Final Report for the NCCA

STEM Education: Curriculum & Literature Overview & Primary Science Education: Systematic Literature Review

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CASTeL

STEM Education: Curriculum & Literature Overview

&

Primary Science Education: Systematic Literature Review

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Acknowledgements

The study was commissioned by the National Council for Curriculum and Assessment (NCCA).

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How to cite this report:
Murphy, C., Venkat, H., Leahy, M., Broderick, N., Kelly, O., Butler, D., Harbison, L., Lawlor, C., & Naughton, Y. (2023). *STEM Education: Curriculum & literature overview & Primary science education: Systematic literature review.* Dublin: National Council for Curriculum and Assessment.

Table of Contents

Acronyms and abbreviations

ACARA	Australian Curriculum, Assessment and Reporting Authority
CfE	Curriculum for Excellence
DES	Department of Education and Science/Education and Skills
DSG	Dialogic Scientific Gatherings
5E	Engage, explore, explain, elaborate and evaluate.
Estyn	Office of His Majesty's Inspectorate for Education and Training in Wales
IBSE	Inquiry-Based Science Education
iSTEM	Integrated STEM
NOS	Nature of Science
NOSK	Nature of Science Knowledge
OECD	Organisation for Economic Co-operation and Development
Ofsted	Office for Standards in Education, Children's Services and Skills
OSE	Outdoor Science Education
POE	Predict-Observe-Explain
SSI	Socioscientific Issues
STEM	Science, Technology, Engineering and Mathematics
STS	Science-Technology-Society
SLR	Systematic Literature Review
TIMSS	Trends in International Mathematics and Science Study

Executive Summary

In this Executive Summary, we summarise the key findings from our curriculum and literature-based overview of Primary STEM integration, and our systematic literature review of learning in Primary Science Education. The Primary STEM integration overview is rooted in the reports, draft curricula, and the literature bases relating to the focal topic drawn on in these documents, with the overview of digital technologies also drawing from a comparative analysis of a sample of international curricula. The Primary Science Education literature review is based on a systematic review of relevant, internationally peer-reviewed research articles from the last decade, guided by a comparative analysis of the structure and science content seen across the same sample of international curricula. Throughout the report, integrated STEM (iSTEM), refers to any attempt at integrating or connecting two or more of the STEM subjects.

Why is STEM Education Important?

There is broad agreement in the literature on the need for access to both high quality disciplinary teaching of Mathematics, Science, Technology and Engineering in primary schools, and to high quality experiences of iSTEM projects. There is also agreement that high quality iSTEM experiences, based in projects that connect with children's interests and concerns about local and global issues, can enhance children's subject-related understandings, develop problem-solving skills, drawing on the disciplines as tools in ways that illuminate the power and usefulness of the STEM subjects, and develop broader key competences including citizenship, digital competence, communication, creativity alongside connectedness and empathy. This problem-solving can include openings for designing models, artefacts and digital programmes that enhance people's lives, in ways that take account of the imperatives for equity and sustainability. However, there is also the caveat that while high quality iSTEM teaching creates these multiplier effects, poor iSTEM teaching damages prospects for both disciplinary learning and learning of transversal competences.

The evidence from implementations of iSTEM projects points to the importance and usefulness of longitudinal professional learning opportunities and engagement time for teachers that can draw attention to the STEM subject related learning opportunities and openings for development of integrated competences. It is also evident from the literature that teachers require time to plan for how the teaching of disciplinary concepts can best be arranged within and around an iSTEM project. The need for the development of STEM frameworks that show the aspects that are core to STEM working and exemplar STEM projects that can be discussed and trialled is important for effectively implementing STEM education in primary schools.

In Ireland and other countries, good quality teaching of the STEM disciplines and of iSTEM is important to ensuring a STEM literate population that can respond to the challenges of the 21st century. Given the skills shortages relating to STEM careers and given too, the evidence of gender imbalance in the take up of STEM subjects at post-primary and tertiary levels, the STEM learning area in the primary curriculum has the potential to feed into the building of a more STEM-literate population with broader options for contributing to the STEM economy.

What are the desired curriculum processes and essential content for children's learning and development in Science? How should they be taught?

It is apparent from the research that, for scientific literacy students need to develop their knowledge of and about science and apply and develop a range of science process and inquiry skills to make sense of local and global everyday science issues. Learning outcomes related to children's conceptual understanding of Biological, Physical, Material and Environmental sciences and the development of science skills are deemed important for learning in science and are commonplace in curricula.

Engagement with scientific content across all science disciplines is yielding positive results in terms of developing students' science knowledge and their ability to explain their scientific inquiries and results using scientific terminology. However, there are concerns regarding children holding naive conceptual understanding even after engaging in science inquiries and teachers not having sufficient conceptual knowledge to effectively implement Science curricula or to address children's naive scientific conceptions.

There is overwhelming evidence that science process, inquiry, critical thinking, argumentation and problem-solving skills are essential skills for scientific literacy and that primary students should be afforded frequent opportunities to apply and develop these skills in meaningful ways during school science. However, while evidence suggests children are being afforded some opportunities to develop their science skills, in many cases the core science skills are not being developed in meaningful ways. It is apparent that explicit instruction of key science skills is required to enable students to apply them in new scenarios and investigations relevant to their everyday lives. Teachers should monitor specific skills during scientific investigations and be provided with professional learning to enable them to scaffold the development of these skills in a progressional manner.

Further shortcomings regarding science education highlighted in the literature include: insufficient instructional materials (including digital technologies); lack of whole school approaches to science; inadequate time for science; low confidence and competence amongst teachers; inadequate professional learning for teachers. These all have implications for curriculum development and implementation.

A number of recommendations for development and effective implementation of the STE (Science, Technology and Engineering) curriculum are proposed:

- Clear descriptions and exemplars of different types of hands-on, structured, guided and open inquiry pedagogies should be explicitly outlined in the STE specifications;
- Key learning outcomes, based on ‘big ideas’ and ‘principles’ in science should be included in the STE curriculum specifications;
- Scientific content must be related to students' everyday lives and should include specific learning outcomes related to Sustainability and Climate Change;
- Succinct learning outcomes related to, descriptors of and rubrics for assessing, working scientifically (process) and related skills should be provided in the STE specifications
- Dedicated time for Science as a subject in its own right must be allocated within the overall curriculum framework;
- Exemplars of effective use of digital technologies to enhance hands-on science inquiries should be provided;

- Specific learning outcomes related to the development of positive attitudes and values towards science, including pro-environmental attitudes should be included in the STE specifications;
- A clear definition of scientific literacy in the context of the STE curriculum needs to be provided;
- Longitudinal professional learning opportunities to support teachers in developing their Science content and pedagogical knowledge must be made available;
- Ring-fenced funding for Science resources and teacher professional learning needs to be provided.

What is the relationship between Technology / Engineering and Science and Mathematics?

While the learning of disciplinary concepts is important, a 'siloed' approach can impede learners' understanding of the connections and interdependencies that exist between disciplinary concepts in science, technology, engineering and mathematics. Understanding the synergies between these concepts is important, not least because the world we live in daily is not compartmentalised into neat 'subject' areas; knowledge from different disciplines is frequently used to inform decisions and action.

The design of curriculum and learning experiences to enable the seamless learning of core STEM disciplinary content and practices, and iSTEM skills and processes is a challenge faced by policy makers and curriculum designers. Many countries have begun to publish curricula that detail the relationship between technology/engineering and science and mathematics. Analysis of approaches adopted towards iSTEM in national technology curricula in 11 countries identified a range of transversal STEM processes present in all the curricula-albeit in different ways with varying degrees of specificity. These include design (design thinking and engineering design thinking), computational thinking and coding, digital competence and data literacy. Further emerging areas of interest are data literacy and artificial intelligence. In considering curriculum development, it is imperative to anticipate and prepare for these emerging areas.

Looking across the technology curricula, some outline the core content and knowledge requirements but are lacking in detail giving schools autonomy both in how they structure the organisation of learning and the pedagogical approaches adopted. As a consequence, there is no consensus relating to the content and implementation of the subject - a practice which leads to insecure teaching. There is also a risk of inequality amongst schools and of the students' STEM experiences becoming fragmented. Although other curricula provide models for iSTEM, they require schools and teachers to design their own curriculum; this represents a significant culture shift for Irish teachers and would demand significant teacher professional learning and support if it were to be successfully implemented in primary schools in Ireland.

Overall conclusions and recommendations

- For effective integration of STEM, students must be afforded opportunities to engage with both the individual STEM disciplines and iSTEM projects. Time therefore must be allocated for teaching Mathematics and Science as disciplines in their own right and for interdisciplinary STEM projects. A balance needs to be struck between disciplinary and integrated STEM.

- Integrated STEM projects require dedicated time. The findings suggest the inclusion of at least one iSTEM project per term, with projects planned purposively to surface or draw from a range of different mathematical, scientific, technology and design components across different projects.
- Effective iSTEM requires careful planning and therefore dedicated time for planning iSTEM projects should be earmarked in schools.
- Clarity is essential for effective iSTEM implementation. Frameworks / models of iSTEM and what progression within iSTEM can look like therefore need to be developed and supported by exemplars of iSTEM projects for use across all stages.
- Longitudinal professional learning opportunities need to be made available for teachers, so they are able to design and implement authentic learning experiences that integrate core STEM competences within real-world contexts.

Section 1

Through the lens of the vision and principles of the *Primary Curriculum Framework*, why is STEM integration important?

1.1 Introduction

This report is written in response to the National Council for Curriculum and Assessment (NCCA) call for a literature review relating to STEM Education at primary level that can feed into conceptualizations of STEM as a curriculum area, and support the development of a primary Science, Technology and Engineering specification. We address both of these areas in this report. It is worth distinguishing at the outset between the 'subjects' that comprise STEM: Science, Technology, Engineering and Mathematics, and integrated STEM (iSTEM in this report), which is the term we use to refer to any attempt at integrating or connecting between two or more of the STEM subjects.

The *Primary Curriculum Framework* (NCCA, 2023a) presents STEM as one of five curriculum areas that structure primary level learning. The structuring of the curriculum into 'areas' rather than as more traditional 'subjects' is a key marker of the advocacy of integration. STEM integration is promoted in the *Primary Curriculum Framework* and in the various STEM Education reports that preceded this document for the following reasons:

- Supporting real-world problem-solving
- Seeing subjects as useful, powerful and connected to the real-world
- Developing the key competences
- Connecting with children's experiences and interests

Each of these rationales are detailed briefly below.

1.1.1 Supporting real-world problem-solving

Problem-solving in the world typically requires knowledge, skills and dispositions drawn from multiple subject areas. A focus on STEM integration provides children with experiences of STEM problem-solving in school that are connected with problems and problem-solving as they occur in the real-world. STEM integration is therefore seen as a route to better preparing children for the nature of problem-solving as it features in authentic situations.

1.1.2 Seeing subjects as useful, powerful and connected to the real-world

There is evidence, in Ireland and elsewhere, that learning within traditional mathematics and science subject boundaries can contribute to a sense of 'divorce' of subject knowledge in these areas from each other and from the world beyond. Isolated work with subjects can also feed into an emphasis on rote learning of facts and procedures. Working in integrated ways with the STEM subjects is seen as a way of highlighting the usefulness of each subject's content, procedures and processes for problem-solving and reasoning in the context of real-world problems, as well as pointing out their interconnections.

It is important to note that the *Primary Curriculum Framework* moves from a curriculum areas model into subjects where "curriculum areas become more differentiated by subjects as children move through the primary classes" (p. 14).

This reflects a sense of subjects – their facts, concepts, procedures and ways of working – emerging from authentic inquiry. The *Primary Curriculum Framework* describes this emergence of subjects as reflecting "children's growing awareness of subjects as a way of organising the world" (p. 16). This point is noteworthy as it contrasts with the view of STEM integration projects as offering a location for the application of previously learned subject knowledge and skills, rather than as situations in which subject-related concepts can emerge. Across the *Primary Curriculum Framework*, there is recurring reference to the need for balanced attention to teaching STEM subject concepts and skills, and teaching for integrated STEM (iSTEM) problem-solving, which can include creative combinations across science, technology, engineering processes seen in designing/making, and mathematics. This balance between STEM subject teaching and iSTEM inquiry and problem-solving is particularly important given Mc Comas, Burgin, and Nouriz (2020) caution that if there is no distinction between the STEM disciplines, students may not understand what is unique about each discipline's content, processes, history and philosophical underpinnings. These arguments make it necessary to consider the need for iSTEM curricula to support the development of disciplinary epistemic and procedural knowledge alongside interdisciplinary knowledge and competences (Mc Comas et al., 2020a).

1.1.3 Developing the key competences

STEM integration, whether set in projects, problems or inquiries/experiments, is seen as a natural place for the development of transversal skills that are relevant across all curriculum areas and to effective functioning in life more generally. This is because iSTEM projects and problem-solving/designing solutions within them usually require and benefit from multiple perspectives and skill sets across several areas. In the *Primary Curriculum Framework,* these transversal skills are referred to as 'key competences'. These encompass being an active citizen, being creative, being a digital learner and being mathematical.

1.1.4 Connecting with children's experiences and interests

Given that STEM integration problems are anchored in the real-world, iSTEM is described in the *Primary Curriculum Framework* as offering an important site for connecting teaching and learning with children's experiences and interests. STEM integration also offers a route into developing children's awareness of environmental issues, and the need for design that protects resources and enables sustainable living.

Beyond these key rationales in the *Primary Curriculum Framework* for including iSTEM, this document and the broader literature base both note the economic imperatives for attention to STEM subjects and integration, with the evidence of skills shortages in STEM-linked careers in Ireland. Within this evidence, the need for inclusive work with both disciplinary learning of the STEM subjects and iSTEM at the early years and primary levels is identified as critical to closing the gender gap in girls' participation in, and take up of, the STEM subjects at post-primary level and beyond.

1.2 The ‘how’ of STEM integration in the *Primary Curriculum Framework*

While specified as an integrated curriculum area across all four primary stages, Mathematics has its own subject specifications and is allocated a minimum *weekly* time period (ranging from 3 hours in Stage 1 to 4 hours in Stages 3 and 4) in the *Primary Curriculum Framework*. Science, Technology and Engineering are allocated a minimum *monthly* time (3 hours, 20 minutes in Stage 1 up to 5 hours in Stages 3 and 4). There are also ‘Flexible Time’ hours that can be used at the discretion of the teacher to follow up and tailor experiences to children’s interests and growing understandings. While iSTEM projects can range across shorter inquiries and more extended investigations, the need to revisit ideas as they recur in children’s experiences and expand their scope, vocabulary, concepts and related skills and design aspects does make it likely that some iSTEM inquiries will work across the allocated Mathematics, Science, Technology and Engineering hours and avail of ‘Flexible Time’.

The broader literature reflects that it is not easy to get the balance between STEM disciplinary subject teaching and iSTEM working into place, but also indicates benefits of giving children access to iSTEM experiences in the early years and in primary schools. Within this, what we highlight in this review is that the quality of iSTEM teaching matters: while high quality iSTEM teaching can supplement and enhance disciplinary learning, poor quality iSTEM teaching can result in lack of instructional focus on the content and processes of the disciplines. English (2016) makes this point in relation to mathematics; Mc Comas et al. (2020) do the same with respect to science. In such cases, there are dangers of low-efficacy moves into design-and-make activities that ostensibly fall under the engineering umbrella, but with limited, if any, focus on science or mathematics concepts and processes. Given these concerns, supporting schools with planned approaches and exemplars for managing the inclusion of STEM integration, in ways that enhance and connect subject learning with real-world problem solving is critical to embedding STEM integration in classrooms in Ireland.

Section 2

What evidence was provided by the literature on children's learning and development through integrated STEM approaches?

2.1 Categories of learning and development in integrated STEM approaches

Empirical evidence on children's learning and development through integrated STEM approaches in the literature base has been noted as limited, and hampered by differences in the ways learning and development are perceived and accounted for across different studies (Honey et al, 2014). However, the available evidence on learning and development is cautiously positive, and can be demarcated into three broad categories:

- Learning and development of the disciplines (content and processes associated with particular STEM disciplines)
- Learning and development of iSTEM (focused on problem-solving/design-make related to authentic situations, rather than with reference to disciplinary content and skills)
- Learning and development of key generic competences (NCCA's key competences; motivation and identity shifts are also mentioned in the literature as reasons for incorporating integrated STEM)

All three of these branches of learning are represented in the *Primary Curriculum Framework*, and in the consultations and literature bases that fed into this document, among these the draft *Primary Mathematics Curriculum* specifications (NCCA, 2022) and the STEM reports (DES, 2017; 2020).

2.1.1 Learning and development of the disciplines

There is some evidence in the literature base of improved disciplinary learning emerging through children's engagement with iSTEM activities, though the extent of empirical evidence of learning and development varies across the disciplines, with science content and processes most widely represented. There is widespread agreement that disciplinary learning within iSTEM inquiries requires planning for inclusion of Science/ Mathematics/ Technology-related learning goals and scaffolding for access to these goals (Bryan et al., 2015), rather than leaving this learning to chance. Below is an overview of studies that point to the possibilities and constraints related to disciplinary learning and development through iSTEM.

- Studies with exemplifications of **science learning** feature most commonly in the iSTEM literature. Given the real-world inquiries that generally form the basis for iSTEM projects, and the emphasis on understanding phenomena in the world, this predominance is unsurprising. Alongside the extensive options for presenting and discussing scientific concepts, inquiries offer openings for investigations and experiments, and via these, into appreciation of scientific argumentation and the nature of science. Guzey et al.'s (2019) study offers an example of longitudinal life-science learning within an iSTEM project that had been carefully planned to focus on life science learning goals using three engineering-focused life science units across three years.

The Systematic Literature Review (SLR) for Science in this report offers evidence of the possibilities for learning about scientific inquiry, and experimental methods and scientific modelling within this, as well as about the nature of science overall through iSTEM working, alongside exemplars of science content learning (e.g. Anwar et al., 2022; Dedeturk, Kirmuziul, & Kaya, 2021).

The 2020 Inspectorate Report on STEM Education Practice in Ireland (Department of Education & Skills [DES], 2020) offers examples of science concept and process foci within iSTEM episodes, and highlights too, the positive impacts of collaborative STEM planning and flexible timetabling in creating and enabling STEM environments for learning.

Curricula that include attention to STEM integration, as noted in Section 3, are relatively recent implementations, and thus, there is limited research into the learning outcomes emanating from them. Where there is evidence, as in Northern Ireland, the picture is mixed, with some evaluations noting that where science is taught as part of an integrated curriculum (in this case integrated with history and geography), that frequently science concepts, skills and knowledge are put aside (Education and Training Inspectorate [ETI], 2014).

Also on the caveat side, primary teachers' lack of confidence with science and its teaching has been argued to contribute to a shying away from science inquiries into an emphasis on the engineering-oriented design/making and digital components in ways that constrain possibilities for scientific learning (Jarrett, 1999).

