem, making a plan, carrying out the plan, and then checking the solution and modifying and extending it. According to Leung, these dominant epistemic problem-solving processes of scientific inquiry, computational thinking, engineering design thinking, and mathematical modelling can be mapped onto the Polya framework, as shown in Table 3. While it may be a question for future research as to whether these inquiry processes are indeed the best representation of each discipline's epistemic stances and practices, recent studies of STEM integration with an explicit focus on mathematics have taken a similar approach. For example, Stohlmann (2020) found evidence that mathematical modelling, engineering design challenges, and game-based learning through programming and robotics were effective in engaging high school students in learning mathematics through an integrated STEM approach.

Leung (2020) suggested that his integrated STEM model could find use as a pedagogical boundary object to mediate communication between teachers of the separate STEM disciplines, that is, as a way to translate between the epistemic knowledge and practices of these disciplines. Throughout the literature that we surveyed are similar proposals for "how" the STEM integration process might be achieved

Table 2 Forms of knowledge associated with the STEM disciplines (adapted from Tytler, 2020)

Form of knowledge	Meaning/examples
Disciplinary knowledge	Concepts, principles, properties, definitions, symbol systems (e.g., geometric relations, energy, chemical bonding, ecosystem principles …)
Epistemic knowledge	How knowledge is built in the STEM disciplines; the role of evidence, representational systems, and argument in testing knowledge claims
Interdisciplinary knowledge	Interdisciplinary processes, links between constituent STEM disciplines and between STEM and other forms of knowledge
Procedural knowledge	Approaches to solving problems within the STEM disciplines

Table 3 A model for integrating epistemic knowledge in the STEM disciplines (adapted from Leung, 2018)

Polya problem solving cycle	STEM discipline inquiry processes			
	Science	Technology	Engineering	Mathematics
Understand the problem	Engage; Explore	Decomposition; Pattern recognition; Abstraction	Research the problem	Real world problem
Make a plan	Explain; Elaborate	Algorithmic thinking; Decomposition; Pattern recognition; Abstraction	Imagine; Plan	Make assumptions; Formulate mathematical problem
Carry out the plan	Elaborate; Evaluate	Construct algorithm	Create	Solve the problem
Check solution, modify, extend	Evaluate	Execute algorithm and check the outcome	Test and evaluate; Improve	Interpret solution; Validate model

through interdisciplinary collaboration. In one of these studies, Rabin et al. (2021) analysed conversations between US biology, chemistry, physics and mathematics college instructors as they designed instructional videos on rates of change concepts from calculus in a multi-year curriculum project collaboration. As the project team discussed creating the videos, they came to realise that each discipline has its own conventions, implicit assumptions, representations, notations, canonical examples, and terminology, even when they were talking about what seemed to be the same concept. As a result, they decided to explicitly focus on understanding the viewpoints of their respective disciplines and critically assessing their own disciplinary perspectives. They urged STEM educators to engage in similar cross-disciplinary discussions and apply the resulting insights to their own teaching. From the perspective of mathematics education, however, this study found that scientists thought of mathematics as a tool that allowed them to make sense of data. Once again, then, mathematics was not the main focus of attention in an interdisciplinary STEM project.

Recent research into integrated STEM curriculum models continues to investigate ways of connecting the constituent disciplines—not only in simple terms of which, and how many, disciplines to integrate, but also by exploring these disciplines' distinctive knowledge forms and epistemic practices. Although more sophisticated curriculum models are emerging, the value of mathematics within integrated STEM models is still uncertain.

4.2 Student experiences and outcomes

Reviewing the broader literature, Li and Anderson (2020) found that this is an under-researched area and also that noncognitive outcomes have gained more research attention than students' cognitive outcomes in the STEM disciplines. Enhancing students' learning experiences within the affective domain is regarded as a significant goal of STEM education, arising from concerns about school students' lack of interest in these subject areas and the career aspirations they might support (Tytler, 2020).

Both experimental and case study designs have been used to shed some light on successful outcomes in the affective domain. For example, Lee et al. (2019) used a quasi-experimental design to investigate the effectiveness of STEM Project-Based Learning on 9th grade students' affective mathematics engagement. Statistically significant differences were found between students in PBL versus non-PBL groups, with the former perceiving higher mathematical value and mathematical self-acknowledgement—the latter being a component of engagement that leads students to recognise their feelings about how well (or not) they understand a mathematical concept. Reporting on a case study of a single primary school (one of 13 schools participating in a yearlong professional development program in Australia), Anderson et al. (2019) used a survey to measure student attitudes towards mathematics, science, and technology and their interest in future careers in these fields. Between the beginning and end of the program, students recorded positive and statistically significant attitudinal shifts for science and technology, but not for mathematics. However, these results were somewhat contradicted by those students who were interviewed reporting that they preferred learning both science and mathematics through integrated STEM projects rather than as separate subjects. These findings illustrate some of the challenges of disentangling different elements of students' affective experiences in learning mathematics through interdisciplinary STEM programs.

Within the cognitive domain, Gao et al. (2020) argued that integrated STEM education should help students develop content knowledge for one or more of STEM's constituent disciplines. To investigate whether STEM programs affect students' achievement in mathematics, Siregar et al. (2020) conducted a meta-analysis that initially identified more than 5000 studies published between 1998 and 2017. For inclusion in the meta-analysis, studies had to use an experimental or quasi-experimental research design, report mathematics achievement as an outcome of a STEM education program, and provide data necessary for computing effect sizes. Across the 17 studies satisfying these criteria, involving more than 130,000 school-age and college students, the weighted average effect size of 0.242 indicated a moderate positive influence on students' mathematics achievement. However, only four of these studies had effect sizes classified as either large (at least 0.8) or medium (between 0.5 and 0.8), with the rest having only small effect sizes (between 0.2 and 0.5).

While meta-analyses and individual experimental studies can provide quantitative evidence that students are making mathematics achievement gains, qualitative studies offer deeper insights into how mathematics learning is enhanced by engagement with the other STEM disciplines and affordances within the STEM learning environment. In one example, Steffensen (2020) reported on a teaching experiment in Norway involving a critical STEM approach where the researcher worked with three mathematics and science teachers and their four classes of 10th grade students to investigate the impacts of climate change (e.g., reducing CO_2 emissions through incentives for buying electric vehicles). This was an action research project over one and a half years, in which the teachers planned and delivered 42 lessons that aligned with the goals of the school mathematics and science curricula. The aim was to identify how students' critical mathematical competencies appeared in their argumentation. Critical approaches are highlighted in the Norwegian curriculum as being important for democratic participation in society, which makes it important for teachers and teacher educators to be able to recognise students' critical competencies—in this case, in mathematics. Analysis of classroom audio and video recordings identified key characteristics of the students' argumentation from three perspectives: different types of knowing; how students critically reflected on ethical issues; and how they communicated in dialogues. The findings indicated that "students' critical mathematics competencies appeared through (intertwined) mathematical, technological, and reflective argumentations" (p. 289). Steffensen concluded that an integrated approach to STEM education, including both content knowledge from the constituent disciplines (mathematics and science in this study) and a critical approach to societal and ethical concerns, can support student argumentation on complex global challenges such as climate change.

The affordances of a computational environment for supporting mathematical reasoning have been the subject of investigation in some studies of STEM education. In a teaching experiment with three pairs of undergraduate students, Lockwood et al. (2019) investigated the students' combinatorial thinking as they solved counting problems in a computational environment using simple Python programming. They proposed that this setting offered students four types of affordances: immediate feedback, experimentation, verification, and connections between mathematical representations. They claimed that, while these affordances may not be necessary for students to solve the counting problems, they did offer unique benefits that are not so easily realised when working "by hand".

Similar arguments were advanced by Hernández-Zavaleta et al. (2021), who analysed the cases of four 7th and 8th grade students learning about geometric transformations in two different computational environments—through video game play and a Scratch programming activity. They found that decomposition (solving a problem by solving a set of smaller problems; see Hoyles & Noss, 2020) appeared as an intersectional practice between computational and mathematical thinking. Other kinds of affordances were developed in the learning environments created by Fitzallen et al. (2019) in their study of a STEM activity investigating seed dispersal devices with Year 5 students. Connections between the STEM disciplines were facilitated by an engineering design process, while content integration was focused on mathematics learning outcomes in data and statistics. The students' use of graphical representations enabled them to draw out the connections they had made between the individual STEM disciplines associated with this learning activity.