- **Learning** related to **technologies (including digital technologies**) is represented in two ways in the STEM integration literature base and in curricula: technologies as tools for modelling/designing, representing and communicating; and technology as content (e.g., programming and coding, robotics, computational thinking models – Bers et al., 2014). The emphasis on developing identities as digital learners as a key competence in the *Primary Curriculum Framework* encompasses both aspects, but the empirical base in iSTEM projects focused on real-world issues, coupled with the relatively rare inclusion of engineering/design that we note below, tends to mean that there are more exemplars in the literature base of technologies featuring as tools for processing and representing data rather than with a content focus. Research reviews point out that instruction focused on, or including, programme design has tended to lie within projects that attend to learning about computational thinking directly rather than more broadly in iSTEM projects (Hsu, Chang, & Hung, 2018). (The review of international curricula includes a summary of digital transversal skills – see Section 4.2.2)

- An **engineering focus** features to a more limited extent in the iSTEM literature base, although recent increases in prevalence are noted in the explicit incorporation of engineering design processes (Larkin & Lowrie, 2023). This growth is also seen in the explicit inclusion of engineering design processes in the recently introduced California, Ontario and Wales curricula. The need for attention in the choice and set-up of iSTEM projects to inquiries that include spaces for authentic design-and-make activities is identified in the literature as a way of ensuring time for these activities (English, 2018). Design-and-make has been advocated as a key part of the STEM curriculum area in Ireland, and it will therefore be important to tie together the emphasis on modeling in mathematics and inquiry in science with design activities. We highlight that a genuine integration of engineering with science and mathematics: concepts, procedures and ways of working, is critical to avoid low-level time given to design and making activities.

- Openings for **mathematics learning** through iSTEM can be linked with both mathematical content and processes. Mathematizing - which refers to creating mathematical models of real (or realistic) situations - is a key principle of the *Draft Primary Mathematics Curriculum* (NCCA, 2022). With its focus on deciding on the variables of interest and creating models of their relationships, there are clear links with aspects of STEM inquiries. Similarly, other mathematical processes come into play in iSTEM projects, e.g. Investigating, sense-making, modeling, representing and predicting. These processes share elements with design and engineering processes.

  Dooley (2019) further notes that 'big' or 'powerful' ideas in mathematics feature as concepts or processes that underlie multiple topics and real-world situations. Proportional reasoning, for example, is a mathematical conceptual relationship that underlies constant speed and distance travelled relationships. Similarly, generalising and formalising are mathematical processes that Dooley describes as naturally arising from young children's everyday experiences. These big ideas have been picked up within both thematic working where a situation is investigated from multiple disciplinary perspectives and in multidisciplinary projects.

  Mathematics, while described as 'foundational' to all the STEM disciplines in the *Primary Curriculum Framework*, is frequently noted as the hardest area to make visible as a focus in iSTEM working, with concerns that low-level mathematical content and processes are often drawn upon (English, 2016). Li and Schoenfeld (2019) note that viewing mathematics in terms of its products (a bank of concepts and related processes) tends to work against the orientation to modeling situations and design activity that iSTEM frequently promotes. The recent NCCA consultation with children and schools on STEM Education noted that using mathematics within iSTEM projects offered a 'collateral benefit' for mathematics teaching and learning, with children more able to see the subject in 'enabling and supporting' rather than 'standalone' roles (NCCA, 2023, p. 21).

2.1.2 Learning and development of integrated STEM

There is a dearth of large-scale empirical studies that analyse children's learning and development of iSTEM as they advance through primary school. However, the results from studies that have trialled this approach point to a number of enhanced learning outcomes for all children regardless of ability.

- In this category of learning, the focus is on understanding or problem-solving related to the situation or project that forms the core of the inquiry. Subject skills may well be drawn upon, but this happens in amalgams that are geared towards solving the problem at hand rather than looking at enhancements of subject learning. The project approach involves an in-depth study of a particular situation or phenomenon where connections are made between and across curriculum subjects.

  In mathematics, project-based learning has been shown to enhance problem-solving skills as learners are given an authentic opportunity to solve problems in the context of the overarching theme or topic (Boaler, 1997, as cited Dooley et al., 2014). This kind of project-based learning has also been shown to contribute to rich learning experiences that build upon children's interactions with the environment. These experiences, in turn, have been shown to contribute to children's development (Government of Ireland [GoI], 1999, pp. 14-17).

A recurring finding in the literature is that different kinds of iSTEM projects are geared towards different openings for STEM-related learning (Roehrig et al., 2021). Authentic real-world problems are a necessary part of what is needed, but English (2018) offers details on the sequence of subject-related teaching, planning and resourcing, and scaffolding with pre-prepared materials and worksheets required to ensure an authentic inquiry in which several aspects of all the STEM subjects and integrated problem-solving can be leveraged.

2.1.3 Learning and development of key generic competences

A recurring theme arising across the literature on STEM education is the benefit to students with regards to an increase in motivation, creativity and engagement termed in the draft *Primary Mathematics Curriculum* (NCCA, 2022) as fostering a 'productive disposition'.

- Creativity and innovation are strongly marked in project- and problem-based learning approaches given the need to devise solutions in context (Aguilera & Ortiz-Revilla, 2021). Project-based learning has been successfully piloted as an alternative mode of developing and assessing key skills at Junior Cycle such as the development of interpersonal skills (Harper, 2016). Local and international research points to significant opportunities for development of a wide range of key competences, described variously as transversal skills, 21st century skills and interdisciplinary competencies (e.g., Costello et al., 2022).

- Further, the SLR for Science in Section 3 of this report points to extensive literature focused on learning related to improved attitudes towards science emanating from openings for creative and critical thinking, collaborative working, and use of digital tools to support real-world problem-solving (see Section 3.6).

- Integrated STEM learning has been shown in some studies to improve performance in assessed learning outcomes on students' achievements using traditional examinations and those that target more generic competencies such as student collaboration (White & Delaney, 2021).

2.1.4 Concluding comments

The need for balanced attention to high-quality disciplinary teaching of mathematics and science alongside high-quality work on iSTEM projects is, perhaps, the strongest concluding point from this overview of the Irish reports underlying the *Primary Curriculum Framework* and recent iSTEM research reviews and empirical studies. For iSTEM to contribute to enhancing the learning of science and mathematics, intentional planning for disciplinary learning goals appears to be necessary, in ways that cohere authentically with the inquiry in focus. There is evidence of subject-based learning, integrated problem-solving involving combinations of content and skills from each of the STEM disciplines in hybrid solutions, and key competence development, as well as findings of increased motivation and confidence. However, the caveats also have to be taken seriously to support a STEM integration into the curricula that can achieve the longer-term goals of extended participation in STEM across schooling and into both careers and adult lives as citizens and in communities. The literature suggests that this will require attention to the development of suggested models for incorporation of iSTEM projects in primary school curricula, exemplars of iSTEM projects for use across the primary grades, and teacher professional learning for substantive STEM subject and iSTEM teaching. Additionally, different kinds of STEM projects focused on learning related to varied combinations of discipline-related goals will need to be exemplified to ensure that aspects such as coding, designing/making, mathematical reasoning and problem-solving are offered at some point in each year of primary schooling, even if different combinations of concepts and skills are drawn upon within specific projects. Planning on a multi-year basis at school levels is necessary to ensure rounded and well-balanced experiences of learning.

The evidence on learning from empirical studies still tends to come from smaller-scale intervention studies in the field. Kelly and Knowles (2016) point out that iSTEM studies continue to offer more ‘contemplation’ than ‘operationalization’, with a priori assumptions of the worth of iSTEM as a productive approach rather than hard evidence. The evidence base is also currently geared towards studies relating to teaching and teachers’ perspectives rather than learning outcomes (e.g., Stohlmann et al., 2012). In many ways, this is unsurprising for a field that is still young, and where STEM integration only recently features in national curricula. There is promise, and the research points to limitations that can be overcome with careful attention to support for teachers in terms of materials and professional development.

Section 3

In response to curriculum overload:

What are the desired curriculum processes and essential curriculum content (knowledge, skills, values and dispositions) for children's learning and development in Science (including design & make applications) within the broad primary curriculum?

How should they be taught?

3.1 Introduction

Science, as a discipline of STEM, has a central role in supporting our understanding of and responses to the significant global challenges faced by humanity. Science provides fundamental knowledge about the world we live in, and as a discipline, enables citizens to observe, investigate, measure, analyse, design and advance our physical environment (DES, 2016). Now, more than ever, it is apparent that school science has a significant role to play in supporting learners in developing the knowledge, skills, values and behaviours to tackle climate and environmental challenges (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2018).

Science education policy has long advocated for and supported an emphasis on core knowledge of scientific disciplines, the processes and practices of science, and relationship between humans and the natural world. Collectively they speak to a global goal of science education – scientific literacy – or abilities to apply scientific knowledge and practices to real world phenomena in everyday life (Forbes, Neumann, & Schiepe-Tiska, 2020). Science education that promotes scientific literacy is crucial to developing students' interest, knowledge and skills in science. Such knowledge includes scientific content knowledge but also an understanding of the Nature of Science (NOS) and consideration of social, cultural, economic and political influences that underpin everyday societal issues (Zeidler & Sadler, 2011). The development of inquiry skills is key to scientific literacy but students must also be supported to interpret, evaluate and critique scientific knowledge presented in the media and elsewhere (Broderick, 2023). Critical thinking, problem-solving and communication skills are necessary if students are to engage in discussion and debate pertaining to societal issues. Furthermore, providing students with opportunities to make informed decisions and take action in response to real-world issues promotes seeing science education as useful and connected to students' lives (Feinstein, 2011).

It is thus important that the redeveloped primary Science, Technology and Engineering (STE) curriculum lays foundations for supporting our youngest citizens to become scientifically literate. Alongside this, it is also critical that this curriculum supports students to develop the requisite knowledge, skills, values and attitudes that will motivate and empower them to take action to live justly, sustainably and with regard to the rights of others.

The purpose of this systematic literature review, that includes a content analysis of international primary Science curricula and their implementation, is to examine, describe and consolidate curricula and research related to primary science education in order to gain insights into **what** content (knowledge, skills, values and attitudes) primary students should engage with and **how** they should learn and engage with science. The findings enable the identification/ refinement of key scientific concepts, skills, values and dispositions that should be included in the redeveloped primary STE curriculum and effective pedagogies to support this.

Later in this section we present the findings from a systematic literature review on children's learning in primary science, which draws on literature published in the past 10 years. Three further considerations are also important to note. First, there is literature on the broad principles, pedagogies and 'best practices' underpinning effective primary science education that have been highlighted in international research literature over a number of decades. It is important to note that this literature underpins much of the writing covered within the systematic review of research from the last decade. Second, we included a contextual piece on primary science education in Ireland, as awareness of conditions and culture are widely acknowledged as critical within curriculum implementation. Third, we drew on the Trends in International Mathematics and Science Study (TIMSS) database to overview primary science curricula from a number of countries in order to learn from their conceptualizations and specifications of STE.

3.2 Primary Science Education: Setting the context

In this first section we present a snapshot of some of the broad principles and pedagogies commonly agreed on in the literature as underpinning effective science teaching and learning.

3.2.1 Principles underpinning effective Primary Science Education

'Principles' and 'Big ideas' in Science Education

Harlen's (2010; 2015) set of guiding "principles" and "big ideas" for science education have been broadly accepted as 'best practices' in science education, practices that support deeper engagement with and understanding of and about science. The principles are underpinned by social constructivist theories and include building on students' prior knowledge and experiences, promoting scientific inquiry and investigation, emphasising the inter-connectedness of science, and supporting critical thinking and scientific literacy. Broadly Harlen (2015) states that science education should aim to develop:

- understanding of a set of big ideas in science which include ideas of science and ideas about science and its applications
- scientific capabilities concerned with gathering and using evidence
- scientific attitudes and dispositions.

Harlen offers ten big ideas of science and four ideas about science and its applications.

Big ideas of science

1. All matter in the universe is made of very small particles
2. Objects can affect other objects at a distance
3. Changing the movement of an object requires a net force to be acting on it

4. The total amount of energy in the Universe is always the same but can be transferred from one energy store to another during an event
5. The composition of the Earth and its atmosphere and the processes occurring within them shape the earth's surface and its climate
6. Our solar system is a very small part of one of billions of galaxies in the Universe
7. Organisms are organised on a cellular basis and have a finite life span
8. Organisms require a supply of energy and materials for which they are often dependent on or in competition with other organisms
9. Genetic information is passed down from one generation of organisms to another
10. The diversity of organisms, living and extinct, is the result of evolution

Ideas about Science and its applications

1. Science is about finding the cause of phenomena in the natural world
2. Scientific explanations, theories and models are those that best fit the evidence available at a particular time
3. The knowledge produced by science is used in engineering and technologies to create products to serve human ends
4. Applications of science often have ethical, social, economic and political implications (Harlen 2015, p. 22)

Constructivist pedagogies in Primary Science

Constructivism is based on the idea that people actively construct or make their own knowledge, and that reality is determined by the experiences of learners. This reflects Dewey's view that experience can expand the understanding of concepts taught in the classroom and give 'real-world' connection and relevance to more traditional studies (Rone, 2008). Dewey saw education as a powerful force in peoples' lives and viewed learning as an active process involving challenging tasks related to real life, promoting learning through experiences and interactions. Constructivists champion a move away from the rigid approach of passive learning towards a more participatory model where children are encouraged to investigate, experiment and make their own sense of the world (Aubrey & Riley, 2016).

Inquiry based Science Education

Inquiry based science education (IBSE) is a child-centred methodology that enables learners to develop their understanding of the scientific aspects of the world around them through the application of different inquiry skills (Harlen & Allende, 2009). The benefits of adopting IBSE methodologies in primary science education are widely accepted in the literature (European Commission, 2015; Harlen, 2012; Rocard, Csermely, Jorde, et al., 2007), and include: supporting the development of students' scientific knowledge and skills; increased interest and motivation in science; affording opportunities for cooperative learning and promoting students' critical thinking and problem solving skills (Artique et al., 2012; Harlen 2012; Murphy, Varley, & Veale, 2012; Rocard et al., 2007).

Nature of Science pedagogy

The terms Nature of Science (NOS)/Nature of Science Knowledge (NOSK) relate to issues regarding the epistemology of science, namely, what science is, how it works, how scientists work as a social group and how science influences and is influenced by society (Lederman, 1992). The inclusion of NOS as an educational goal has been the focus of numerous studies over the past three decades (Lederman & Lederman, 2019; McComas, Clough, & Nouri, 2022) with its inclusion in primary science education noted as offering mutual benefits for both teaching and learning. For students, opportunities to engage with NOS inquiries support: greater awareness of the scientific process skills they are using during school science; more frequent engagement with inquiry-based approaches; greater links between school science and science in the real world (Murphy, Smith, & Broderick, 2021a; Khisfe, 2022). From a teacher's perspective, adopting NOS pedagogies makes them: more confident in using inquiry-based approaches to science; affords their students more frequent opportunities to plan and carry out their own investigations; and affords students more frequent opportunities for collaboration, discussion and reflection in science class (Abd-El Khalick, 2012: Khisfe, 2022; McComas et al., 2022; Murphy et al., 2021a; Murphy et al., 2012; Murphy, Murphy, & Kilfeather, 2011).

Socio scientific issues (SSIs) instruction

Over the last two decades research on science learning within the context of Socioscientific Issues (SSIs) has shown that SSIs-based education can be effective in promoting students' scientific literacy. SSIs are complex and open-ended, often controversial, social issues linked to science with multiple plausible solutions influenced by scientific, social, economic, political and ethical factors which often relate to everyday issues (Holbrook & Rannikmae, 2009; Sadler, 2011; Zoller & Levi Nahum, 2011). Research suggests that SSI based education can enhance students' scientific literacy and moral development and can support the development of students' scientific knowledge, skills and attitudes fundamental in decision making on issues that affect students' everyday lives (Burek & Zeidler, 2015; Zeidler, 2015). SSIs-based education supports a process of inquiry and negotiation where students ask questions and gather evidence related to complex issues.

Outdoor learning

Outdoor learning encompasses a holistic pedagogy which enables children to make connections to people, places and the natural and manmade world (Kelly, 2022), particularly within a place-based context (Sobel, 2013). Place based and outdoor science learning have been shown to develop primary children's 'working scientifically' skills (Lloyd, Truong, & Gray, 2018; Rios & Brewer, 2014), and to increase their curiosity and interest in science (Lloyd et al., 2018). Green and Raynor (2020) indicate that school ground pedagogies, particularly when framed by self-directed learning tasks, increase primary students' autonomy, efficacy and achievement. Recent research indicates that nature-based science education reveals positive trends regarding increasing content knowledge in science and pro-environmental behaviours (Schilhab, 2021).

Empirical national and international evidence suggests that these pedagogies and principles are effective in supporting effective teaching and learning in primary science with numerous positive impacts (Aubusson et al., 2015). Implementation studies also provide evidence that primary school children are interested in science, enjoy school science and are more motivated when they engage in science that relates to their everyday lives (Australian Curriculum, Assessment and Reporting Authority [ACARA], 2013; Murphy et al., 2021; Murphy, Broderick, & Mallon, 2020a). While the research suggests that teachers are positively disposed towards implementing these child-centred pedagogies, and appreciate their effectiveness in supporting children's learning, implementation of these pedagogies also poses a number of challenges for teachers. Some of these challenges relate to teachers' perceived lack of confidence and competence with science (ETI, 2014; Office for Standards in Education, Children's Services and Skills [Ofsted], 2021), or to their lack of content and pedagogical content knowledge (Ofsted, 2021). But there are also systemic challenges that impact effective science teaching. These include: insufficient time for implementing inquiries (Jenkinson & Benson, 2010); reduced curriculum status for science (Ofsted, 2021); insufficient resources (Estyn, 2017); overcrowded curricula (APPA, 2014); socio-economic challenges (Estyn, 2017: Sullivan, Perry, & McConney, 2018) and management structures (ACARA, 2020).

The TIMSS data over the past 25 years also show that children's foundational primary science experiences have not yet enabled them to reach their full potential (Martin et al., 1997; Thomson et al., 2020). A particular point of concern is that the TIMSS data indicate that 90% of fourth-class children (9-10 years) in all TIMSS participating countries fail to meet the High International Benchmark (550): a measure of children's capacity to generalise their science learning beyond the classroom. We now consider these findings in the Irish context.

3.2.2 Primary Science in Ireland

The overall aims of the 1999 *Primary Science Curriculum* (Department of Education & Science [DES], 1999) are to develop scientific content knowledge and 'working scientifically' skills, and to promote positive attitudes towards science. Content in the Science curriculum is organised under four content strands: Living Things, Energy and Forces, Materials and Environmental Awareness and Care. The skills include predicting, questioning, observing, investigating, recording and communicating. Design and make skills include exploring, planning, making and evaluating. Learning through hands-on activities, discovery and practical investigations, whereby students are provided opportunities to test and develop their ideas, is emphasised throughout.

Irish primary students, like their counterparts worldwide, enjoy hands-on science and have opportunities to work collaboratively in small groups (DES, 2012; Murphy et al., 2021a; 2020a Murphy et al., 2011; Varley, Murphy, & Veale, 2008). Further, Irish primary students hold positive attitudes towards, and confidence in, learning science, are positive about their instruction in science class, enjoy learning science in school and are performing above average on international assessments (Clerkin, Perkins, & Cunningham, 2016; Eivers, 2013; Mullis, Martin & Foy, 2016; Murphy et al., 2021,2020a; 2012; 2011; Perkins & Clerkin, 2020; Smith, 2015; Varley et al., 2008).