To advance knowledge about the role of mathematics in interdisciplinary STEM education, it seems crucial to identify the cognitive and noncognitive benefits students are gaining from this approach. This was the aim of the systematic literature review conducted by Gao et al. (2020). These researchers created a two-dimensional framework to identify what is typically included in assessments of student learning in STEM education. The first dimension classified the nature of the connections between the STEM disciplines as being either monodisciplinary (no connections), interdisciplinary (integrating knowledge and skills in two or more disciplines, but with the learning in each discipline still clearly discernible), or transdisciplinary (focusing on solving a complex problem by combining ideas and subject matter of the STEM disciplines into a seamless whole). The second dimension identified the learning objectives of the STEM task or program as developing students' knowledge, skills, practices, or affective response (e.g., positive attitudes, interest, engagement, career aspirations). The resulting 3×4 matrix gives rise to twelve categories that were used to code the set of articles included in the analysis (noting that multiple types of assessment could be reported in any article).

From an initial pool of 10,527 articles published between 2000 and 2019, Gao et al. (2020) deemed that 49 were relevant to the study. The affective domain was found to be the most common assessment target, with 16 articles (32.7%) reporting on monodisciplinary affective perspectives and 18 (36.7%) transdisciplinary affective perspectives. Within the cognitive domain, the most common assessment was of monodisciplinary knowledge (199 articles, 38.8%). There was little evidence of assessment of interdisciplinary learning, even though most of these STEM programs aimed to improve students' interdisciplinary understanding or skills. Clearly, there is more work to do on delineating the core learning objectives of interdisciplinary STEM education and their relationship with mathematical and other disciplinary processes and practices.

4.3 Teacher preparation and professional development

We might think of this part of the research field as defined by two dimensions: the target educational level (e.g., primary or secondary school) and the research focus on the stage of teacher development (pre-service or in-service). Within the first of these dimensions, there are differences in the structure of the school curriculum and the school timetable, with secondary schools tending to be organised around teaching separate subjects with potentially fewer opportunities for STEM integration than in primary schools. With respect to the second dimension, in some countries there are external requirements for accreditation of initial teacher education programs that impact the depth and breadth of STEM subject matter knowledge teachers are offered as well as knowledge of pedagogical approaches to STEM integration. We selected three studies to illustrate these key challenges in preparing teachers to integrate mathematics learning in interdisciplinary STEM education.

The first study, conducted by Arnone and Hanuscin (2019), examined ways in which a small sample of US elementary teachers ($n = 29$) conceptualised STEM education and the integrative approaches they used when teaching STEM content. They speculated that, because US elementary school teachers are prepared as generalists teaching all subjects, they might experience unique opportunities to effectively integrate the STEM disciplines. These researchers conducted an exploratory cross-sectional study using a survey, lesson plan analysis, and interviews to investigate perceived levels of preparedness to implement integrated STEM education, ways in which the teachers approached integrated STEM education in their lesson plans, and how they conceptualised STEM education. Contrary to their expectations, they found that the participating teachers were generally unprepared to implement integrated STEM education, they struggled to design appropriate STEM lessons, and showed little consensus regarding what is or should be taught in STEM education. In addition, teachers believed that mathematics was the most difficult subject to integrate with other STEM disciplines and they preferred to teach mathematics concepts separately. Although teachers identified problem solving as their primary goal for integrated STEM education, their teaching of mathematics relied on surface-level strategies such as memorisation of multiplication facts. This study highlighted not only the need to build elementary teachers' knowledge of discipline content and integrative pedagogies, but also the importance of attending to teacher beliefs about the role of mathematics in STEM education.

In secondary school contexts, STEM integration usually requires collaboration between teachers who are specialists in the constituent disciplines. This was the case in our second example, reported by Shriki and Lavy (2017), in which participants were secondary school mathematics and science teachers ($n = 40$) participating in a Master of Education program at a college of education in Israel. The aim of the study was to investigate the features, effects, and feasibility of collaboration between the mathematics and science teachers to plan interdisciplinary lesson units that integrated mathematics with science. Analysis of questionnaires at the start and end of the course, teacher reflective journals and interviews, observations of the teachers' collaborative planning work, and the content of their integrated lesson units revealed advantages and disadvantages of this approach. Although the teachers were positive about collaboration and said they had gained new knowledge and experience of interdisciplinary teaching, the mathematics teachers felt the collaboration was imbalanced with science learning goals dictating the unit content and structure. These findings align with the concerns expressed by Tytler (2020), that mathematics in interdisciplinary STEM occupies a subservient role as a tool for representing science concepts and solving science problems.

Both these studies are representative of a common theme in the "M in STEM" literature suggesting that teachers find it challenging to meaningfully incorporate mathematics into integrated STEM education. In our third illustrative study, Preciado-Babb and Friesen (2021) investigated reasons for these difficulties by identifying (1) the types of mathematics involved in different educational settings related to STEM education and (2) the specialised mathematical knowledge required for teaching in this context. They analysed tasks, student work samples, and lesson plans produced or collected by pre-service and experienced teachers who participated in university courses ($n = 29$) and an eight-session professional learning series ($n = 50$) in Alberta, Canada. These courses addressed a range of topics, including enriching understanding of number concepts; geometry in nature, art, and computer graphics; mathematics for sustainability; and transdisciplinary STEM education.

The analysis conducted by Preciado-Babb and Friesen (2021) identified five categories of mathematics underpinning transdisciplinary STEM tasks: (1) embodied mathematics requiring student movement to understand concepts of number as distance and angle as rotation; (2) spatial reasoning involving mental rotation and understanding a 2D representation of a 3D object; (3) geometric transformations using vectors, polar and cylindrical coordinates in robotics and animations; (4) computational thinking, in particular the use of iteration and recursion in creating algorithms; and (5) networking and flow diagrams as mathematical tools for modelling sustainability issues. Yet none of these STEM-relevant mathematical topics were addressed explicitly in mathematics courses mandated for teacher preparation, nor were they represented in common resources designed for teachers. Although this study was conducted in Canada, the findings may have broader implications in suggesting that teacher education programs "lack specific mathematical content required to address STEM tasks" (p. 335) that focus on transdisciplinary inquiry and innovation.

4.4 Classroom implementation and task design

Nearly half of the studies in this cluster provided rich descriptions of classroom implementation or tasks, but lacked a theoretical framework that informed the pedagogical design. There were some exceptions in the form of studies that combined description of tasks and teaching approaches with investigation of the effects on student experience and learning. For example, in Australia, Watson et al. (2020) reported on their longitudinal research program that aimed to build statistical understanding in a series of integrated STEM activities with primary school children (aged 8–12 years). They argued that statistical practice assists in making decisions based on data collected across the fields of science, technology, and engineering, and thus offers a mechanism for integrating the disciplines from the beginning of students' experiences at school. In particular, they claimed that "dealing with variation and uncertainty could be a goal of all meaningful STEM investigations" (p. 92). They described a progression of statistical activities that students completed over three years that were accessed via the science curriculum with links to the design and digital technologies curriculum. These activities included exploring variation in the mass of liquorice sticks manufactured via two different methods, creating online surveys to compare lifestyle and climate with a primary school class in another part of the country, and designing catapults to maximise the distance they could launch ping pong balls.

Although Watson et al. (2020) had not fully analysed the longitudinal impact of these activities, they found promising improvements in students' statistical literacy scores between the start of the first year and the end of the third year of the project. Longitudinal studies are also valuable for collecting and analysing qualitative data, such as classroom video-recordings and student work samples, that can reveal changes in students' statistical practice over time, as demonstrated by the study of Watson et al. The next challenge for studies such as these is to link changes in student outcomes to specific characteristics of teachers' classroom implementation of STEM activities.

Task design is a well-developed field of research within mathematics education (e.g., see Watson & Ohtani, 2015). However, less is known about how to design "good" interdisciplinary STEM tasks than how to create tasks within single disciplines. Reinholz et al. (2018) investigated what makes a good disciplinary or interdisciplinary problem by analysing problems in both categories that were nominated as exemplars by participants attending two STEM education conferences in the US. Participants were first placed in discipline-based groups to brainstorm features of good problems in their respective disciplines: this activity yielded disciplinary tasks characterised by real-world connections, reinforcement of conceptual understanding, multiple solution paths, a low floor and high ceiling, and capacity to build the dispositions of professionals in the discipline. However, when the conference participants were re-organised into cross-disciplinary groups they found it much more difficult to generate good interdisciplinary problems. Nevertheless, this process provided some insights into two salient features of good interdisciplinary problems: (1) they have a rich contextual intersection that is interesting and relevant to multiple disciplines; and (2) they generate knowledge in multiple disciplines, for example, through the use of crosscutting concepts. These insights confirm that it is not enough to find an interesting context for STEM tasks that require students to use some mathematics. In addition, mathematics educators need to find conceptual intersections with other STEM disciplines that support mathematical knowledge-building.