The achievement findings from the different cycles of the TIMSS assessment are informative. In TIMSS 2019, fourth-class students (n=5051) in the Republic of Ireland (RoI) achieved a mean score of 528, which was significantly above the TIMSS centre-point and similar to RoI's performance in TIMSS 2015 where a mean score of 529 was reported. Irish fourth-class students performed significantly higher than 33 countries and remained behind 12 countries. The RoI fourth class students displayed relative strengths on earth science topics (much of this content is part of the geography curriculum in RoI) and relative weaknesses on physical science topics (including physical states and changes in matter, light and sound, electricity and magnetism, and forces and motion) (Perkins & Clerkin, 2020). These findings reflected the DES (2012) evaluation of primary school students' content knowledge, where approximately half of the students failed to complete tasks relating to physical sciences (energy, light, sound, heat).

In cognitive domain terms, fourth-class students displayed relative strengths in 'Knowing' (including skills such as recalling, recognising information, describing and providing examples) (Perkins & Clerkin, 2020). Students were able to apply knowledge (including skills such as recalling, recognising information, describing and providing examples) and reason (including higher-order thinking skills such as analysing a problem, synthesising information, formulating hypotheses) on par with the overall national science score. There are broader concerns regarding the development and application of students' science skills with older primary students operating at skill levels similar to that of younger students.

The limited evidence of science skills development can be linked with concerns regarding the nature and frequency of 'hands-on science', with Irish students tending to be involved in more prescriptive, step-by-step, hands-on investigations than the child-led inquiry approach advocated by the curriculum (DES, 2016; Murphy et al., 2015; Smith, 2015). The scientific content with which children engage is often not particularly relevant to the children (DES, 2016; Murphy et al., 2012; 2011; Smith, 2015; Varley et al., 2008). Critical to these concerns is the time allocated to the teaching of science (Clerkin et al., 2016; Eivers, 2013; Murphy, 2013; Murphy et al., 2020a; Murphy et al., 2015; Perkins & Clerkin, 2020). International research indicates that Irish primary teachers spend less time teaching science than all OECD countries. The current time allocated for science in the Irish curriculum (at 4% of overall instructional time) is one of the lowest primary curriculum allocations for science worldwide. The TIMSS 2019 data reveal that Irish teachers report teaching only 32 hours of science per year, in comparison to the TIMSS mean of 73 hours.

In terms of teaching, Irish primary school teachers report: positive attitudes towards teaching science, giving students opportunities to engage in hands-on science (DES, 2012; DES, 2020: Murphy et al., 2015; Smith, 2014), and using Inquiry-Based Science Education (IBSE) methodologies (Clerkin, Perkins, & Chubb, 2017; Perkins & Clerkin, 2020). Despite this, there is strong evidence that teachers in Ireland tend to adopt traditional approaches to teaching science with largely teacher-directed lessons (DES, 2016; Murphy et al., 2015; 2012; Smith, 2014). As with primary teachers worldwide, many Irish teachers also lack confidence when teaching science and do not believe they have sufficient scientific content knowledge to teach science effectively (Murphy & Smyth, 2012; Murphy et al., 2015; NCCA, 2008; Smith, 2014).

The big ideas and principles of science, and key pedagogic approaches to science teaching identified earlier in this section underpin our analysis of international curricula that follows, and also the vast majority of studies in our literature review. The redevelopment of the primary STE curriculum in Ireland offers opportunities to entrench key ideas and pedagogies, and address the challenges of time, teacher confidence and competence relating to primary science.

3.3 Methodology

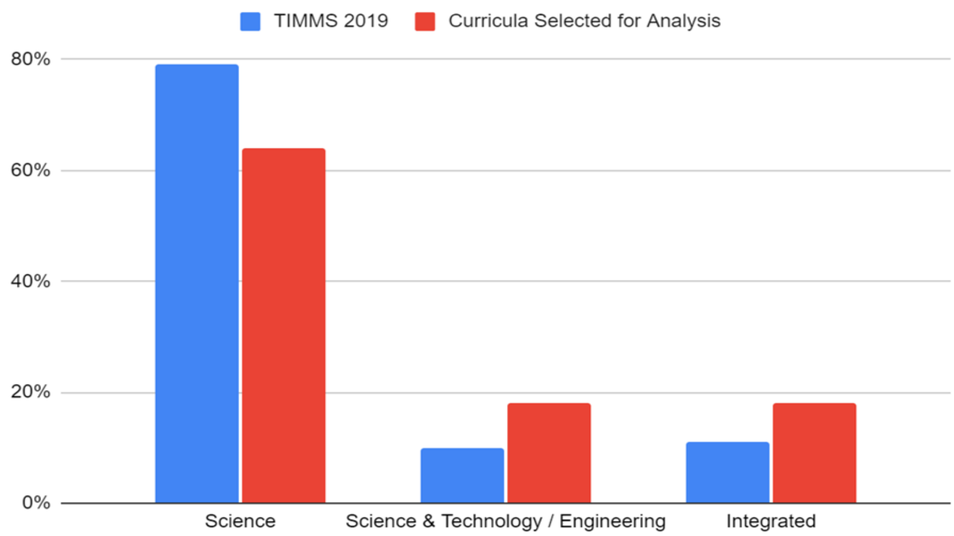
A comparative curriculum content analysis of 11 international Science curricula was conducted to explore their aims, structure and content. This analysis can inform the development of the STE specifications with detail on the structure, content specifications, pedagogies and time allocations for science as a separate/ integrated subject in these countries.

3.3.1 Curriculum Content Analysis

Eleven curricula were selected for the comparative analysis. The rationale for the selection of these 11 curricula was as follows. Firstly, the Science curricula from England, Wales, Scotland and Northern Ireland were selected due to their close proximity to Ireland. With data readily available from the most recent 2019 cycle of TIMSS, we decided to examine a sample of Science curricula of countries that participated in the fourth-grade assessment. All 62 participating countries' names were numbered and put into a random selector programme. If the randomly selected countries did not have their Science curricula available in English they were excluded. The USA and Canada emerged in the selection, but both these countries have national science frameworks/ standards around which individual US states and Canadian provinces must develop curricula, so curricula from one US state (California) and one Canadian province (Ontario) were randomly selected for inclusion in the analysis. The next five curricula from the random selection were Australia, Hong Kong, New Zealand, Sweden, and Singapore. Among these 11 countries, seven have Science curricula, two have Science and Technology/Engineering curricula and two have integrated curricula. These 11 curricula were representative of the overall structure of primary Science curricula across all 62 countries participating in TIMSS 2019: Figure 3.1 shows similar representation and balance across the Science/Science-Technology-Engineering/Integrated categories in our sample in relation to the overall dataset. A systematic content analysis of the 11 curricula was then conducted.

Figure 3.1.

Comparison of TIMSS 2019 Curricula and Curricula selected for Analysis



Analysis

The content analysis comprised three analytical stages. Researcher meetings were scheduled after each stage of analysis to ensure consistency in the content analysis process.

Stage 1

All researchers completed an initial read of curricula summarising the content of each. The following were recorded: year of publication, overall curriculum aims, underpinning pedagogies and the content of the curriculum.

Stage 2
A second reading of each curriculum followed where all researchers reread each of the curricula. The Stage 1 analysis table headings were refined to include the following: year of publication; rhetoric (overall aims, rationale, theorists); methodology/ pedagogy; form and structure of the curriculum (content) and researcher's initial thoughts/ comments.

Stage 3
Thematic analysis using Braun and Clarke's (2013) six step approach was followed, see table 3.1 below.

Table 3.1.

Braun & Clarke (2013) Six Step Approach to Qualitative Data Analysis

Phase	Description of the process
1. Familiarising yourself with your data	The researchers were already familiar with each of the curricula after engaging with Analysis Stage 2 and 3.
2. Generating initial codes	Each researcher coded interesting features of the curricula in a systematic fashion. A 'code' refers to the most basic part or element of the raw data that can be assessed in a meaningful way (Boyatzis, 1998). 46 initial codes were identified. A codebook was developed
3. Searching for themes	Codes were collated into three main themes: (i) Overall aims of the curricula (ii) Underpinning methodologies/pedagogies (iii) Curriculum content. The three participating researchers agreed on these themes.
4. Reviewing themes	The researchers then checked if the themes worked for the coded extracts and entire data set. They reread the curricula documents to explicitly search for codes. Some codes were redefined at this stage with the codebook book updated accordingly. The codes and selection criteria were reviewed until there was 100% inter-rater reliability.
5. Defining and naming themes	Researchers conducted ongoing analysis to refine the specifics of each theme.
6. Producing the report	Using the themes and codes the Curricula Analysis Report was written.

While presented linearly, in reality the researchers moved back and forth between phases analysing the curricula, refining codes and themes and reviewing findings (King et al., 2016; Nowell et al., 2017; Robson, 2011).

3.3.2 Literature on implementation

A review of National / State reports, evaluations and research articles relating to curriculum implementation across the 11 countries was also conducted. Keywords for each curriculum were inserted into ebscohost and google scholar (see Table 3.2 for the keywords searched for within each curriculum).

Table 3.2

Keywords for Literature Search on Primary Science Curriculum Implementation

Country / State	Key Words
Scotland	CfE. Curriculum for Excellence. Primary Science in CfE, Curriculum review of primary science, Primary science in CfE review of implementation.
Northern Ireland	The World Around Us review, Primary Science in World Around us Implementation, primary science and technology review, primary science and technology implementation
Wales	Wales Primary Science curriculum, Inspectorate, review of Welsh primary science curriculum,
England	England Primary Science Curriculum, review of Primary science curriculum England, OFSTED
Australia	Australia Primary Science curriculum, evaluation of primary science curriculum in Australia implementation of primary science curriculum,
New Zealand	New Zealand Primary Science curriculum, evaluation of New Zealand primary curriculum; science, implementation of primary science curriculum in New Zealand
California	California Next Generation Science Standard (NGSS) Implementation, NGSS review, NGSS curriculum implementation
Ontario	Ontario Primary Science curriculum, evaluation of Ontario primary curriculum; science, implementation of primary science curriculum in Ontario
Hong Kong	Hong Kong Primary Science curriculum, evaluation of Hong Kong primary curriculum; science, implementation of primary science curriculum in Hong Kong
Singapore	Singapore Primary Science curriculum, evaluation of Singapore primary curriculum; science, implementation of primary science curriculum in Singapore
Sweden	Swedish Primary Science curriculum, evaluation of Swedish primary curriculum; implementation of primary science curriculum in Swedish

3.4 Comparative curriculum analysis: Findings

In this section, we compare the content specifications across the 11 selected countries, and overview the available research on curriculum implementation in these jurisdictions.

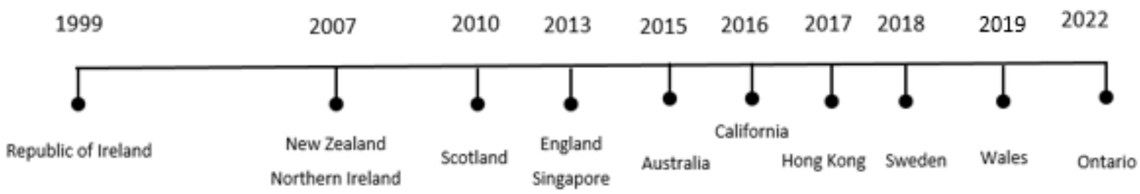
3.4.1 Content Analysis of Curricula

Broad Overview of Curricula

As stated above, of the 11 curricula selected for analysis, seven have a curriculum specifically for Science: Australia, California, New Zealand, England, Scotland, Sweden, and Singapore. With the exception of California and Singapore, these countries also have a separate Technology curriculum. The two most recent curricula in our sample, Ontario and Wales, have a Science and Technology curriculum. In terms of the technology component, the Welsh curriculum emphasises the relationship between science and technology and has 'computational thinking' as one of six underpinning mandatory learning statements. The Ontario curriculum emphasises practical applications of Science and technology and has 'coding and emerging technologies' as an overarching curriculum expectation (these Technology curricula are discussed further in Section 4.2.2). Northern Ireland and Hong Kong have integrated Science curricula. Science and Technology, as one subject, is combined with History and Geography in the Northern Ireland *World Around Us* curriculum. In Hong Kong, Science is one subject in a General technology education, personal, social and humanities education. The year of publication for each country/state in this analysis is shown in Figure 3.2 below.

Figure 3.2

Year of Publication



The overall time allocated for science varies amongst the 11 jurisdictions. Table 3.3 provides a summary of percentage time for science, based on total yearly instructional time. These data, self-reported by each country, were extracted from the contextual data in TIMSS 2019. It is worth noting that the time allocated for primary science in Ireland was one of the lowest of all countries that participated in TIMSS 2019.

Table 3.3

Time allocation for Science based on Total Instructional Time

Location	Time (time on science as % of total instructional time)	Time (hours/school year spent teaching science)
Hong Kong	12-15% (recommended allocation)	Not available

Sweden	9%	75 hours
Singapore	8%	84 hours
USA (California)	8%	83 hours
Canada (Ontario)	8%	80 hours
England	6%*	61 hours
Australia	5%	53 hours
New Zealand	4%	40 hours
Northern Ireland: WAU	4%	38 hours
Ireland	4%	32 hours
Scotland	No statutory guidance	Not available
Wales	No statutory guidance	Not available

*Based on 2015 TIMSS data as data for 2019 is not available

Analysis of the structural organisation of each curriculum revealed a number of similarities. The majority of the curricula had an overall aim, comprising general statements about the purpose of the Science /Science and Technology curriculum. Specific pedagogies underpinning the Science curricula were presented in nine curricula. Each curriculum also had a description of content to be covered aligned with different class/grade levels. Of note, many curricula had unique subsections. For example, Hong Kong has a subsection on Science Technology Society Environment Connections whereby students are encouraged to appreciate and comprehend the interconnection between these areas. These unique features are captured in the overall analysis presented in the sections that follow.

Frameworks

Of the 11 curricula studied, four (Australia, California, Hong Kong and Singapore) provide specific frameworks that underpin their Science curricula. The New Zealand primary curriculum has an overarching framework that foregrounds the Science curriculum. The remaining six curricula documents (England, Northern Ireland, Ontario, Scotland, Sweden and Wales) do not present science frameworks as such, but provide rationales that underpin the overall aims and objectives of the Science curricula. Table 3.4 summarises the underpinning foci of the different curriculum frameworks / overall rationales.

Table 3.4.

Summary of Foci of Different Curriculum Frameworks

Curriculum	**Aust**	**Calif**	**Engl**	**HK**	**N. Irel**	**NZ**	**Ont**	**Scot**	**Swe**	**Singapore**	**Wales**
Science knowledge & skills	•	•	•	•	•	•	•	•	•	•	•
Technological understanding/ skills				•	•		•			•	•
Engineering process		•		•			•				•
Scientific Literacy	•			•			•	•		•	
Science education responding to local/ global issues	•	•		•		•	•		•	•	•
S/ ST role for future careers	•	•		•							
Processes of inquiry	•	•	•	•		•	•	•	•	•	•
Fostering curiosity	•		•	•			•	•	•	•	•

Overall, across the curriculum frameworks and rationales, some common themes emerge. Beyond the expected emphasis on developing subject knowledge and skills, there is focus on scientific literacy, the importance of science education in responding to local and global issues in ethical and socially responsible ways or through the lens of a 'global citizen' in just over half of the curricula. Some curricula focus on science (and technology) education and its role for future careers. Skills, questioning and the role of the scientific process of inquiry is a common feature and central to some of the curricula. Finally, fostering positive attitudes is a feature in some of the curricula. These are considered in greater depth in the next section.

Overall aims of the curricula

All of the science curricula had a section on aims. Some of these were presented as broad learning outcomes while others used the aims section to provide a rationale for the teaching of science. Table 3.6 summarises the broad aims of the 11 curricula.

Table 3.6

Summary of Broad Aims of Curricula

Overall Aims	**Aust**	**Calif**	**Engl**	**HK**	**N. Irel**	**NZ**	**Ont**	**Scot**	**Swe**	**Singapore**	**Wales**
Understanding science concepts	•	•	•	•	•	•	•	•	•	•	•
Developing science skills	•	•	•	•	•	•	•	•	•	•	•
Application of scientific knowledge	•	•	•	•		•	•	•	•	•	•
Problem solving, critical thinking, creative thinking	•	•		•		•	•	•	•		•
Develop and apply technological knowledge and skills		•		•			•				•
Interest in science	•			•				•	•		
Scientific literacy				•			•	•			
Developing values and attitudes				•						•	

All of the science curricula aimed to develop students' **scientific content knowledge.** With the exception of Northern Ireland[1] all curriculum documents also emphasise the importance of developing **students' scientific skills.** The application of scientific knowledge and skills to both society and to daily lives emerged as a broad aim in all but the Northern Ireland curricula. The importance of using scientific knowledge and skills to (i) make informed decisions about local and global issues; (ii) recognise science's contribution to society or (iii) consider the application of science to our daily lives were identified as broad aims. The development and application of students' technological knowledge and skills is emphasised in Wales and Ontario, both of which offer integrated Science and Technology curricula. The Hong Kong Science curriculum highlights the importance of contributing to a scientific and technological world but does not explicitly mention the development of technological knowledge and/or skills in their curricular aims.

[1]The World Around Us statutory requirements were published in 2007 and these are what have been included for the curriculum content analysis. However, in 2018 progression guidelines were published to support the implementation that include guidelines on skill application and development. The progression guidelines were not included in the curriculum content analysis.

Developing students' understanding of the **processes of science** was another key theme. This theme relates to understanding the **Nature of Science** and the practices/methods used to develop scientific knowledge. The Australian curriculum aims to develop students' understanding of "the practices used to develop scientific knowledge" (p. 4), and this is echoed in the New Zealand curriculum. The England, California and Hong Kong Science curricula all emphasise developing understandings of the processes of science in their overall aims.

Problem solving, critical thinking and creative thinking emerged as themes explicitly mentioned in a number of the curricula aims. The Australian, Welsh and Swedish curricula aim to develop students' critical thinking skills, with the Australian curriculum also emphasising creative thinking. The New Zealand, Californian and Scottish Science curricula highlight the importance of developing children's problem-solving skills. The Ontario Science and Technology curriculum aims to develop all three skills: problem solving, critical thinking and creative thinking.

Values and Attitudes were identified as a theme in the Hong Kong and Singapore Science curricula. The Singapore curriculum emphasises the importance of "developing skills, habits or minds and attitudes necessary for scientific inquiry" (Ministry of Education, Singapore, p. 5, 2013). Hong Kong takes a holistic perspective highlighting the need for positive values and attitudes towards science to contribute to a scientific and technological world. The importance of developing children's interest in science is noted in the Australia, Scotland, Hong Kong and Sweden aims.

Holbrook and Rannikmae (2007; 2009) and others (Dillon, 2009; Hodson, 2010; Roberts, 2007) note divergent views on **scientific literacy**: a) advocacy of knowledge of science as central b) scientific literacy as societally useful and c) advocacy for global citizenship and socio-ecojustice. Roberts (2007) presented two visions of scientific literacy: Vision I scientific literacy focuses on decontextualized science subject knowledge and preparation for careers in science; Vision II scientific literacy connects science to students' everyday perspectives and develops their ability to make decisions on societal and environmental issues as informed, active citizens (Haglund & Hultén, 2017; Osborne, 2012; Roberts, 2007). In recent years, researchers have proposed an additional vision, Vision III, which moves beyond preparing individuals for participation in society towards a politicised science education aimed at dialogic emancipation, critical global citizenship, and socio-ecojustice in which controversial, relevant issues become the curriculum drivers (Hodson, 2003; Sjöström & Eilks, 2018). Using the different visions as a lens, the 11 curricular aims can be considered in terms of the vision of scientific literacy they propose – see Table 3.7 for this summary.

Table 3.7

Summary of Aims in Relation to Visions I, II, III

Overall Aims	**Aust**	**Calif**	**Engl**	**HK**	**N.Irel**	**NZ**	**Ont**	**Scot**	**Swe**	**Singapore**	**Wales**
Vision I	•	•	•	•	•		•	•	•	•	•
Vision II	•	•		•		•	•	•	•		•
Vision III	•*										•

*Limited action component

Underpinning Methodologies/Pedagogies

A number of themes emerged across the 11 curricula in terms of underpinning methodologies/pedagogies. Nine curricula had specific detail on methodologies/pedagogies while key methodologies emerged as themes from the other two curricula based on an analysis of curriculum aims and content. The Singapore curriculum presents comprehensive detail of teaching and learning through inquiry including a description of the characteristics of scientific inquiry, inquiry-based teaching strategies and an overview of alternative conceptions associated with the teaching of science through inquiry (pp. 13-17). In contrast, the Swedish curriculum has no specific section on pedagogies, but underpinning pedagogies can be inferred from statements like "through teaching pupils should also develop an understanding that statements can be tested and evaluated using scientific methods" (p. 168). General pedagogies supporting an entire country's curriculum (e.g. all subjects) were excluded from this content analysis. See Table 3.8 for an overview of the pedagogies underpinning the 11 curricula.

Table 3.8

Summary of Pedagogies Underpinning Curricula

Pedagogies	**Aust**	**Calif**	**Engl**	**HK**	**N. Irel**	**NZ**	**Ont**	**Scot**	**Swe**	**Singapore**	**Wales**
Scientific inquiry & investigation	•	•	•	•		•		•	•	•	•
Social constructivist principles	•	•	•	•	•	•	•	•	•	•	•
Conducting research	•		•	•			•	•			
Engineering design process / Design & Make		•		•			•				•
Problem based learning	•	•		•					•	•	
Application of coding and computational thinking		•		•			•				•
Using the environment								•		•	•
Integration		•		•	•		•	•			•
Arts and movement				•						•	
Argumentation	•	•							•		

Scientific inquiry and investigation was identified as an underpinning pedagogy in 9/11 curricula. These nine countries presented scientific inquiry and scientific investigation in similar ways with nuances in the scientific process or skills identified. For example, the Californian Science Standards emphasise that questions or problems should be student- generated, and then guide teaching and learning. In contrast, the Singapore curriculum advocates both teacher directed and student led scientific inquiries. The Australia and Ontario curricula also identify the experimentation process in addition to scientific inquiry, thereby demarcating the two. These countries state that experimentation involves students investigating to test and validate or reject a hypothesis. It often involves the use of fair test investigations where students control and manipulate variables.

The Engineering Design Process and Design and Make process were considered under one theme. The Engineering Design Process (EDP) involves a series of steps that engineers follow to find a solution to a problem. Similarly, Design and Make enables children to apply their scientific knowledge and understanding to devise a method or solution, carry it out practically and evaluate the final product (DES, 1999, p. 8). In the Welsh Science and Technology curriculum 'Design thinking and Engineering' as 'technical and creative ways to meet society's needs and wants' is one of the six underpinning principles that emphasise the importance of providing learners with opportunities to apply their experiences, skills and knowledge to design and shape innovative engineered solutions. Similarly, the Ontario curriculum has the EDP under the strand STEM Skills and Connections, with an Engineer Design Process framework for students and teachers as they plan and build solutions to problems. The Ontario curriculum also highlights the role of technology where students may develop a computer simulation or model as part of their design solutions. The Australian curriculum refers to design as "to plan and evaluate the construction of a product or process including an investigation" (p. 89). However, there are only two references to design in the learning outcomes, e.g. "investigating the development of vehicles over time, including the application of science to contemporary designs of solar powered vehicles" (p. 64).

Constructivist principles, while not explicitly stated, emerged as an overarching theme. New Zealand, Scotland and Hong Kong's emphasis on connecting students' learning to their prior experience is a core principle of constructivist approaches to the teaching of primary science (Cakir, 2008; Harlen & Qualter, 2018). Social constructivist principles were seen in these countries' science curriculum guidelines in the advocacy of opportunities to work collaboratively and share learning experiences.

The Singapore Science curriculum and Californian Science Standards advocate the pedagogical use of concept cartoons and/or concept maps, maps representing a person's structural knowledge about certain concepts or subjects, with crucial terms related by explanatory links of relationships between concepts (Van Zele, Lenaerts, & Wieme, 2004). Developed by Keogh and Naylor (1991) as a strategy to elicit/challenge learners' ideas and provide opportunities to investigate their ideas, concept cartoons can both elicit prior knowledge and assess developments of knowledge at the end of a lesson or unit of work. The importance of providing students with **practical experience and engaging in hands-on** practical science-based activities also emerged as a key theme. Harlen and Qualter (2018) highlight this as a key component of constructivism. Six countries: England, Hong Kong, Ontario, Wales, Singapore and Sweden indicated hands-on practical science-based activities as a pedagogical feature of their Science/Science and Technology curriculum.

Problem Based Learning emerged in five curricula (Australia, California, Hong Kong, Sweden and Singapore). In problem-based learning, the problem is the stimulus and context for learning (Pease & Kuhn, 2010). It typically involves students working collaboratively in groups to contemplate the problem, identify what they need to learn to achieve the solution and work towards this goal (Pease & Kuhn, 2010). The Singapore curriculum supports a process where students analyse a problem, choose an innovative and relevant solution in order to remedy or alter the problem situation. The California Science standards include development of students' problem-solving skills in their overall curriculum aim. The Hong Kong curriculum emphasises helping students acquire, integrate and apply knowledge and skills to real-life problems and enhance the ability to meet contemporary science and technology challenges.

Research as a pedagogical approach emerged in five countries (Australia, England, Hong Kong, Ontario and Scotland). In the Hong Kong curriculum, students must demonstrate the process of researching and analysing information, and construct research proposals and research projects. The Australian curriculum interprets research as linked to society: "scientific research is itself influenced by the needs and priorities of society" (p. 8) and includes a focus on History of Science where students explore the past work of scientists, e.g., Galileo, through research. The Ontario curriculum presents research as a key curriculum aim where students should use research to help find solutions to complex problems in their own lives and communities. The Scientific Research Process is described as a key pedagogy for students to find, analyse and evaluate appropriate information. The Scottish and English curricula refer to research within developing students' ability to answer inquiry questions.

Application of **coding and computational thinking** emerged as a pedagogy in the Science and Technology curricula of Ontario and Wales. Computation as the 'foundation for our digital world' is one of the key principles underpinning the Welsh curriculum, which describes the importance of students learning how digital technologies work and how they can be used to solve a wide range of real-world problems. The social and ethical consequences associated with the use of technology are also explored so that students can make informed decisions about the future development and application of technology, with detailed descriptions of learning in this strand. The Ontario Science and Technology curriculum includes Coding Concepts and Skills under the STEM skills and connection strand. It too includes a strong focus on computational thinking and coding, and opportunities for students to critically assess the impact of coding and emerging technologies on their own lives and lives of others.

Using the **environment as** a pedagogy emerged in three curricula, Scotland, Singapore and Wales. The Singapore curriculum encourages teachers to use field trips, as one of 16 strategies that facilitate the inquiry process. The exploration and experience of the world through fieldwork and outdoor environments is a core pedagogical principle of the Welsh curriculum and deemed crucial to: 'help build learners' understanding of different environmental issues and help to demonstrate care, responsibility, concern and respect for all living things and the environment in which we live'. Similarly, the Scotland curriculum describes how teachers should 'take advantage of opportunities for study in the local, natural and built environments, as an opportunity to deepen their knowledge and understanding of the big ideas of the sciences'.

Art and movement based pedagogies such as games, stories, role play, drama, dance and movement were mentioned in two curriculum documents, Singapore and Hong Kong. Singapore included these strategies for supporting teachers with the inquiry process. Hong Kong, where Science is integrated under general studies, highlights the importance of integration with other curricular areas including Arts education and Physical education.

Argumentation emerged as a theme in the California Science Standards and the Australia and Sweden curricula referring to this as a pedagogy. Argumentation is the process of coordinating evidence and theory to support or refute an explanatory conclusion, model or prediction (Erduran, Ozdem, & Park, 2015). The Californian standards have Engaging in Argument from Evidence as one of eight science and engineering practice standards, and emphasise engaging in scientific argumentation to experience authentic science practice and develop critical thinking skills. The teacher's role in supporting scientific argumentation is also presented. Distinguishing between an opinion and evidence, and recognising flawed arguments are highlighted, alongside listening skills and constructing counter-arguments. The Swedish curriculum also refers to providing pupils opportunities to develop knowledge and tools for expressing arguments and examining arguments of others in ways which carry the discussion forward, but pedagogical support for teachers is not provided in the Swedish curriculum. The Australia curriculum situates the development of evidence-based arguments within science inquiry skills.

Predictably, both Northern Ireland and Hong Kong (where science curricula are integrated with other subject areas) emphasise the importance **of integration.** The Californian, Ontario Welsh and Scottish curricula also include integration as a pedagogy in their curriculum documents. The Californian standards emphasise the importance of a coherent integrated curriculum presenting examples of integration across mathematics and literacy. The Welsh curriculum highlights key links with other curriculum areas to take into consideration when planning science and technology learning experiences.

Learning Outcomes / Content in Curriculum

All 11 curricula identified the development of students' science conceptual knowledge as a key learning outcome, and referred to **Biological, Chemical and Physical** science content. Seven curricula specifically identified **environmental-related knowledge**, including climate change education and education for sustainability. Developing students' **earth science / geoscience** knowledge or knowledge about the earth's systems was included as content in six of the curriculum documents, while six curricula included content specifically related to **Space and the solar system.**

With the exception of the Northern Ireland *World Around Us* curriculum document, all countries have explicit learning outcomes related to developing students' **science skills, science process skills or inquiry skills.** Some curricula make reference to all three.

Developing students' understanding of the **Nature of Science** including students' understanding of the knowledge and epistemology of science emerged as a key theme in three countries: Australia, California and New Zealand. The Australian Science curriculum has a strand Science as a Human Endeavour which encompasses the units 'Nature and development of science'. Similarly, the New Zealand Science curriculum has a 'Nature of Science' strand which aims to develop students' understanding about science, investigating science, communicating science and participating and contributing.

Problem-solving and decision-making learning outcomes emerged in four countries: California, Ontario, Scotland and Wales. In the Ontario curriculum there are a limited number of specific expectations related to problem solving. The Scottish curriculum refers to the development of students' problem solving competencies across the curriculum. The Welsh

Science and Technology curriculum makes explicit reference to developing students' ability to solve problems in the Progressional Steps, e.g., under Design Thinking and Engineering, students are provided with opportunities to tackle challenging problems independently and collaboratively to address design requirements in unfamiliar contexts. There is also reference to decision making under this strand in the knowledge and skills required to refine design decisions and produce purposeful outcomes.

Four curricula include learning outcomes related to students' **Design and Make/ Engineering/Design thinking or Design and Technology skills**. The Welsh curriculum includes Design Thinking and Engineering as one of six core learning statements. The Ontario Science and Technology curriculum expects students to use an engineer design process and associated skills to design, build and test devices, models, structures and systems. There is also reference to coding and emerging technologies during the design process.

3.4.2 Implementation of Curriculum

Insight into implementation of the 11 curricula was gained through a review of National/ State reports/evaluations and research articles. Keywords for each curriculum were inserted into ebscohost and google scholar (see Table 3.9 for the keywords searched for each curriculum).

Table 3.9

Keywords for Literature Search on Primary Science Curriculum Implementation

Country / State	***Key Words***
Scotland	CfE. Curriculum for Excellence. Primary Science in CfE, Curriculum review of primary science, Primary science in CfE review of implementation.
Northern Ireland	The World Around Us review, Primary science in World Around us Implementation, primary science and technology review, primary science and technology implementation
Wales	Wales Primary science curriculum, Inspectorate, review of Welsh primary science curriculum,
England	England Primary Science Curriculum, review of Primary science curriculum England, OFSTED
Australia	Australia Primary science curriculum, evaluation of primary science curriculum in Australia implementation of primary science curriculum,
New Zealand	New Zealand Primary science curriculum, evaluation of New Zealand primary curriculum; science, implementation of primary science curriculum in New Zealand
California	California Next Generation Science Standard (NGSS) Implementation, NGSS review, NGSS curriculum implementation
Ontario	Ontario science curriculum, evaluation of Ontario primary curriculum; science, implementation of primary science curriculum in Ontario

Hong Kong	Hong Kong Primary science curriculum, evaluation of Hong Kong primary curriculum; science, implementation of primary science curriculum in Hong Kong
Singapore	Singapore Primary science curriculum, evaluation of Singapore primary curriculum; science, implementation of primary science curriculum in Singapore
Sweden	Swedish Primary science curriculum, evaluation of Swedish primary curriculum; science, implementation of primary science curriculum in Sweden

The search revealed no published national/ state reports, evaluations or research articles (written in English) on primary science curriculum implementation for Ontario, Hong Kong, Singapore or Sweden. In addition to searches for relevant reports /articles, the research team also emailed academics in Ontario and Sweden for any unpublished reports/ articles on primary science curriculum implementation. These correspondences confirmed no reports/ articles on implementation for these countries' primary science curricula. For the remaining seven countries, the extent to which national reviews or evaluations of implementation of primary science curricula had been undertaken varied in scope.

Australia

No national evaluation of the Australian curriculum was conducted prior to June 2020 when Australia's education ministers tasked ACARA to undertake a review of the Australian Science Curriculum from Foundation to Year 10 to ensure that it was still meeting the needs of students and providing clear guidance on what teachers need to teach, and to refine, realign and declutter the content of the curriculum within its existing structure. The review examined the existing three dimensions of the Australian Curriculum. There was strong support for the proposals for changes and refinements to the introductory rationale and aims and the year level descriptions, the inclusion of inquiry questions and revised content descriptions. However, of respondents who provided specific feedback on the introductory elements of the curriculum, the majority asserted that further refinements were needed to the strands / sub- strands and core concepts and some indicated that further review of the content descriptions was needed in order to remove any ambiguity and to provide better guidance to teachers about what to teach. Some stakeholders asserted that there was further scope to reduce content and some voiced concerns about the resequencing of content in some year levels to be more age appropriate (ACARA, 2021).

California

Following the 2013 adoption in California of the Next Generation Science Standards (NGSS) in K–12 schools, in 2018, the Policy Institute of California published findings from a survey conducted at the end of the 2016–2017 academic year on districts' implementation of the new standards. The findings revealed that implementation of the standards was uneven. While the majority of respondents were either very familiar (60%) or somewhat familiar (31%) with the NGSS, 25% of respondents in low-performance districts were only slightly familiar with the new standards. Seventy-eight percent of districts reported that they were implementing the new standards, with substantially higher percentages (94%) of urban districts reporting this. Instructional materials, science labs and equipment, teacher shortage, and teacher education presented big challenges. The state of California was scheduled to adopt textbooks and other instructional materials in 2018. However, at the time the survey was administered (Spring 2017), over half (59%) of districts reported instructional materials as a big challenge.

Furthermore, about 25% of districts reported not having sufficient credentialed science teachers, and more than 70% of districts faced challenges in teacher education.

England

Two relevant reports related to primary science curriculum implementation in England are presented here. The first report by Bianchi, Whittaker, and Pool (2021) presented findings from a targeted survey to a range of primary science specialist stakeholders (n=72) to identify issues impacting on children's learning experiences within primary science in England. They noted a dwindling profile of primary science in primary schools with science frequently taught for fewer than the recommended hours, and referencing research pointing to a frequent lack of confidence and skills in science, leading to a lack of coherence in the sequencing of the curriculum resulting in children's misconceptions being left uncorrected (Wellcome Trust, 2017; 2020; Ofsted, 2021). Bianchi et al. (2021) identified a number of shortcomings in the learning and teaching of science which included, superficial learning, an over-reliance on teacher direction, limited building on prior learning, and prescriptive practical work.

Bianchi and colleagues (2021) put forward two recommendations and encouraged further exploration into primary children's experience of science in schools in England. The first recommendation was that children's experiences of learning science in school should continue to be monitored and that this should occur via a regular programme of school reviews to examine issues that appear to be impacting children's learning in science. They also recommended annual engagement with stakeholders in primary science to discuss and consider emergent issues and to work collaboratively to mitigate them (Bianchi et al., 2021).

A second report was Ofsted's 2021 review of literature to identify factors contributing to high-quality school science curricula, assessment, pedagogy and systems. The report used this understanding of subject quality to examine science teaching in England's schools. The report noted that earlier concerns about science being squeezed out of the primary school curriculum coincided with an assessment-led dominant focus on English and mathematics, (Wellcome Trust, 2017; Ofsted, 2019). Ofsted (2021) cited Wellcome Trust 2020 reporting on primary science education that found an average of 1 hour 24 minutes per week of science teaching in the UK, with younger children receiving fewer weekly hours than older children.

The Ofsted (2021) report identified three general principles for effective teaching and learning in science. Firstly, high-quality science education should be rooted in an authentic understanding of what science is. Secondly, science education should prioritise pupils building knowledge of key concepts in a meaningful way that reflects how knowledge is organised in the scientific disciplines. Thirdly, for a science education to be of high-quality, science curricula should be planned to take account of the function of knowledge in relation to future learning. Further, to ensure the implementation of high-quality science education, teachers and subject leaders require in-depth knowledge of science and how to teach it and an understanding of how pupils learn. Supporting teachers in developing good PCK in science is therefore essential for high-quality science education.

New Zealand

In 2012 the Education Review Office (ERO) in New Zealand evaluated the quality of science teaching and learning, its place within the curriculum and its relationship to literacy and numeracy teaching in Years 5 to 8 in 100 New Zealand primary schools. The findings revealed that effective science teaching and learning in Years 5 to 8 was evident in less than a third of the 100 schools. The quality of leadership was a significant contributor to the quality of science teaching and learning. In schools where effective science teaching and learning was observed, principals and lead teachers actively promoted science programmes of learning that ensured students learned concepts from all strands of the science curriculum and lessons regularly focused on the Nature of Science strand, with particular emphasis on the process of investigation and the language of science. In these schools there was also evidence of carefully designed science programmes that provided opportunities for students to investigate, understand, explain and apply their learning in meaningful and relevant contexts. Effective science teachers were able to adopt inquiry-based approaches in science, facilitated their students in directing their own learning and their students demonstrated an ability to confidently discuss their science learning using appropriate scientific language. In effective primary school science programmes, teachers effectively integrated science teaching and learning with literacy and mathematics. However, it was apparent that few principals and teachers demonstrated an understanding of how they could integrate the National Standards in reading, writing and mathematics into their science lessons (ERO, 2012).

In schools where the teaching of science was largely less effective, principals gave science a low priority. These schools struggled to maintain a balance between effective literacy and numeracy teaching, and providing sufficient time for teaching science. An integrated approach resulted in the science learning being lost. Students attending these schools did not have access to the science curriculum knowledge strands, and the overarching Nature of Science strand. In these schools, content-based science lessons dominated over more interactive, hands- on reflective approaches to learning science. Science programmes in the less effective schools lacked coherence and continuity, teachers frequently taught stand-alone lessons that were not clearly linked to the science curriculum and the frequency of student engagement in hands-on experimental work varied. Teachers in many schools lacked knowledge and understanding of the science curriculum requirements, and of effective science teaching. Many teachers were not confident or well prepared for teaching science, and had limited ongoing professional learning development opportunities in science (ERO, 2012).