4.5 Policy, structures, and leadership

Only four of the literature sources that we selected for this survey addressed issues concerning policy, structures, and leadership in STEM education. Despite this thematic cluster being smaller than the other four clusters that organise our survey, we believe it is essential to draw attention to under-researched issues that have a significant impact on the ways in which schools implement integrated STEM programs and the role of mathematics in such programs.

From a policy perspective, the rationale for promoting STEM education has been aligned with national economic well-being and global competitiveness ever since the acronym "STEM" was first introduced in 2001 by Judith A. Ramaley, a former director of the US National Science Foundation's Education and Human Resources Division (Breiner et al., 2012). Tytler (2020) suggests that arguments for increasing focus on STEM education are also linked to performance on international comparative assessment regimes such as PISA and TIMSS, together with concerns about a decline in young people's participation in STEM subjects in secondary school—often portrayed as "leakage" from the "STEM pipeline". This kind of policy narrative might influence STEM education practice and research towards boosting student engagement, participation, and aspiration—that is, by emphasising elements of the affective domain that have been a major focus of research on student experiences and outcomes of integrated STEM education.

But, in addition to influencing research directions, policy that aims to "fill the STEM pipeline" needs to be research informed so that the problems it seeks to solve, and their possible causes, are accurately represented and productively investigated. For example, research conducted by Lane et al. (2022) showed that both student attitudes and perceptions of their ability in relation to subject difficulty can influence participation in secondary school STEM subjects. In particular, mathematics—the discipline acknowledged as underpinning all STEM learning—was more highly valued by students than the other STEM disciplines, even though students had lower interest and confidence in mathematics, and experienced mathematics as being more difficult, than subjects in science, technology, and engineering. Although this study did not investigate the role of mathematics in integrated STEM education, it does suggest that STEM education policy formulation would benefit from a more nuanced understanding of how school students experience STEM learning.

Structural conditions affecting integrated STEM approaches in schools were highlighted by Anderson et al. (2019), who reported on a yearlong professional learning program involving 45 teachers in 13 Australian primary schools. This paper presented a case study of one school, with the aim of documenting changes in students' attitudes and aspirations towards STEM, changes in the school's development and delivery of the STEM curriculum over the course of the year, and characteristics of the program that appeared to have influenced students' attitudes and aspirations. But the researchers also observed factors that might influence the sustainability and scalability of integrated STEM programs in schools, such as school leadership, commitment to teacher capacity building, and a positive school culture.

These structural factors were further investigated by Anderson and Tully (2021) in a project delivered to 306 teachers in 57 Australian secondary schools between 2014 and 2017. Understanding the constraints experienced by secondary schools in developing integrated STEM approaches is especially important in the context of mandated curriculum and high stakes assessment at this educational level. Through analysis of semi-structured interviews with 27 teachers and 5 principals from 20 of the project schools, the researchers identified key challenges involving resources, use of space, timetabling of classes, and allocation of teachers to subjects and classes. By far the most important driver for success and sustainability of the integrated STEM programs in these schools was support from the schools' executive leadership. This entailed providing tangible support for STEM middle-level leaders and teachers in the form of regular timetabled meetings that enabled collaboration between teachers in the different STEM disciplines and appropriate resourcing of the integrated program. School leaders also displayed willingness to find flexible ways to work within rigid school structures and timetabling practices.

School principals' STEM leadership was the focus of another Australian study conducted from 2017 to 2020. The Principals as STEM Leaders (PASL) program delivered professional development to 150 primary and secondary school principals and generated case studies of schools to document approaches to STEM education and STEM leadership. Reporting on a cross-case analysis of two primary and two secondary schools participating in this project, Falloon et al. (2021) claimed that interdisciplinary STEM represents a "disruptive innovation to traditional curriculum and structures" (p. 120). Thus, the role of the principal was critical in communicating a consistent, evidence-based purpose and vision for STEM and in creating school cultures and climates that supported risk taking and innovation. As well as building strong whole-of-school understanding of and commitment to interdisciplinary STEM education, principals also supported teachers' efforts to educate parents about the value of interdisciplinary learning. Studies such as this might contribute new insights into how principals as STEM leaders could shift teacher perceptions of the role of mathematics in integrated STEM education.