Northern Ireland

While there is little research on the impact of Northern Ireland's *World Around Us* (WAU) curriculum on the teaching of science, two 2014 reports provide insights into the teaching and learning of primary science in the WAU curriculum. The first report - a briefing paper written by James Stewart for the Northern Ireland Assembly - noted concerns about the less stringent statutory requirements on content coverage in the WAU, and the option opened for less confident teachers to reduce the amount /type of science taught (Stewart, 2014). Second, the ETI Northern Ireland evaluated the implementation of the WAU in primary schools. While this was a relatively small-scale study with a low response rate it yielded some interesting findings. Of the lessons the inspectors observed over half were science and technology and the quality of most (86%) of the teaching and learning of science and technology was rated good or better and over half of the lessons evaluated were rated very good or outstanding. The majority of schools in the survey connected children's science learning with the development of literacy, numeracy, information and communication technology (ICT), thinking skills and personal capabilities. General consensus amongst schools on the importance of providing meaningful contexts in the WAU to develop children's core skills was reported. There was some evidence of effective questioning and quality interactions that established children's knowledge and deepened understanding, and of children engaging in inquiry-based approaches and leading their own inquiries (ETI, 2014)

On the concerns side, while almost all responding schools reported that teachers had sufficient skills and knowledge to teach the history and geography strands, only 67% believed they had adequate skills and knowledge to confidently implement the science and technology strand. On the web-survey only 46% of the schools agreed that their WAU programme ensured sufficient emphasis on science and technology teaching and learning. In schools with a less well-developed science and technology strand of WAU, the reasons provided included: the continued focus on raising standards in literacy and numeracy; emphasis on assessment; lack of access to relevant training and professional learning programmes; and insufficient access to essential resources to support children's engagement in the practical elements of science.

The ETI recommendations for different stakeholders included: the Department of Education should encourage and support full implementation of the science and technology strand of WAU in primary schools and re-emphasise the importance of WAU, with particular focus on science and technology in policy and planning for initial teacher education; the Council for the Curriculum, Examinations & Assessment (CCEA) should provide more detailed guidance on the development of the discrete concepts, skills and knowledge within the science and technology strands to support schools to plan for continuity and progression in children's learning; schools and school coordinators should: ensure this progression; plan the WAU programme and the use of the available time to connect children's developing skills and knowledge in a range of meaningful contexts; make WAU, particularly the science and technology strand, more investigative and inquiry-based and emphasise its place in everyday life, including careers and the world of work (ETI, 2014)

Scotland

In 2021 the Scottish Government invited the OECD to assess the implementation of CfE. While the OECD reported the ongoing relevance of the CfE's main vision and objectives to the Education 2030 vision of the OECD, no information on implementation of the science curriculum was provided in this report and no other national data on implementation of the science curriculum was published.

One article, by Day and Bryce (2013), emerged from the literature search. These authors noted that the experiences and outcomes in the CfE have been criticised by many science teachers as being too vague and so wide ranging that their interpretation by different interest groups leads to differing emphases, and warned that consistency in pupils' experiences could be compromised in different schools' interpretations and implementations of the curriculum. The lack of definition of scientific literacy and pedagogies to achieve scientific literacy in the CfE was also criticised. They argued that curriculum planners needed to define intended purposes for the science curriculum, and offer guidance on how to assess scientific literacy in a valid and reliable manner (Day & Bryce, 2013).

Wales

A 2017 Estyn (Education and training inspectorate for Wales) report focused on standards, provision and leadership in the previous National Curriculum subjects of Science (Welsh Government, 2008a) and Design and Technology (Welsh Government, 2008b) at key stage 2 in primary schools in Wales (Estyn, 2017). Inspectors observed primary science and technology lessons, interviewed pupils, teachers and school leaders, inspected planning and pupils' work, and took primary school inspection evidence into account in their report. Findings revealed that by the end of key stage 2 many pupils had developed a good understanding of basic science concepts and of the nature of science. Girls' and boys' achievements in science were similar, and virtually all students engaged in science lessons enthusiastically. Many pupils showed an ability to explain their enquiries, predictions and results using scientific terminology. A minority did not explain reasons for their conclusions well and did not have a robust understanding of the relevant underlying scientific principles or concepts. When presenting results, high percentages of pupils (and some teachers) did not know which chart to use for representing different types of data. A wide attainment gap in science between pupils eligible for free school meals and their peers at the end of key stage 2 was reported with this gap continuing to grow subsequently (Estyn, 2017).

Most Welsh schools had robust plans to ensure access to a broad and balanced science curriculum. While many schools allocated a suitable amount of time to teach science, a few had not implemented the two hours per week recommendation. The findings also revealed that when schools' science curriculum policy was unclear, leaving individual teachers with open choice in deciding how often pupils carry out investigative work, pupils in different classes had inconsistent opportunities to develop investigative skills. While high quality science teaching was evident in many schools, a minority did not adequately challenge the more able pupils. The report recommended science lessons that challenge all pupils and self-evaluation processes that focus on pupils' content knowledge, understanding and skills and on the quality of teaching. Adequate professional learning opportunities to support competent and confident implementation of the science curriculum were also recommended (Estyn, 2017)

3.4.3 Summary

Although the evidence base on implementation of science curricula is limited, in these jurisdictions there is evidence of good or high-quality primary science lessons, of teachers challenging children's prior science conceptions, and relating science content to children's interests and daily lives. It is also evident that primary science teaching and learning is most effective when there are strong science leaders in schools and when teachers engage in effective professional learning programmes. The evidence shows that primary aged children enjoy and are enthusiastic about primary science, and that many develop good understanding of science concepts and applying a range of scientific skills appropriately. Furthermore, there is some evidence to suggest that children are engaging in inquiry-based activities and are afforded opportunities to direct their own learning. Importantly in relation to later gender disparities, achievement in primary science is similar amongst boys and girls.

However, it is also evident that primary science faces a number of challenges. First, the dearth of studies that examine implementation of primary science curricula is, in itself, problematic and revealing. Second, primary teachers in all jurisdictions tend to lack confidence and competence in teaching science, leading to many teachers not teaching the requisite amount of science as per National / State guidelines. It is also clear that teachers' lack of competence in science leads to children holding on to inaccurate science conceptions. Where science is not a core subject (e.g. England), and in some cases where science is integrated with other subject areas (e.g. Northern Ireland), primary teachers are not prioritising teaching science or are putting aside science concepts, skills and knowledge. There is broad evidence that hands-on science activities tend to be more teacher directed. Across several countries, professional learning opportunities in science for primary teachers are described as limited.

Recommendations include professional learning opportunities that support teachers to develop an in-depth knowledge of science, how to teach science and of how pupils learn. This ensures teachers are confident and competent to implement curricula. On the policy side, science curriculum policy should be clear and curriculum documents need to provide succinct accounts of the overall aims, content and methodologies to effectively implement curricula, and offer precise curricular specifications. If scientific literacy is an overarching aim, clear definitions of scientific literacy in the context of science curricula need to be provided. Whole school approaches to effective science teaching and learning are helpful. Government and ministries therefore should encourage and support the full implementation of the science curricula and re-emphasise the importance of science in policy and planning for initial teacher education.

3.5 Systematic Literature Review: Methodology

A systematic approach was undertaken to identify relevant research literature in response to the research questions guiding this report:

1. **What** are the desired curriculum processes and essential curriculum content (knowledge, skills, values and dispositions) for children's learning and development in Science (including design & make applications) within the broad primary curriculum?

2. **How** should children learn in primary science education?

The review adhered to the recommendations outlined in the Preferred Reporting Items for Systematic reviews and Meta- Analysis (PRISMA) Statement (Page et al., 2021). A targeted systematic approach to identifying relevant research studies was conducted. To do this search criteria were developed (see table 3.10) and inserted into three indexed databases in January 2023; Web of Science, Academic Search Complete and Education Research Complete. Based on the research questions, the relevant studies were identified as primary or elementary school based science education interventions which gathered data on children's learning in science including knowledge, skills, values or dispositions. Both quantitative and qualitative studies that gathered empirical data were included. Studies that focused on teachers only, in-service or pre-service, were not included in the study. However, studies which looked at the impact of pre-service or in-service teachers' science teaching on children's learning were included. Table 3.10 presents an overview of the search criteria that were applied.

Table 3.10.

Overview of the Search Criteria

Concept 1	Concept 2	Concept 3
TI (primary or elementary or junior or "key stage 1" or "key stage 2" Or Middle OR "early childhood") OR AB (primary or elementary or junior or "key stage 1" or "key stage 2" Or Middle OR "early childhood") OR KW (primary or elementary or junior or "key stage 1" or "key stage 2" Or Middle OR "early childhood"	TI ("science education" or "science teaching" or "science learning" or "science instruction" OR scientific) OR AB ("science education" or "science teaching" or "science learning" or "science instruction" OR scientific) OR KW ("science education" or "science teaching" or "science learning" or "science instruction" OR scientific)	TI (pupil* OR student* OR learner* OR children OR kids OR youth OR child) OR AB (pupil* OR student* OR learner* OR children OR kids OR youth OR child) OR KW (pupil* OR student* OR learner* OR children OR kids OR youth OR child)

NOT TI ("student teacher*" OR "pre service teacher*" OR "teacher candidate*" OR "initial teacher education") NOT AB ("student teacher*" OR "pre service teacher*" OR "teacher candidate*" OR "initial teacher education") NOT KW ("student teacher*" OR "pre service teacher*" OR "teacher candidate*" OR "initial teacher education")

To provide an example of how these criteria were applied, a paper had to include a concept from Concept 1, Concept 2 and Concept 3 in either the Title (T), Key Words (KW) or Abstract (A). Papers that were not available in English were excluded. Only peer reviewed academic articles that were published in the last 10 years were included. The NOT criteria (see above) was applied to eliminate studies that were only focused on in-service and preservice teachers. The search returned the following numbers of studies:

Table 3.11.

Number of Studies Identified for Data Abstraction

Database	**No. of studies identified**
Web of Science	1628
Education Research Complete	2956
Academic Search Complete	2396
Total	**4699** (2272 duplicates removed)

4699 studies were identified and uploaded to Covidence. Abstract screening was then conducted.

Abstract Screening

This phase involved screening the 4699 studies based on Title and Abstract. Table 3.12 presents the inclusion and exclusion criteria which were applied during this phase.

Table 3.12.

Inclusion and Exclusion Criteria

Criteria	**Inclusion Criteria**	**Exclusion Criteria**
Type of Research	Empirical Research	• Not empirical research • Unclear empirical research • Second hand or indirect research
Language	Published in English	Published in a language other than English without an English executive summary

Focus of study	• Focus of the study is an intervention for primary science education • Focus of study is STEM but explicitly addresses children's learning in science • Focus of study is engineering but explicitly addresses children's learning in science	• Focus of the study is something other than a primary science intervention • Focus of the study is a STEM intervention with ill-defined links to children's learning in science (content, skills, values, attitudes) • Study uses a science context but does not investigate children's learning in science • Focus of study is on the development of teachers' pedagogical content knowledge that *does not* include data on children's learning of science (content, skills, values, attitudes) • Descriptive units or modules to support science learning but that have not been evaluated to measure impact on children's learning in science
Age of participants	Study explicitly includes primary school-age students (i.e. 4–12 years of age and/or Kindergarten)	Study is for students older or younger than the specified age and year level range
Data	The study seeks to evaluate an intervention by measuring or exploring children's learning in science (content/ skills/values/ attitudes)	The study does not seek to evaluate an intervention through data collected

3290 studies were excluded based on one or more of the exclusion criteria presented above. Thus, 1409 studies articles were included in the Full Text Review.

Full text review

This was completed through a peer review process. Two reviewers reviewed each research article. If the reviewers agreed the article met the above inclusion criteria it was put through to the Full Text Review. In a similar manner, if the reviewers agreed that an article was not relevant, the article was removed from the screening process. If there was disagreement between the reviewers, the article remained in a 'conflict' section where an external reviewer reviewed the article and made a final decision. The inclusion and exclusion criteria for the Full Text Review can be found in table 3.12. It should be noted that some of the criteria from the Abstract Review (Table 3.12) are similar to the Full Text Review criteria (Table 3.13). If the reviewers were unclear of some criteria from the abstract, e.g. if the age of participants was not provided in the abstract, these studies were still included for Full Text Review. During the Full Text Review, the age of participants was provided in the main text which would then have resulted in the study being included/excluded. If it was unclear whether the study included data on children's learning in science from the Abstract, the study was put forward for Full Text Review. The Full Text Review then provided explicit details regarding the data gathered resulting in an informed decision being made as to whether or not the study should be included/excluded.

Table 3.13.

Full Text Review: Inclusion and Exclusion Criteria

Criteria	Inclusion Criteria	Exclusion Criteria
1. Journal Ranking	Journal - ranked in Scimago	Journal - Not ranked in Scimago
2. Access	Journal available via DCU library	Journal behind a paywall
3. Duplicates	Study is not a duplicate	Study is a duplicate
4. Age of participants	Age: 4 - 13 years	• <4yrs or >13yrs • Age unclear (e,g just says middle schools/ junior high) • If mixed 50% of sample must be > 4 yrs and < 13 yrs
5. Language	Available in English	Not available in English (abstract was available in English but not full text)
6. Research Aims	• Research aims / questions related specifically to science learning (content, skills, interest, attitudes, values) • Study in STEM if focus specifically on science learning • Study in Science and Engineering if focus on science learning	• Research aims / questions not related to children's learning in science • STEM intervention but not focussed on science • Engineering intervention not focused on science learning outcomes • Science used as a context but outcomes not focused on science learning
7. Research Setting	• Research carried out in a formal school setting. • Teacher was involved in the delivery of the intervention in a non-formal school setting • School initiative in a non-formal school setting	• Out of school projects • After school programmes / summer programme • Outreach centres where teacher / school not involved
8. Type of Intervention	• An intervention on children's learning	• The study does not evaluate an intervention by measuring or

		exploring students' learning in science (knowledge/skills/values/attitudes) • A survey / study on attitudes or opinions - or state of knowledge. This is not as a result of an intervention
9. Methodology	• Robust Methodology	• No Methodology • Unclear / no robust methodology • Methodology not suitable to address research questions • Data not collected on at least two separate occasions: No pre / post test OR Not multiple methods of data collection if examining intervention • In adequate reporting e.g. ○ *No context provided* ○ *Insufficient detail on sample* ○ *Poor analytical techniques* ○ *Lack of clarity*

Based on the criteria presented 737 studies were excluded. While a study could have been excluded based on a number of criteria, for the purpose of the Full Text Review only one criteria was selected (Covidence software only permits one exclusion criteria to be selected per study). This was completed in a hierarchical order whereby the reviewers started at Criteria 1 Journal Ranking and then made their way through the other criteria. If the article adhered to all nine inclusion criteria, it was put forward to the Extraction Phase.

Extraction phase

The next phase of the review involved extracting relevant data from each eligible study. For this phase, a table with a set of 'labels' was developed that guided the researchers in identifying what information was to be extracted from each study. These labels were:

- Author / Year / Location
- Description (including overview of intervention)
- Sample
- Study design / methodology
- Outcome / key findings
- Limitations
- Science content

- Pedagogy
- Main theme / focus

As the data were extracted and themes began to emerge, a number of 'tags' were applied to the studies to initiate the process of identifying the final themes for the narrative of the systematic review. Section 3.6 of this report provides an overview of these themes.

3.5.1 Limitations

While extensive and rigorous, this review, like other systematic reviews, has some limitations. First among these, we restricted our remit to articles that were published in the last 10 years. This meant that some older articles that have a seminal status in the field, and particularly in terms of 'best practices' underpinning effective primary science education were excluded. This limitation was addressed in part by our context-setting piece at the start of section 3, where we drew on these articles as important in their setting up of the groundwork of assumptions upon which much of the research of the last decade is premised.

Further limitations also relate to our delimiting of the scope of our search. Only articles available in English were included. The age was limited to children aged 4yrs - 13yrs. In studies that included children aged, for example 13, 14, 15, unless 50% of the sample were in the 4-13yr age profile, the study was excluded. This may have resulted in some relevant studies being excluded but was necessary for relevance to the Irish primary school context.

A number of studies were situated in international middle school contexts, some of which involve lessons taught by specialist science teachers rather than generalist teachers. Furthermore in some studies the experimental group was taught by the researcher. Both of these criteria somewhat restrict the application of findings to an Irish context of predominantly generalist primary science teaching. However, given that these studies frequently revealed the potential of science education interventions, we thought them important to include in the context of curriculum development that seeks to be ambitious in its vision for primary science, and useful in the detail that the studies offered on resources and professional development.

3.6 Findings from the Primary Science Learning: Systematic Literature Review

The systematic review methods outlined above revealed a large number of studies related to children's learning in primary science. After applying the inclusion and exclusion criteria a total of 250 studies were deemed eligible for inclusion in the review. General information on the characteristics of the studies selected was collected which included: year of publication, country in which the research was conducted, targeted age group and research design. Details of these are now presented.

Characteristics of Studies

As detailed in figure 3.8, 150 (60%) of the studies included in the review were published between 2018 and 2023 while 99 (40%) published between 2012 and 2017. This reflects the growing rates of international academic publication.

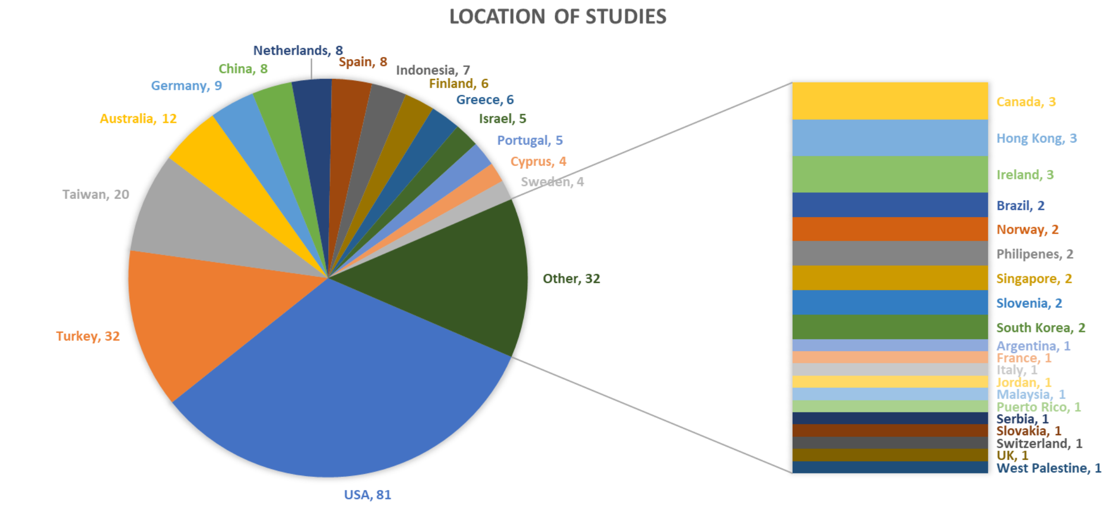
Figure 3.8.

Year of Publication of Studies

Overall the studies were located in 35 countries with USA, Turkey and Taiwan making up over half (133) of the studies (Figure 3.9).