5 In this special issue

The articles in the special issue document challenges and opportunities for mathematics and interdisciplinary STEM education, thus informing an agenda for future research in this field. We briefly introduce the set of 12 articles, linking them to the 5 thematic clusters that organised our literature survey. Table 4 summarises this classification, together with the diversity of educational levels addressed by each article and the countries of the authors. Although many of the articles align with more than one thematic cluster, our introduction below highlights what we consider to be their primary themes.

5.1 Mathematical ways of knowing and being in interdisciplinary STEM education

Two papers propose new frameworks or philosophies for thinking about interdisciplinarity and the role of mathematics in STEM education. English's *Ways of Thinking in STEM-Based Problem-Solving* framework comprises critical thinking, incorporating critical mathematical modelling and philosophical inquiry, systems thinking, and design-based thinking. She argues that the ultimate purpose of developing STEM-based problem-solving is to support the kind of adaptive and innovative thinking that students will need to navigate disruptive and uncertain futures.

Nicol et al. draw on Indigenous and ecological perspectives to explore a radical reconceptualisation of *STEM as place*. For these researchers, "integrated STEM education" refers to the interdependence between humans and the natural world. They offer examples of classroom STEM activities that encourage students to appreciate the mathematical complexity and beauty within ecological phenomena.

5.2 Evidencing student learning in interdisciplinary STEM education

Two papers investigate ways of assessing students' learning experiences and outcomes in interdisciplinary STEM courses or learning sequences. Van der Wal et al. report on a study in the Netherlands that designed a new university course to develop interdisciplinary Techno-mathematical

Table 4 Classification of special issue articles

Source	Thematic cluster(s)[a]					Educational level[b]	Country of author(s)
	1	2	3	4	5		
Lyn English	*					N	Australia
Cynthia Nicol, Jennifer Thom, Edward Doolittle, Florence Glanfield, & Elmer Ghostkeeper	*					N	Canada
Oi-Lam Ng, Allen Leung, & Huiyan Ye	*	*		*		S	Hong Kong
Nathalie van der Wal, Arthur Bakker, & Paul Drijvers	*	*				U	Netherlands
Mónica Baptista, Hélia Jacinto, & Iva Martins		*				S	Portugal
Sabine Wiegand & Rita Borromeo Ferri			*			S	Germany
Zaira Ortiz-Laso, José-Manuel Diego-Mantecón, Zsolt Lavicza, & Teresa F. Blanco			*	*		S	Spain, Austria
Russell Tytler, Judy Anderson, & Gaye Williams	*	*		*		S	Australia
Immaculate Namukasa, Zeynep Gecu-Parmaksiz, Janette Hughes, & Ricardo Scucuglia		*	*	*		P, S	Canada and Brazil
Hans-Stefan Siller, Ortal Nitzan-Tamar, & Zehavit Kohen			*	*		S	Germany and Israel
Judah Makonye & Nageshwari Pam Moodley				*	*	S	South Africa
Chaereen Han, Yujin Lee, Kyungwon Lee, & Oh Nam Kwon					*	P, S	South Korea

[a]1 Interdisciplinary curriculum models and approaches; 2 Student experience and outcomes; 3 Teacher preparation and professional development; 4 Classroom implementation and task design; 5 Policy, structures, and leadership

[b]P primary school; S secondary school; U undergraduate; N not specified

Literacies (TmL) in first-year STEM students. The researchers designed an instrument to evaluate student learning in the course, since no examples of assessment of TmL could be found in the literature. Their findings have implications for assessing interdisciplinary competencies in STEM courses.

In the second paper, Baptista et al. analysed explanations produced by 9th grade students in Portugal who participated in an integrated STEM learning sequence. Encouraging students to provide explanations both enhances their learning and reveals their understanding. Analysis of students' written responses to an integrated STEM problem informed development of a framework that distinguished between descriptive, relational, and integrated-STEM explanations.

5.3 Preparing teachers for interdisciplinary STEM education

Two papers report on teacher education studies that integrated mathematics into STEM education. Wiegand and Borromeo Ferri described how they supported pre-service mathematics teachers in Germany to develop an integrative approach to STE(A)M education and education for sustainable development through mathematical modelling. Ortiz-Laso et al. worked with two experienced Spanish secondary school mathematics teachers over three years as each teacher iteratively implemented and refined a STE(A)M project with their students. The long-term nature of this professional development initiative, together with continuous support from expert advisors, were crucial in developing the teachers' pedagogical competencies.