Figure 3.9

Location of Studies



Most of the studies adopted either quasi-experimental or experimental designs with a smaller number of studies adopting exploratory case study approaches. All studies included an intervention and gathered data from children via pre/post questionnaires or surveys, interviews with children, focus groups, classroom observations and/or children's artefacts. The age of the participants ranged from 4 years to 13 years.

Predictably, the articles reviewed revealed a range of different themes related to learning in primary science. Some of these themes related to content children were engaging with (the 'what' of learning science), others related to pedagogies and/or tools teachers were implementing to support children's learning in science (the 'how' of learning science). In some cases the research had one main focus (e.g. learning of 'difficult' content in science) while others had a number of foci (e.g. using model-based learning to support the development of children's scientific knowledge and reasoning skills). Nine broad themes emerged from the analysis. The findings from the literature review and their implications for curriculum development are now presented under these themes.

3.6.1 Key themes

Theme 1: Scientific Literacy

In this section studies related to scientific literacy have been grouped into three sub-themes, Scientific literacy (SL), Nature of Science (NOS) and Socio Scientific Issues (SSIs).

Scientific Literacy

Nine articles that specifically focused on scientific literacy were identified in the SLR. Table 3.14 provides an overview of these.

Table 3.14

Overview of Studies with Scientific Literacy as a Theme

Author	**Location**	**Sample Size**	**Age Range**
Allison 2018	USA	20	10-11
Boaventura 2013	Portugal	136	9-10
Diez-Palomoar 2022	Spain	8	10
Fazio 2019	Canada	118	10-11
Pratama 2018	Indonesia	64	13-14
Vieira 2016	Portugal	22	11-12
Wahyu 2020	Indonesia	516	9-10
Qinarni 2021	Indonesia	36	9-10
Yuliana 2021	Indonesia	58	10-11

Three studies focused on the merging of multiliteracies, language and critical thinking skills in scientific literacy (Vieira & Tenreiro-Vieira, 2016; Allison & Goldston, 2018; Fazio & Gallagher, 2019). Multiliteracies refers to literacy in its various forms, including cultural and linguistic diversity (Allison & Goldston, 2018). Critical thinking (CT) is defined as deciding what to believe or do about a challenge and is an integral component of SL (Yore et al., 2007). All three studies pointed to expansions on the teaching and/or learning side. Allison and Goldston (2018), investigating the use of multiliteracies and its union with scientific literacy among fifth grade students found that science activities were enriched with multiliteracies and scientific practices, and students were engaged in their development of skills and knowledge. Fazio and Gallagher (2019) studied the way in which teachers integrated language within their science teaching, and illustrated impacts on fifth grade students' science achievement, vocabulary and language comprehension. Vieira and Tenreiro-Vieira's (2016) findings demonstrated improved levels of CT and SL among the sixth grade students in their study.

Two studies examined the promotion of scientific literacy through Dialogic Scientific Gatherings (DSG) and outdoor activities. DSGs are a type of evidence-based action which have previously been implemented with adults to successfully promote their SL. Diez-Palomar et al (2022), applying DSGs to promote SL among culturally diverse primary school children, found enhanced SL linked to analytical, critical thinking and social abilities and that DSGs have an impact on decision-making and participation in society which can be transferred to school-aged children (Buslón et al., 2020). Boaventura et al. (2013) investigated the promotion of SL with students through an outdoor activity conducted in a marine biology research laboratory. Students participated in the development of two experiments and completed a questionnaire based on the experiments and their conceptions about scientists and scientific work. Findings showed that students engaged in scientific activities including prediction, observation and explanation, though misinterpretations of experimental results were present, with engagement in this type of outdoor activity promoting meaningful learning in science.

Four studies explored the effect of different approaches/tools on SL. Pratama, Abdurrahman and Jalmo (2018) examined the effect of a Science-Technology-Society (STS) approach (which acknowledges the connections and contributions of these three aspects to knowledge) on students' SL of environmental pollution in a junior high school in Indonesia. They found that the STS approach increased students' SL levels. Two studies used Mobile Augmented Reality (MAR) tools (Saltan & Arslan, 2016; Wahyu, Suastra, Sadia & Suarni, 2020). Both these studies claimed improvements in students' achievement in science, with Wayhu et al also noting that MAR assisted STEM-based learning effectively increased students' SL. Similarly, Winarni, Hambali and Purwandari (2020) pointed to the use of ICT media significantly improving SL relating to the topic of ecology among elementary school students. The last study explored the effect of ethno-science themed picture books in context-based learning on fifth grade students' SL (Yuliana et al., 2021) and found them more effective in promoting SL than traditional teaching methods.

Implications for curriculum development

Three approaches are represented within the articles focused on SL: a focus on languages and multiliteracies; dialogic and outdoor working; and STS modes involving digital tools and resources. Across all three categories, there is evidence of the development of enhanced SL among students. It is important to note that whilst only nine studies explicitly stated that they focused on the development of scientific literacy, it could be inferred that all studies in the SLR focused on the development of specific scientific literacy competences. For instance, a large number of studies focused on the development of science content knowledge while other studies looked at the development of scientific skills, for instance inquiry, argumentation and reasoning. A substantial number of studies also looked at developing positive attitudes and interest in science. These are all considered essential components of scientific literacy.

Socio Scientific Issues

Eight studies in the SLR examined outcomes associated with Socio Scientific Issues (SSI) based interventions in a primary school context. Table 3.15 provides an overview.

Table 3.15

Overview of Studies with SSI as a Theme

Author	Location	Sample size	Age Range
Belland 2016	USA	69	12-13 yrs
Dawson 2022	Australia	52	12-13 yrs
Demir 2019	Turkey	17	10 yrs
Karkkainen 2017	Finland	36	9-12 yrs
Lin 2020	Taiwan	146	10-11 yrs
Nioclaou 2015	Cyprus	19	11-12 yrs
Xiao 2017	USA	49	11-12 yrs
Zangori 2020	USA	54	8-9 yrs

Four of the eight studies were situated in personally relevant local SSI contexts, reflecting Dawson and Venville's (2020) finding that personally relevant SSIs enhanced the relevance of school science and fostered student engagement. The 'issues' in focus ranged across: interpreting and evaluating the credibility of data related to the water quality of a local river (Belland et al, 2016); representations of local park landscapes (Karkkainen et al., 2017); self-reporting emotions about an SSI issue associated with their local lake (Nicolaou, Evagorou, & Lymbouridou, 2015). All four studies reported that the SSI context enhanced students' engagement in the science learning process.

Pedagogies associated with SSI-based interventions featured strongly within the eight studies. Two studies included scaffolding as a pedagogic strategy. Dawson and Venville (2020) used teacher scaffolding and whole class discussion; Belland and colleagues (2016) used computer-based scaffolding. Both pedagogies were found to be successful at enhancing student argumentation skills, a core feature of SSI-based education. Web search skills were highlighted by Lin et al. (2020) as important for changing students' scientific epistemological beliefs, but they noted the need to enhance students' searching evaluative standards as a research and educational priority. Zangori et al. (2020) found that engagement in a model-oriented issue-based teaching (MOIB) had significant impacts on students' use of knowledge when reasoning their positions on the SSI.

Implications for curriculum development

The studies in this cluster point to the opportunities that emerge in teaching science through SSIs, with the relevance of science enhanced and thus promoting student engagement with science. SSIs that were personally relevant to the students were particularly powerful in this regard. Effective pedagogies highlighted in these SSIs studies included whole class discussion, teacher scaffolding, technology based scaffolding, argumentation and modelling. There is evidence that SSIs have the potential to develop students' complex reasoning skills, argumentation skills, ability to evaluate and interpret data, thus supporting the students' development of scientific literacy competencies.

Nature of Science

In the review eight studies from five countries focussed on Nature of Science (NOS) pedagogy (see Table 3.16)

Table 3.16

Overview of Studies with Nature of Science as a Theme

Author	Location	Sample size	Age Range
Ackay 2015	Turkey	356	Middle school
Akerson 2014	USA	24	8-9 yrs
Bruner 2019	USA	185	9-11 yrs
Dickes 2019	USA	43	8-11 yrs
Forbes 2019	Australia	27	10-12 yrs
Kortam 2021	Israel	270	6-13 yrs
Murphy 2021	Ireland	459	6-12 yrs
Akaygun 2021	Turkey	68	11-12 yrs

All eight of these studies examined the impact of a NOS intervention on students' understanding of NOS but with slightly different nuances. Commonly, they highlighted the importance of holding good conceptions of NOS to support the development of students' scientific literacy, were underpinned by social constructivist theories, adopted inquiry-based methodologies and utilised explicit-reflective approaches to learning about NOS. They also revealed that following the interventions, students had developed more in-depth conceptualisations of different aspects of NOS and had developed more positive attitudes towards science. This suggests that the various explicit reflective methods used to teach about NOS and scientific inquiry were impactful in these regards.

It is also apparent that students' NOS inquiries enabled them to make greater links between school science and science and gain a greater understanding of the role and importance of science in society (Ackay, Behiye, Ackay, et al., 2015; Akerson et al., 2014; Bruner & Abd-El-Klhalick, 2019; Forbes & Skamp 2019; Murphy, Smith, & Broderick, 2021). Studies also reported positive correlations between students' developing NOS conceptions and engagement with scientific processes and improved scientific literacy, whereby students were bringing concepts and rules together and applying them to new situations (Ackay et al., 2015; Akerson et al., 2014; Murphy et al., 2021). Furthermore, engagement with more child-centred, explicit reflective NOS methodologies supported the development of creativity, critical thinking and problem solving skills (Ackay et al., 2015; Akerson et al., 2015; Murphy et al., 2021a).

Implications for curriculum development

Two important points emerge from this theme for curriculum development. First, these studies and their outcomes highlight the importance of using explicit reflective approaches to support students learning about NOS, rather than assuming children will learn about NOS as a by-product of 'doing' science in school. Second, in addition to developing their scientific process skills, opportunities for students to engage with inquiries specifically designed to learn about NOS enabled them to develop their critical thinking and problem-solving skills, thus supporting the development of students' scientific literacy, namely their ability to bring concepts and processes together and apply them to new situations.

If scientific literacy is a key overall aim of the STE curriculum, these studies suggest that learning outcomes and pedagogies explicitly geared to SSI and NOS are critical to include in the curriculum specifications. It is also recommended that explicit approaches to develop scientific literacy competencies are required in order to achieve the aims of a scientifically literate society.

Theme 2: Scientific Content

In this section studies have been grouped under three themes: Biological, Physical and Material world, Environmental Education and Assessment.

Biological, Physical and Material World

All of the articles in the SLR reported to some extent on the impact or effect of a particular intervention or initiative on the development of children's scientific conceptual knowledge or on students' engagement with scientific content. However, in 26 articles the development of children's scientific knowledge was a main focus. Table 3.17 provides an overview of the studies that had science content knowledge as a theme.

Table 3.17

Overview of Studies with Scientific Content Knowledge as a Theme

Author	Location	Science	Sample	Age
Berti 2017	Italy	Biological	89	8-9
Damerau 2022	Germany	Biological	35	8-9

DeAbreu-Carlan 2014	Brazil	Biological	65	12-13
Jesus-Leibovitz 2017	Portugal	Biological	164	7-9
McCormack 2014	Ireland	Biological, Physical, Material	1,460	11-12 & 13-14
Peppler 2020	USA	Biological	63	6-7
Ruiz-Gallardo 2018	Spain	Biological	199	7-8 & 11-12
Wünschmann 2017	Germany	Biological	65	8-10
Zangori 2014	USA	Biological	59	8-9
Fortus 2019	USA	Physical	418	12-13
Havu-Nuutinen 2018	Finland	Material	41	10-11
Maričić 2022	Serbia	Physical	80	9-10
Mason 2019	Italy	Physical	91	9-10
Minárechová 2016	Slovakia	Physical, Biological, Material	34	9-10
Pitts 2014	Australia	Physical	26	10-11
Schalk 2019	Switzerland	Physical	189	8-9
Sissamperi 2021	Greece	Physical	21	11-12
Abadan 2021	Turkey	Material	112	11-12 SLE
Haeusler 2020	Australia	Material	74	8-9
Peikos 2022	Greece	Material	60	11-12
RogayanJur 2020	Philippines	Material	47	11-12
Yilmaz 2019	Turkey	Physical Space	24	11-12
Peffer 2021	USA	Biological	80	6-12
Leuchter 2014	Germany	Physical	244	4-9
Akerblom 2019	Sweden	Physical	22	6
Weber 2020	Germany	Physical	183	5-6

Of the 26, 12 studies worked with content that typically features in post-primary science curricula rather than primary curricula. Several studies were underpinned by constructivist theories and adopted inquiry-based pedagogies (e.g. Adadan & Ataman, 2021; Jesus-Leibovitz et al., 2017; McCormack, Finlayson, & McCloughlin, 2014; Peikos, Spyrtou, Pnevmatikos, et al., 2022; Peppler, Thompson, Danish, et al., 2020; Rogayan Jr., & Macanas, 2020; Schalk, Edelsbrunner, Deiglmayr, et al., 2019; Sissamperi & Koliopoulos, 2021; Zangori & Forbes, 2014). These studies engaged students in structured inquiries that were aimed at supporting the development of children's conceptual knowledge and scientific process skills. Other studies (e.g. Bert, Barbetta, & Toneatti, 2017; Damerau et al., 2022; De Abreau Carlan et al., 2014; Fortus et al., 2019; Haseusler & Donovan, 2017; Havu-Nuutinen, Kärkkäinen, & Keinonen, 2018: Maričić, Cvjeticanin, & Andevski, 2022; Minárechová, 2016; Mason et al., 2019; Pitts, Venville, Blair, et al., 2014; Ruiz-Gallaro & Panos, 2018; Wünschmann et al., 2017) adopted more didactic approaches to teaching science, but did include opportunities for students to engage with hands-on activities.

Models for including access to more advanced content featured within this set of papers. For example, structured inquiries and computer simulations to support students in understanding the honeybee system by viewing it from third person perspectives (taking the perspective of an agent in a system e.g. a bee) and from a first-person perspective (exploring the system as a whole) were used in Peppler et al.'s (2020) US study. Play-based approaches were used with younger learners in Akerblom, Souckova, and Pramling (2019) and Weber, Reuter, and Leuchter's (2020) studies.

The majority of the 26 articles indicated some improvements in students' knowledge, process skills, understanding and reasoning. However, there were caveats. For example, De Abreau-Carlan et al. (2014) noted that while students who were taught about abstract topics related to cell biology showed some improvement in their conceptual understanding, topics like structures and functions of subcellular organelles remained difficult to teach in primary schools even when a range of concrete resources were used to support learning. Similarly, Zangori et al.'s 2014 study indicated that while the students had multiple and lengthy opportunities to engage in hands-on activities with seeds, fruit, and seed growth, a considerable majority did not show evidence of scientific explanations in their written work and did not indicate that they engaged in sense making about their investigations. Several studies acknowledged that some misconceptions remained amidst improvements.

Implications for curriculum development

Three important points emerge from this theme for curriculum development. First, these studies and their outcomes show that traditionally higher level content can be meaningfully introduced to primary level students, and taught and learned successfully, with evidence of longer term impact on knowledge and reasoning. Second, the studies offer examples and approaches for incorporation, with constructivist approaches predominating. Third, the evidence echoes the broader evidence in science education that even in the midst of learning, some misconceptions remain to be addressed in future experiences.

Environmental Education

Twenty-five studies focused on the environment emerged in the SLR. Table 3.18 provides an overview of these studies. Seventeen studies were situated in outdoor environments; ten examined environmental issues in classrooms and three in laboratory settings, with some studies situated across multiple contexts.

Table 3.18

Studies with Environment as a Theme

Author	Location	Sample	Age
Cheng 2019	Taiwan	50	9-10
Davies 2012	UK	450	9-10
Harris 2020	USA	217	11-12
Guilherme 2016	Portugal	49	7-9
Harris 2020	USA	3	8-9
Istiqomah 2021	Indonesia	121	9-10
Hashimoto-Martell, 2012	USA	39	11-13
Kos 2016	Slovenia	40	5-6
Lai 2018	Taiwan	24	10-11
Lombardi 2016	USA	85	12-13
Lombardi 2013	USA	169	12-13
Raab 2021	Germany	444	9-11
Schellinger 2017	USA	125	9-11
Silvia 2023	Portugal	42	12-13
Su 2015	Taiwan	102	10-11
Xiao 2017	USA	49	11-12
Zanogri 2015	USA	116	8-9
Boaventura 2013	Portugal	136	9-10
Boyce 2014	USA	55	10-11
Fisher-Maltese 2015	USA	66	7-8
López-Banet 2022	Spain	38	4-5
Skalstad 2021	Norway	Sample size not provided	5-10
Stevenson 2021	USA	1290	9-12
Murphy 2021	Ireland	145	8-11
Winarni 2020	Indonesia	36	9-10

A number of studies focused specifically on the development of environmental content knowledge and skills. For example, Stevenson, Szczytko, Carrier, et al. (2021), reporting on the impact of an Outdoor Science Education (OSE) programme on the grades, knowledge and self-efficacy of fifth grade students, found that OSE increased knowledge and maintained achievement in science among girls, but self-efficacy decreased among boys and girls in the treatment group. Harris and Ballard (2020) tracked three third-grade students pursuing their own interest driven inquiries on ladybirds across the classroom, school garden and science labs. Their evidence showed that the students developed scientific content knowledge and practice, and carried their learning to new settings.

In terms of scientific skills, Lombardi and colleagues (2013) examined how students' plausibility judgments and knowledge of human-induced climate change transformed during instruction promoting critical evaluation. Critical evaluation is described as involving: “judgements about the relationship between evidence and alternative explanations of a particular phenomenon” (McNeill, Lizotte, Krajcik, et al., 2006, p. 1394). Results indicate that the experimental group made a significant shift in their plausibility judgements towards the scientifically accepted model of human-induced climate change. Significant conceptual change was also evident and maintained after six months. Lombardi and colleagues (2016) also investigated students' ability to engage in critical evaluation when confronted with alternative explanations of the complex and controversial topic of climate change. Post study, critical evaluation was demonstrated at a relatively low frequency.

Some studies looked specifically at developing students’ scientific inquiry skills in the context of the environment. For example, Skalstad and Munkebye (2021) examined questions asked by children when learning about natural science in an outdoor environment. Their findings highlight that supporting children’s explorations of nature encouraged subject matter questions aimed at acquiring factual information and first-hand experiences. Boaventura et al. (2013) reported that an outdoor activity conducted in a marine biology research laboratory promoted students’ prediction, observation and explanation skills.

Numerous studies indicated that the use of digital technologies enhanced students’ ability to gather, analyse and share data in an environmental context. For instance, Davies, Collier, and Howe (2012) reported positive findings with students’ use of data loggers with GPS to produce Google Earth visualisations of environmental quality in their school’s locality. Their findings revealed that all students made greater use of scientific data than before the project to develop their environmental knowledge. Schellinger et al.’s (2017) study on using a digitally-supported, inquiry oriented curriculum in the context of wildlife and natural habitats resulted in the development of students' more informed views of inquiry, diversity of methods, developing scientific explanations, and role of subjectivity.

Five studies reported positive impacts on primary students’ attitudes towards the environment. Three of these indicated that the pedagogical tool used in the study impacted students’ attitudes: a mobile technology-supported experiential learning system Cheng, Hwang, and Chen (2019); mobile and gamification technologies in a botanical learning environment Su and Cheng’s

(2015); and, an environment-based comic Istiqomah Subiyantoro, & Rintayati, 2021). The other two studies indicated that it was the positioning of the learning experience in the environment that enhanced students' attitudes towards the environment (Harris et al., 2020; López Banet et al., 2022). López-Banet et al.'s 2022 study that involved practical observation of plants, measurement and interpretation of data in both classroom and garden settings found that the children were motivated in all the activities throughout the intervention, which provided the chance to develop interest in environmental science and further develop food competence in the early years. In contrast to the above, Hashimoto-Martell, McNeill, and Hoffman (2012) reported no significant changes in students' beliefs about the environment after participation in an urban ecology programme.

Pro-environmental actions also emerged as a theme in a number of studies. For example, Kos et al. (2016) explored kindergarten children's understanding of pro-environmental behaviours and their influence on the environment, and found that the experimental group's awareness of the influence of pro-environmental behaviours strongly improved. Murphy et al.'s (2021b) Irish study found children's engagement with learning about sustainability through inquiry-based approaches resulted in improved scientific knowledge and skills, improved understanding of key sustainability issues and evidence of students developing sustainability competences, including systems, futures and values thinking.

Implications for curriculum development

The substantial number of studies in this cluster points to a growing area that can both enhance environmental knowledge, sustainable action and competencies and feed into scientific knowledge and skill development in the following ways. Environmental education is often situated in an outdoor context but can also be situated/ supported in classroom and/or laboratory settings. Development of scientific knowledge pertaining to environmental studies significantly enhances students' understanding of environmental issues. Scientific skills are enhanced through environmental based studies including prediction, observation, questioning, critical evaluation of data and plausibility appraisal. Digital technologies enhance students' ability to collect and interpret data in an outdoor environmental context. Outdoor environmental studies have the potential to enhance engagement with the environment and promote positive attitudes and pro-environmental actions.

Assessment

In the SLR five studies focused on assessment (Table 3.19)

Table 3.19

Studies with Assessment as a Theme

Author	Location	Sample	Age
Decristan 2015	Germany	1070	8-9
Decristan 2015b	Germany	1070	8-9
Kruit 2020	Netherlands	403	10-13
Smith 2019	USA	95	9-10
Yilmaz 2019	Turkey	24	10-11

Formative assessment was a feature of four papers in the SLR. Decristian and colleagues (2015a, b) presented findings indicating that the relationship between curriculum-embedded formative assessment and general features of classroom process quality (e.g. cognitive affection, supportive climate, classroom management) enhanced elementary school students' understanding of the scientific concepts of floating and sinking, particularly supporting the conceptual understanding of students with poor language proficiency. Similarly, Yilmaz and Bulunuz (2019) examined the impact of formative assessment based learning on 5th grade students' understanding of astronomical concepts. Findings indicated that students' conceptual understanding increased from pre to post assessment, although some students still found it challenging to explain their answers at the exit stages. Kruit et al. (2020) used a performance assessment as a diagnostic tool for formative assessment to guide instruction of science skills in primary education. Findings indicated that the approach promoted grade 5-6 students' awareness and understanding of their own learning. It also made teachers aware of students' overall performance so that they could then make informed decisions regarding subsequent science activities. Finally, Smith et al. (2019) reported that a multimodal automated framework accurately assessed students' conceptual understanding. These studies therefore all recommended the use of formative assessment-based education in science classes to enhance conceptual understanding.

Implications for curriculum development

These studies recommend the use of formative assessment strategies to help develop students' conceptual understanding. These strategies have also been found to promote students' awareness and understanding of their own learning.

Theme 3: Working Scientifically

In this section studies related to working scientifically are grouped under six sub-themes: process skills, reasoning, argumentation, model-based learning, problem-based learning and design-based learning and engineering.

Process Skills

In the literature review, twenty-one studies were identified as focusing explicitly on the development of science process skills. An overview of these studies is provided in Table 3.20.

Table 3.20

Overview of Studies Focused on Process Skills

Author	Location	Sample size	Age range
Cotabish 2013	USA	1750	7-11
Delen 2015	USA	116	11-12
DiMauro 2016	USA	30	9-10
Durmaz 2017	Turkey	43	12-13
Efstahiou 2018	Cyprus	26	10-11
Gillies 2014	Australia	108	12-13
Gultekin 2022	Turkey	30	8-9
Hugerat 2014	Israel	44	11-12
Kapici 2019	Turkey	143	12-14
Kim 2021	South Korea	125	6
Kruit 2020	Netherlands	705	10-13
Kruit 2018	Netherlands	403	10-13
Lazonder 2014	Netherlands	67	11
Macanas 2019	Philippines	59	10-12
Mulyeni 2019	Indonesia	23	7
Panos 2022	Spain	72	3-6
Park 2016	South Korea	68	5-7
Schlatter 2022	Netherlands	153	9-12
Sole Llussa 2022	Spain	30	10-12
Taşkın-Can 2013	Turkey	60	10-11
Tekerci 2017	Turkey	40	5-5.5

The majority of these studies focused on multiple skills simultaneously, for example, looking at the umbrella terms of process skills, inquiry skills or problem-solving skills. A small number looked at individual skills, for example reasoning or data handling.

All but one of the studies which used pre and post tests to measure changes in conceptual knowledge, achievement or skill development reported improvements when opportunities were explicitly provided for students to use their working scientifically skills (e.g., Hugerat et al., 2014; Mulyeni, Jamaris, & Supriyati, 2019; Tekerci & Kandir, 2017). Schlatter, Molenaar and Lazonder's (2022) intervention, using worksheets with different levels of scaffolding and support depending on standard test scores or previous performance in inquiry tasks, reported that adaptive instruction had no effect when all process skills were targeted together. An argument was made for teachers monitoring specific skills in real time and providing extra support for these students. Findings from a study by Kruit et al. (2020) reinforce this argument, and they claim that performance assessments have the potential to monitor students' performance of skills.

While improvements in science achievement or skill development were seen in most studies, other articles warned of short-term gains that could not be seen beyond the implemented activity or intervention. For example, Lazonder and Egberink (2014) reported that while scaffolding during their inquiry task strengthened children's performance, it was ineffective in the long term to learn about inquiry itself. Kruit et al. (2018) stated that while both implicit and explicit instruction facilitated the acquisition of science inquiry skills, only explicit instruction had a positive effect on students' abilities to apply these skills to new and unfamiliar topics.

Kapici, Akcay and de Jong (2019) found that using hands-on and virtual laboratories sequentially rather than in isolation yielded better results for students' acquisition of knowledge and inquiry skills. Efstahiou et al. (2018) also reported that computer scaffolding had positive effects on students' inquiry skills, specifically identifying variables and designing experiments.

A number of studies examined the use of real-world scenarios as means to practise science skills. For example, Gultekin and Altun (2022) reported on a "Market Place" activity which involved setting up a small market counter in the classroom enabling students to improve their measurement skills. The authors noted that activities involving scientific process skills developed students' problem-solving skills. Delen and Krajcik (2015) compared students' interpretation of first-hand data when analysing the water quality of a local river, to their handling of similar data provided to them from another school. Students made more accurate justifications with the data they generated from a real-world scenario. The authors acknowledge that dealing with second hand data is an important part of what scientists do and that students should therefore be provided with opportunities to both generate data and handle generated data.

Implications for curriculum development

Improvements to conceptual knowledge and skill development were seen when students were afforded opportunities to use science process skills. Explicit instruction of these skills is required to enable students to apply skills to future problems and investigations and some monitoring of specific skills during scientific investigations may also be required for some students. Incorporating digital learning was shown to have a positive impact on the development of process skills.

Reasoning

Four studies in the SLR explicitly explored the impact of an intervention on the development of students' reasoning skills - see Table 3.27.

Table 3.27

Studies with Reasoning as a Theme

Author	Location	Sample size	Age Range
Demir 2019	Turkey	18	10
Leuchter 2014	Germany	244	4-9
Samon 2020	Israel	12	12-13
Varma 2014	USA	4	6-9

Demir and Namir (2019) reported that modelling activities enhanced students' informal reasoning about a real-life issue through support for developing scientific knowledge and evidence-based reasoning in constructing arguments/ counter- arguments and rebuttals. Leuchter, Saalbach, and Hardy (2014), using structured learning materials in a problem-based environment to promote conceptual change and foster students' scientific reasoning skills in early science learning, found improved comparison and scientific reasoning that supported children's conceptual change. Similarly, Samon, and Levy (2020) reported that the use of a complexity reasoning-based curriculum in upper primary science developed students' conceptual understanding in chemistry.

Implications for curriculum development

Model-based learning and problem-based learning pedagogies are indicated as key pedagogies for supporting reasoning. Reasoning skills are seen as important because they connect strongly with both argumentation skills and with conceptual understanding and change across all primary classes.

Argumentation

Argumentation is the process of arguing, in which the construction, justification, and refutation of arguments take place (Dawson & Clarke, 2020). Toulmin (1958) describes scientific argumentation as a process of using data, warrants and backings to convince others of the validity of a claim. Many assert that scientific argumentation is analogous to the process that scientists undergo when justifying scientific knowledge; scientists must construct persuasive and convincing arguments that relate explanatory theories to evidence (Martin & Hand, 2009; National Research Council [NRC], 1996)

Sixteen research articles in the SLR centred on the development of primary school aged students' argumentation competences. Across all of these studies, argumentation is considered as a critical component of scientific literacy and thus, as a central feature of primary science. Further, all the studies within this theme take the view that primary school aged students are capable of engaging in argumentation. Of the sixteen studies reviewed, eight explicitly focused on different features of scientific argumentation while the remaining studies were situated in the context of SSIs. Table 3.21 details the papers in this cluster.

Table 3.21

Overview of Studies with Argumentation as a Main Theme

Author	**Location**	**Sample**	**Age**
Arias 2017	USA	1031	8-10
Bathgate 2015	USA	34	11-12
Belland 2015a	USA	69	12-13
Belland 2016	USA	69	12-13
Bulgren 2014	USA	282	11-15
Canoz 2022	Turkey	15	12-13
Dawson 2022	Australia	52	12
Evagorou 2020	Cyprus	19	10-12
Fishman 2017	USA	37 classes (no sample size given)	8-11
Hand 2016	USA	700	4-12
Hsu 2016	USA & Taiwan	68	11-12
Jun 2021	Canada	19	11-13
Lin. 2018	Taiwan	55	11-12
Novak 2017	USA & Australia	58	12-13

Peffer 2021	USA	80	6-11
Ryu 2012	USA	21	8-10

Several papers in this cluster illustrate students' construction of arguments after SSI interventions (e.g. Dawson & Venville, 2022), their argumentative discourse (Bathgate et al., 2015) and their coherent relating of claims (Ryu & Sandoval, 2012). Eleven studies examined the impact of pedagogical approaches on the development of students' argumentation competencies. These approaches varied across collaborative whole class discussion, teacher scaffolding and explicit literacy support (Dawson & Venville, 2022); use of predictions as a stimulus for argumentation (Arias et al., 2017); problem-based learning (Peffer et al., 2021); and an extensive argumentation professional development programme (Fisher et al., 2017), amongst others.

Six studies explicitly related to the role of scaffolding when developing argumentation. Three of these explored the use of computer based pedagogical scaffolds (Belland, Armbrust & Cook, 2015; Van Dyke, Chen, & Smith, 2016; Lin et al., 2018). All of these studies reported improvements in middle school students' construction of evidence-based arguments, with Belland et al.'s study showing significantly greater impact on lower-achieving students. Van Dyke et al.'s study (2016) specifically highlighted the success of the programme at developing student counterargument and rebuttal skills, something other studies reported as challenging (for example Fisher at al., 2017). These authors also noted that cultural differences between the American and Taiwanese student participants impacted the development of some argumentation skills (e.g., the use of rebuttals).

Three other studies used explicit scaffolds in some way to develop elementary school students' ability to engage in argumentation: an Argumentation and Evaluation framework in Bulgren, Eilis & Marquis' (2013) study, a Science Writing Heuristic framework in Hands et al (2016) and Argument-Focused Metacognitive Scaffolds in Quinga & Mijung's (2021) study. All three studies reported positive correlations between student engagement with the intervention and the development of argumentation competencies.

As with other pedagogic approaches reviewed in the SLR, a number of studies highlighted the significant role of teacher guidance (Arias et al., 2017; Hands et al., (2016) and establishing expectations for argumentation (Ryu & Sandoval, 2012). Challenges in teaching argumentation were also reported. Bathgate et al. (2015) reported that peer social groups often inhibited adolescent participation in argumentation discourse with little benefit for students who preferred not to disagree with their peers. Novak and Treagust's study (2017) provided insight into the complexity of students having to adjust claims when faced with anomalous evidence, and Demir and Namar (2019) illustrate that even with explicit argumentation intervention, students did not create higher-level arguments.

A key benefit linked with engaging in argumentation is its intersections with other scientific processes. Evagorou, Nicolaou, and Lymbouridou (2020) indicate intersections between higher-level modelling cognitive processes and higher-level argumentation epistemic aspects, and Peffer, Renken, Enderle, et al. (2021) connect argumentation and reasoning. Bathgate et al. (2015) highlighted the positive relationship between argumentation and the development of students' sense-making ability and the ability to learn science content knowledge (e.g. of genetic principles in Peffer et al.'s (2021) study). Demir and Namdar (2019) found that students' informal reasoning quality improved after engaging with argumentation activities situated in real-life contexts.

Implications for curriculum development

Argumentation is strongly considered to be a critical component of scientific literacy and should therefore be a central feature of primary science classrooms. It has been found to enhance students' sense-making ability, science content knowledge and informal reasoning. Socio-scientific argumentation is widely documented as an approach that can support the development of argumentation as well as being important as a key skill. Pedagogies to support the development of students' argumentation competencies include collaborative whole class discussion, teacher scaffolding, technology supported scaffolding, problem-based learning and the use of models.

Model-based learning

Model-based teaching and learning involves the use of models as tools for teaching and learning scientific concepts, whereby students are afforded opportunities to use models to develop their understanding of complex and abstract scientific concepts and phenomena. Krajick and Merrit, describe model-based teaching and learning as a process whereby learners develop and use abstract representations of different components, interactions and processes that constitute a particular science concept or phenomenon (Krajcik & Merrit, 2012).

In the literature review 10 articles explicitly focussed on scientific modelling as a methodology to support the teaching and learning of science. Table 2.22 provides an overview of these studies.

Table 3.22

Overview of Studies with Model-based Learning as a Focus

Author	Location	Sample size	Age Range
Bamberger 2013	USA	65	11 - 12
Baumfalk 2018	USA	201	8 - 9
Demir 2019	Turkey	17	10
Evagorou 2020	Cyprus	19	10 - 12
Fried 2019	USA	26	10 - 13

Nicolaou 2015	Cyprus	19	11 - 12
Zangori 2015	USA	116	8 - 9
Zangori 2016	USA	73	8 - 9
Zangori 2017	USA	110	8 - 9
Zangori 2020	USA	54	8 - 9

The studies focussed on a range of Physical, Biological, Material and Environmental science concepts and outlined alternative conceptions learners hold within the different scientific disciplines. All of the studies indicated that engagement with model-based pedagogies was effective in developing children's conceptual understanding, argumentation and reasoning skills to some extent. However, there were caveats. For example, Zangori and Forbes (2016) noted that after the model-based intervention students held a mixture of scientifically accepted and naïve biological understandings about how and why plants grow, develop and survive, amidst moving towards more sophisticated reasoning skills. Students showed evidence of reflecting on their scientific knowledge, using this knowledge to make predictions about how and why processes work, testing their predictions and then developing explanations. In this way the students were engaging in evidence-based scientific reasoning throughout their scientific inquiries. Demir and Namdar (2019) found that while most students' informal reasoning quality improved after modelling activities, students could not construct high-quality arguments even after engaging in modelling activities. More positively, Zangori et al. (2020) found that students who engaged with model-based reasoning about SSIs significantly increased their causal complexity. These experiences enabled students to use their own ideas and conjectures about interactions within the ecosystem in new ways.

Implications for curriculum development

These studies indicate that model-based methodologies can support the development of students' scientific content knowledge, argumentation and reasoning skills, all of which are essential components of scientific literacy. However, it is also apparent that model-based learning poses challenges for children. If model-based methodologies are to be proposed for the new STE curriculum, clear guidelines and resources for teachers on how to support children in engaging with model-based learning will need to be provided.

Design Based Learning / Engineering

Twenty three studies in the SLR focussed on design based learning in a Science setting. An overview of these studies is presented below in Table 3.23.

Table 3.23

Overview of Studies with a Design Based Learning / Engineering Focus

Author	Location	Sample	Age
Anwar 2022	USA	1305	11-12
Aranda 2020	USA	26	11-12
BozkurtAltan 2021	Turkey	24	13-14
Capobianco 2021	USA	93	8-12
Cunningham 2020	USA	14015	8-11
Danish 2015	USA	39	6-9
Dankenbring 2016	USA	67	10-11
Dasgupta 2019	USA	408	11-14
Dedeturk 2021	Turkey	40	11-12
Guzey 2019	USA	330	11-12
Jimenez 2021	Australia	43	8-13
Kelley 2017	USA	275	10-11
Kim 2021	USA	6	8-10
Lie 2019	USA	732	9-14
Magana 2019	USA	318	11-14
Marulcu 2014	USA	32	9-10
Marulcu 2016	USA	79	10-11
Marulcu 2013	USA	33	10-11
Slim 2022	Netherlands	73	9-12
Tas 2019	Turkey	77	12-13
Wendell 2013	USA	433	8-10
Yanyan Li 2016	China	30	10

Author	Location	Sample	Age
Zangori 2016	USA	73	8-9

In 17 of the studies in this cluster, design-based learning involved building a 3D prototype. Of these 3D designs, six involved the use of specific materials (e.g., LEGO). While not as common, four articles reported on the use of 2D representations and verbal explanations as the design task, and one study which was reported on in two articles used computer simulation for the design process. Yanyan Li, Menglu, & Ting-Wen (2016) altered an Engineering workplace design process to a simplified design which was more suitable to the 10-year old participants in their study. This approach involved the following five steps: Find a problem → Develop possible solutions → Decide the optimal solution → Build a prototype → Test the prototype.

The literature outlines problems which arise when engaging in design-based learning. For example, BozurtAltan and Tan (2021) reported that students were easily influenced by each other; once a student had suggested a proposal, no other suggestions were required from others in the group. They suggested students are seated apart and given time to work individually on the planning process behind a design. Yanyan Li et al. (2016) acknowledged that it was impractical to monitor, supervise and advise a large number of students engaged in a design activity.

A common approach that emerged was the use of relevant real-life examples to inspire the design based tasks. Some examples included local river pollution (Anwar et al., 2022), aids for people with visual impairments, water cups for small animals, shelters for birds (BozkurtAltan & Tan, 2021), door alarms, boat brakes (Capobianco, Radoff, & Lehman, 2021), lunch boxes (Kim, Kim & Barnett, 2021) and musical instruments (Wendall & Rogers, 2013; Slim, van Schaik, Dobber, et al, 2022)

Many of the studies used a control, or pre/post-test to comment on student achievement when engaging with design-based learning activities. Significant improvement was reported in all studies that measured content knowledge. Other studies noted better retention of scientific content (Anwar et al., 2022), and improved attitudes and enjoyment for the students involved in design-based tasks (Danish & Saleh, 2015; Lie, Guzey & Moore, 2019).