5.4 Classroom implementation issues

Five papers addressed issues around classroom implementation of interdisciplinary STEM education. Tytler et al. presented case studies of two Australian secondary schools that created interdisciplinary teams of teachers to implement STEM curricular experiences. Evaluation of the cases using Roehrig's et al. (2021) conceptual framework for integrated STEM led these researchers to propose refinements to the framework to better highlight approaches that support students' mathematical engagement. Ng et al. proposed that computational thinking is a boundary object connecting mathematics and computer science, and used this interdisciplinary framework to analyse middle school students' mathematical problem-solving within a programming environment in three Hong Kong schools. Similarly, Namukasa et al. investigated the role of computational thinking skills in learning mathematics within maker space environments in Canada and Brazil. Siller et al. explored the characteristics of scaffolding practices used by Israeli teachers when introducing students to mathematical modelling tasks set in real-world STEM industry contexts. In South Africa, Makonye and Moodley interviewed teachers at specialist STEM secondary schools to explore their perceptions of the role of mathematics in STEM.

5.5 STE(A)M education policy

Han et al. conducted an interview study to examine the perspectives of 13 stakeholders involved in implementing STEAM education policy in South Korea. They included policymakers, national institution directors, regional supervisors, administrators, principals, STEAM lead teachers, and mathematics teachers who had created the country's STEAM-based curriculum. The analysis revealed conflicting perspectives among stakeholders and structural impediments experienced by mathematics teachers.

6 Implications and future research directions

This special issue provides a space for debate about the role of mathematics in interdisciplinary STEM education. This approach inevitably raises questions about teaching practices and current school and academic cultures; additionally, from a curricular point of view, integrated STEM education is quite unsettling. Nevertheless, the search for connections or hinges between the various STEM areas, whether in content, expert modes of thinking, or epistemic nature, is gaining momentum. It is still unclear what learning (and teaching) means in a STEM context; it is still unclear what it might mean to learn mathematics in an integrated approach to multi- or inter-disciplinary contents, processes, or problems. The idealisation of a "good" integrated STEM task is far from settled. However, we can see that interdisciplinarity seems to be at the core. And this shows that dialogue between different forms of knowledge (and, therefore, specialist teachers and experts) is urgently needed. In fact, the results that emerge as most promising blur some of the boundaries between disciplines. Moreover, it is apparent that longitudinal studies or longer duration experiences lead to better results. New conclusions and conceptualisations about student learning gains, in mathematics and beyond, apparently require long-term research work alongside long-term practical experiences.

As was the case before 2017, the starting point for our literature survey, research into teaching and learning (particularly mathematics) in interdisciplinary STEM contexts is still in its infancy. It shows no broad and unanimous vision of what is required of curricula, teachers, students, and educational systems. STEM education is currently discussed and investigated by several research communities (science education, mathematics education, engineering education, university education, computers education, etc.). Our survey focused on mathematics education, revealing a growing awareness that it is impossible to think about the role of mathematics without thinking about the roles of the other areas. Thus, we argue that teachers and students need to keep mathematics in the foreground to demonstrate its central role in helping us understand and solve complex scientific and social problems in an inherently interdisciplinary world.

We conclude by suggesting questions for future research to strengthen our understanding of this important issue.

(1) Methods and rationales for connecting the constituent STEM disciplines need further investigation. A question that could guide future studies is:
- What interdisciplinary curriculum models and approaches best represent the distinctive epistemic stances and practices of mathematics, as well as differences and connections between the STEM disciplines?

(2) Research into student experiences and outcomes of learning in integrated STEM programs has focused mainly on the affective domain. We need studies that ask more penetrating questions about what "success" looks like in these programs. Is success evidenced by improvements in student aspiration and participation in advanced mathematics and other STEM subjects in upper secondary school and university? Or should research look for changes in students' interdisciplinary and disciplinary learning? We suggest that more studies might address the following questions:

- How does interdisciplinary STEM education improve students' learning of mathematics?
- What contribution does mathematics make to students' interdisciplinary STEM learning?

(3) Many questions remain about how to help teachers think differently about the potential role of mathematics in interdisciplinary STEM education, moving beyond current practices that position mathematics as a tool for solving problems in other disciplines. Research into teacher education and development might pursue questions such as the following:

- How can pre-service and in-service teacher education programs support integrated STEM teaching practices that preserve the disciplinary integrity of mathematics?
- What mathematical knowledge do teachers need for interdisciplinary STEM teaching?

(4) Classroom implementation studies frequently describe engaging STEM tasks, but more research is needed to understand what makes a STEM task mathematically rich. We also know very little about how to assess student performance on these tasks. Questions that arise within this domain are:

- What approaches to classroom implementation will allow mathematical affordances to be fully explored and realised?
- What approaches to task design will yield "good" interdisciplinary problems?
- How should student performance on such problems be assessed?

(5) We found very few studies in the area of STEM policy and leadership and how these influence implementation of interdisciplinary STEM programs in schools. While such issues might seem far away from classrooms and teachers, research that informs policy development and school leadership practice is vital for supporting the scaling up and sustainability of innovative STEM programs. More studies are therefore needed to answer the following questions:

- How can STEM education research productively shape STEM education policy?
- What role is mathematics assumed to play in this policy landscape?
- What school leadership practices support sustainable approaches to integrated STEM education that promote student learning and appreciation of mathematics?

To conclude, we now have more evidence that learning occurs in different STEM contexts, but not yet a precise idea of "interdisciplinary STEM learning". We hope that the papers published in this special issue will help move the field of interdisciplinary STEM education forward in some of the ways we outlined above.

Appendix: Classification of literature sources by thematic cluster and educational level

Source	Thematic cluster(s)[a]					Educational level[b]
	1	2	3	4	5	
Den Braber et al. (2019)	*					S
Leung (2020)	*					S
Leung (2021)	*					E, P, S
Rabin et al. (2021)	*					U
Maass et al. (2019)	*					N
Raymond (2018)	*					N
Thom et al. (2021)	*					N
Zhao and Schuchardt (2021)	*					N
Fitzallen et al. (2019)	*	*				P
Ubuz et al. (2019)	*	*	*			P, S, U
Galanti & Holincheck (2021)	*		*			P
Preciado-Babb and Friesen (2021)	*		*			P, S
Mayes et al. (2017)	*		*			S
Shriki and Lavy (2017)	*		*			S
Margot and Kettler (2019)	*			*		E, P, S
Baldinger et al. (2020)	*			*		S
Stohlmann (2020)	*			*		S
Reinholz et al. (2018)	*			*		S, U
Tytler (2020)	*				*	N
Kim et al. (2021)		*				P
Li and Anderson (2020)		*				P, S
Siregar et al. (2020)		*				P, S, U
Anderson and Katrak (2017)		*				S
Lee et al. (2019)		*				S
Steffensen (2020)		*				S
Chorney and Lin (2021)		*				S
Gao et al. (2020)		*				S, U
Lockwood et al. (2019)		*				U
Coxon et al. (2018)		*		*		P
Watson et al. (2020)		*		*		P
Hernández-Zavaleta et al. (2021)		*		*		S
Touitou et al. (2020)		*		*		S
Anderson et al. (2019)		*	*	*	*	P
Arnone and Hanuscin (2019)			*			P
Aydeniz and Bilican (2018)			*			P
Conner et al. (2020)			*			P
Costa and Domingos (2019)			*			P
Costa et al. (2020)			*			P
Kelana et al. (2020)			*			P
Anderson and Tully (2020)			*			P, S
Beswick and Fraser (2019)			*			P, S
Shernoff et al. (2017)			*			P, S
Brown and Bogiages (2018)			*			S
Henriques et al. (2020)			*			S

Source	Thematic cluster(s)[a]					Educational level[b]
	1	2	3	4	5	
Oliveira et al. (2019)			*			S
Evans et al. (2019)			*			N
Anderson and Tully (2021)			*		*	S
Dickes et al. (2020)				*		P
Abboud et al. (2019)				*		P, S
Bock et al. (2019)				*		S
Walker and Sherman (2017)				*		S
Liu and Zhang (2021)				*		N
Falloon et al. (2021)					*	P, S

[a] 1 Interdisciplinary curriculum models and approaches; 2 Student experience and outcomes; 3 Teacher preparation and professional development; 4 Classroom implementation and task design; 5 Policy, structures, and leadership

[b] E early childhood, P primary school; S secondary school; U undergraduate; N not specified

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