Development and application of process skills was an emergent theme in the articles that focused on Engineering. An improvement in problem solving skills was reported in studies that included design-based tasks (Yanyan Li et al., 2016; Marulcu & Barnett, 2016). Marulcu and Barnett (2016) also highlighted that engineering design-based curriculum encourages students to think and talk through how to solve more open-ended problems and noted the use of engineering-design as a context for science teaching without sacrificing content learning in a way that engages students in real-life related engineering-design procedures.

A number of articles presented arguments for including an Engineering curriculum for Science students. Marulcu (2014) notes that although STEM education for early years has become more important, Engineering has been historically neglected especially in the lower primary classes. Lie et al (2019) noted that a gender divide appears with Engineering and incorporating it as early as possible will help to form an interest for girls.

Cunningham et al (2014) introduced an Engineering curriculum over a two-year period in a large-scale study, and analysed its efficacy and impact compared to a more traditional curriculum. The authors noted that curriculum design affects student learning experience and noted that incorporating some specific principles into the curriculum allowed students to better understand both the science and the engineering content. These principles included introducing engineering content in a narrative context rather than textbook style; incorporating maths and science when designing solutions to problem solving tasks; facilitating collaboration and negotiating amongst team members; and using failure constructively to improve solutions as they design iteratively. Jiminez, Croft, Twine, and colleagues (2021) aimed to investigate the effect of an Engineering curriculum and real-world design tasks on the habits of mind of students with intellectual disabilities. From their findings, they concluded that the justification for introducing engineering education is to facilitate students to grow within their development of initiation, thinking, collaboration and problem-solving skills.

Implications for curriculum development

The studies in this theme indicate largely positive impacts from including DBL within Science and offer examples of projects and approaches for doing this, often involving the building of 3-D prototype models or 2-D representations. The outcomes from studies in the DBL cluster include improved science attainment, better open-ended real-life problem-solving skills, and improved attitudes and enjoyment of tasks. Here too, the need for pedagogic attention to manage individual engagement in group-based DBL tasks and projects is emphasised. When implementing an Engineering curriculum, or organising Engineering based design tasks, the Engineering design approach should be fully integrated alongside Science content (including application of science process skills).

Theme 4: Inquiry

There are four sub-themes in this section: Inquiry, 5E / POE, Problem-based learning and Digital Learning technologies and inquiry.

Inquiry

Inquiry-based learning was referred to some extent in the majority of the articles in the review. However, seventeen studies had inquiry-based approaches as a main theme. Table 3.24 provides an overview of these 17 studies.

Table 3.24

Overview of Studies with Inquiry as a Theme

Author	Location	Sample size	Age
Gillies 2015	Australia	248	11-12
Kim 2012	USA	3,300	5-9
Kong 2014	Hong Kong	27	9-10
Lazonder 2015	Netherlands	55	11
Lu 2020	Taiwan	111	9 and 12
Martella 2020	USA	145	8-10
Murphy 2021b	Ireland	459	6-12
van Uum 2017	Netherlands	101	10-11
Akaygun 2021	Turkey	68	11-12
Decristan 2015	Germany	1670	8-9
Di Mauro 2016	USA	30	9-10
Hand 2016	USA	700	4-12
Kruit 2018	Netherlands	403	10-13
Mulyeni 2019	Indonesia	23	7
Nichols 2022	Australia	159	10-12
Rogayan Jr 2020	Philippines	47	11-12
Schalk 2019	Switzerland	189	8-9

All 17 studies revealed that engagement with inquiry-based pedagogies had a positive impact on students' conceptual learning and scientific skill development. Three studies (Kim et al., 2012; Lu et al., 2020; Murphy et al., 2021b) revealed that engagement in inquiry-based approaches promoted students' critical thinking skills and two studies reported that inquiry-based approaches had a positive impact on children's scientific language and attitudes towards science (Gillies, Nichols, & Khan, 2015: Murphy et al., 2021b).

5 E and POE

In the review, 10 articles had a particular focus on the 5E framework or the Predict- Observe-Explain (POE) strategy. See Table 3.25 for an overview of these studies.

Table 3.25

Overview of 5E and PoE Studies

Author	Location	Focus	Sample size	Age range

Akaygun 2021	Turkey	5E	68	11-12
Andrikopoulou 2021	Greece	5E	7	12
Kim 2021	South Korea	5E	125	6
Mulyeni 2019	Indonesia	5E	23	7
Looi 2014	Singapore	5E	1196	9
Akaygun 2021	Turkey	POE	68	11-12
Cengiz 2018	Turkey	POE	41	11-12
Kiriktas 2021	Turkey	POE	27	5-6
Hashweh 2016	West Palestine	POE	29	12-13
Akpinar 2014	Turkey	POE	57	12-13

The 5E teaching and learning model (Bybee, 1997) is a form of guided inquiry with five phases: Engage, explore, explain, elaborate and evaluate. The Predict-Observe-Explain (POE) strategy, a form of structured inquiry developed by White and Gunstone (1992), can be used to support the development of students' scientific knowledge and process skills.

The science focus of these studies encompassed the Biological, Physical and Environmental sciences. All these studies, underpinned by social constructivist theories and focussed on guided and structured inquiries, revealed positive findings on the development of students' scientific knowledge, skills, improvement in students' perceptions of the tentative and subjective nature of science and the development of more positive attitudes towards science. Two studies used digital technologies to support the implementation of the 5E and POE strategies. Looi et al's (2012) study integrated the 5E inquiry phases into a mobile technology science unit and found that engagement with the 5E framework through the different mobile technology tools led to developments in students' reflective thinking and reasoning skills. Akpinar's (2014) study revealed that students' engagement with POE-based dynamic and interactive animations had a significant impact on students' understanding of static electricity.

Implications for Curriculum Implementation

The findings from the studies on inquiry-based pedagogies add to the extensive body of research on the effectiveness of inquiry-based approaches (structured, guided and open-inquiry) in developing students' scientific conceptual knowledge, scientific skills, understanding about the NOS, resulting in more positive attitudes towards science.

Problem-based learning

Across the 12 studies within this theme, there was a focus on problem-based and project-based approaches to develop science learning across the primary phase.

Table 3.26

Overview of Studies with Problem Based Learning as a Focus

Author	Location	Sample size	Age Range
Bahar 2020	Turkey	32	5-6
DiMauro 2016	Argentina	30	4th grade
Harris 2015	US	1700+	10 - 11
Hwang 2021	Taiwan	75	5th grade
Lavonen 2022	Finland	19	7-8
Lin 2019	China	312	12-13
Peffer 2021	USA	80	Primary (not specified)
Rimm-Kaufman 2021	USA	868	8 - 9
Terrazas-Arellanes 2018	USA	2303	10 - 14
Unal 2014	Turkey	42	6
YanyanLi 2016	China	30	10
Yi HsuanWang 2020	Taiwan	51	Primary (not specified)

A number of these studies (Bahar & AksÜt, 2020; Di Mauro & Furman, 2016; Peffer et al., 2021; Unal & Aral, 2014; Yanyan Li et al., 2016) measured the impact on scientific skills and processes, including problem-solving, argumentation and experimental design skills, with all showing positive impacts on skills. At lower primary level, Bahar and AksÜt (2020), examining problem-based approaches with 5-6 year olds in a preschool setting, found significant positive immediate and longer term impact on children's problem-solving skills. Unal and Aral (2014) reported similar impacts when exploring experiment-based science education with problems as context on 6 year-olds' problem-solving skills.

At upper primary level, Yanyan Li et al.'s (2016) intervention study focussed on engineering through a design-based methodology and Di Mauro & Furman's (2016) guided inquiry intervention both showed significant impacts on problem-solving and experimental design skills, alongside development of subject knowledge. Using project-based approaches, including service learning (Rimm-Kaufmann 2021), yielded positive results across a number of studies. Harris et al's (2015) large scale project-based inquiry science curriculum study with 6th grade students reported positive impacts on process skills: constructing explanations and developing and using models. Importantly, classrooms with higher concentrations of low-achieving students benefited from the curriculum as much as classrooms with lower concentrations of these students.

A number of studies incorporated digital learning as part of their problem-based approach. For example, Hwang et al., (2021) compared the impact of a concept map guided problem-posing strategy for flipped learning against problem-posing flipped learning (without the assistance of the interactive concept map) and regular flipped learning. The concept map guided problem-posing strategy was effective in improving students' learning performance, especially for students with higher levels of critical thinking tendency. In Terrazas-Arellanes et al.'s (2018) large scale study, project based learning was coupled with a culturally informed multimedia learning environment, and significantly increased gains in science content knowledge, including for English learners and students with learning disabilities.

Implications for Curriculum Implementation

This set of studies offer strong evidence of impact on aspects of science learning, given that measuring outcomes features commonly across the articles. Problem- and project-based approaches indicate strong impacts on science process skills, and opportunities for integrating technology and engineering. The use of technology and multimedia was marked within this theme, with evidence of improved content knowledge, independent working and greater equity of outcomes seen in this incorporation.

Digital Learning Technologies and Scientific Inquiry

In the systematic review, 22 studies explored digital learning and technology in an inquiry framework. The inquiries ranged from structured to guided e.g 5E (Akgunduz & Akinoglu 2016), POE (e.g., Akpinar, 2014), and in a minority of cases, open inquiry approaches. A variety of digital learning and technology modalities were considered including immersive learning and interactive online learning environments, as well as hardware such as data loggers and digital multimedia tools e.g. tablets and smartphones for researching and content creation.

Table 3.34

Overview of Digital Learning Technology in Inquiry Framework Studies

Author	Location	Sample size	Age range
Akgunduz 2016	Turkey	74	12 - 13
Akpinar 2014	Turkey	57	12-13
Blanchard 2016	USA	2321	10 -13
Cai 2022	China	41	10-13
Chen 2015	Taiwan	139	12
Davies 2012	UK	450	9-10
Dickies 2019	USA	43	8-11
Efstathiou 2018	Cyprus	26	10-11

Fridberg 2018	Sweden	9	3-6
JuanaWu 2021	China	54	10
Kapici 2019	Turkey	143	12-14
Kermani 2015	USA	58	4-6
Lehtinen 2022	Finland	96	8, 10, 12
Looi 2014	Singapore	1196	9
Schellinger 2017	USA	125	8 – 10
Schellinger 2019	USA	129	8 - 10
Solé-Llussà 2021	Spain	30	9-11
Solé-Llussà 2022	Spain	30	av age 11.32
Sung 2018	Taiwan	53	11
Terrazas-Arellanes 2018	USA	2303	10 - 14
Varma 2014	USA	64	6-11
Wang 2020	China	80	10

Blanchard and colleagues (2016) explored the role of a technology enhanced CPD for teachers in a guided inquiry constructivist framework and found this to have a significant positive effect on students' science achievement tests, particularly for African-American students. Technologies included handheld data loggers (e.g., pH, conductivity, heart rate), graphing calculators, Mimio or SMART interactive whiteboards, document cameras, interactive tablets, and data analysis software (TinkerPlots and Logger Pro by Vernier).

A variety of interactive online learning environments studies featured in the studies including: virtual laboratories (Efstathiou et al., 2018; Solé-Llussà, Aguilar, & Ibáñez, 2022; Wang, Ma, & Wu, 2020), interactive games (Kermani & Aldemir, 2015; Sung, Hwang, Wu, et al., 2018) and multimedia learning environments (Chen & Chou, 2015; Lehtinen et al., 2022; Schellinger et al., 2017; Terrazas-Arellanes et al., 2018), blended learning (Akgunduz & Akinoglu 2016) and a Learning Management System (Looi et al., 2014). The Looi et al (2014) large scale study noted significant learning gains in science content knowledge and inquiry skills following scaling up of a mobilized 5E science curriculum that used a Learning system with multiple media, a range of supporting tools including a mobile blog, camera and search engine, and applications such as Sketchbook, MapIt, Notepad.

Across the studies exploring interactive multimedia learning environments in an inquiry frame, positive impacts on science outcomes were reported, including impact on students' science learning (Chen & Chou, 2015, Terrazas-Arellanes et al., 2018), inquiry skills (Schellinger et al., 2017), understanding of Nature of Science (Schellinger et al., 2019), attitude (Akgunduz & Akinoglu, 2016) and motivation (Chen & Chou, 2015). Lehtinen et al. (2022) explored the effectiveness of implicit and explicit model progressions in an inquiry-based simulation-based learning environment with 8-12 year-olds. The results showed that while both implicit and explicit configuration learning environments were generally beneficial for learning, the 2nd graders, unlike the 4th and 6th graders, did not benefit from using either the implicit or explicit learning environment.

In the two studies exploring virtual laboratories in an inquiry frame, positive outcomes were noted for inquiry skills, particularly in identifying variables and designing experiments (Efstathiou et al., 2018), and also with collecting, organising, representing and analysing data to draw conclusions and process skills (Solé-Llussà et al., 2021; 2022). Wang, Ma and Wu (2020) investigated science knowledge development from a virtual lab in three modalities: a virtual manipulative per student/ per group/ per class. Their results suggested the importance of collaboration in virtual laboratories in supporting science learning. Kapici et al.'s (2019) study with students engaged in four different combinations of virtual and hands-on laboratory work around the topic of electricity noted that when students alternated the medium, their science content knowledge improved.

Two studies exploring the use of digital game-based learning showed positive outcomes. Game-based learning (GBL) refers to the type of learning environment that involves digital or non-digital games to enhance knowledge and skills (Qian & Clark, 2016). Sung et al.'s (2018) study showed that the game significantly enhanced students' learning achievement and problem-solving awareness as well as their learning approach. Kermani and Aldemir (2015) described how access to tablets and games with pre-kindergarten learners developed their awareness and interest in science-related subjects and in their skills in asking a variety of questions, making predictions, and producing explanations.

Three studies investigating immersive learning showed improvements in science inquiry skills and competencies, specifically, more nuanced causal explanations in immersive virtual environments with agent-based computational modelling tools (Dickes et al., 2019), problem-solving skills in a VR environment (Juana Wu et al., 2021) and inquiry skills in an augmented reality inquiry environment, with a focus on real-time attention feedback using a brain-computer interface (Cai et al., 2022).

Implications for curriculum development

There is strong evidence of digital environments with an inquiry framework producing a range of positive outcomes linked to scientific knowledge, processes and attitudes. The studies offer a range of examples of digital tools and infrastructures for supporting this learning.

Theme 5: Attitudes / Values / Motivation

Twenty-six articles focused on students' attitudes and motivations towards science were identified in the review. Table 3.28 provides an overview of these. Attitude is defined as positive or negative feelings, beliefs and values as well as a willingness to learn science (Lovelace & Brickman, 2003). According to Savelsbergh et al. (2016), motivation is defined as 'what energies an individual to perform an activity or task' and is regarded as an essential element of successful learning (Prensky, 2003). Self-efficacy refers to perceptions of our ability to carry out a task and predicts the amount of effort and perseverance a person will apply to complete a task (Bandura & Watts, 1996).

Three sub-categories featured within this theme in relation to students' attitudes and motivations to learn science: digital learning, outreach/outdoor learning and fieldwork experiences, and scaffolding and teachers' roles.

Table 3.28

Overview of Studies with Attitudes / Values as a Theme

Author	**Location**	**Sample size**	**Age range**	**Intervention tool:** digital/outdoor/teacher
Basar 2022	Turkey	36	8-9	Digital Stories
Boda 2020	USA	400	10-11	Digital - VR 360
Chen 2015	Taiwan	139	13-14	Digital - Multimedia Learning with Agent
Cheng 2020	Taiwan	76	10-11	Digital - VR
Dejonckheere 2013	Belgium	344	10-12	Teaching Didactics
Ekici 2015	Turkey	44	10-11	Digital - ICT Supported Narratives
González-Espada 2015	USA	57	9-14	Teacher - Science Essays
Harris 2020	USA	217	11-12	Outdoor - Environmental Outreach Activity
Hashimoto-Martell 2012	USA	39	11-13	Outdoor - Urban Ecology Course
Helsel 2022	USA	609	7-11	Teaching - SciTrek Curr
Jesus-Leibovitz 2017	Portugal	164	7-10	Outdoor - Marine Ecology
Kleickmann 2016	Germany	Trs - 73 Stud's - 1039	Tr Mean Age: 43.7 Stud's Mean Age: 9.3	Teaching - Teacher PD & Scaffolding
Lai 2016	Taiwan	106	8-9	Teaching - iPod Inquiry

Lin 2019	China	312	12-13	Digital - Mobile Assisted
Metcalf 2014	USA	198	11-12	Digital - Virtual Environment
Park 2016	South Korea	336	5-7	Outdoor - Horticultural Programme
Rhodes 2019	USA	501	4-7	Teaching - Language for Science Learning
Ribosa 2022	Spain	44	11-12	Digital - Educational Video
So 2019	Hong Kong	330	8-12	Digital - Multimedia E-Learning
Stevenson 2021	USA	1290	9-12	Outdoor Science Education
Su 2015	Taiwan	102	10-11	Digital - Mobile Gamification
ToprakYallihep 2021	Turkey	18	9-10	Digital - Serious Games
Uyanik 2016	Turkey	65	8-9	Teaching - Learning Inquiry Approach
Uysal 2022	Turkey	55	8-9	Digital - Web 2.0
Wang 2021	China	93	12-13	Digital - Game Based Learning
Xiao 2017	USA	49	11-13	Teaching - Surveys

Thirteen studies utilised a range of digital tools to understand students' attitudes towards and motivations to learn science. These included: Virtual Reality (VR) (e.g., Cheng & Tsai, 2020); mobile and gamification technologies (e.g., Su & Cheng, 2015); digital stories (Basar, 2022).

A range of outcomes related to attitudes, motivation, self-efficacy and science learning outcomes were identified across these studies. For example, Lin et al. (2019), using mobile-assisted learning, found that learning practices such as authentic learning and self-directed learning, and authentic problem-solving efficacy are fundamental and jointly reinforcing, with self-directed learning being a more significant contributor to academic self-efficacy than authentic learning and problem solving. ToprakYallihep, Ackay, and Kapici (2021) found that using games developed positive attitudes towards science, but did not find effects on student achievement, but achievement gains are noted in a number of other studies in the digital tools sub-group (e.g., Ekici & Pekmezci, 2015; Basar, 2022)

Other studies identified the valuing of choice and collaboration in technology-assisted science learning (Ribosa & Duran, 2022), improvements in self-regulated learning (Chen & Wan, 2019) and motivation (Su & Cheng, 2015). The importance of a 'knowledgeable other' for guiding learning and motivational gains was also noted (Chen et al., 2014).

Seven studies outlined the design and development of outreach activities, programmes and fieldwork relating to students' attitudes towards and motivations to learn science. Park et al.'s South Korean study (2016) found that after engaging in a horticultural activity programme there was improved emotional intelligence, prosocial behaviour, scientific investigation abilities and attitudes among the kindergarten students. Rhodes, Leslie, Yee and colleagues (2019) found gender effects when describing science in terms of actions rather than identities, girls' persistence in new science games and activities increased. Stevenson and colleagues (2021) however, offer contra-indicators, in that their study revealed achievement for girls but lower self-efficacy for both boys and girls.

Finally, six studies revealed positive findings on the impact of teacher scaffolding on students' conceptual knowledge, understanding of the processes and strategy of thinking and in promoting more positive attitudes towards science (Dejonckheere et al., 2013; González-Espada et al., 2015, Kleickmann et al., 2016; Lai, 2016; Uyanki, 2016; Xiao & Sandoval, 2017).

Implications for curriculum development

Across the studies in this group, three main 'leverage' tools are seen for improving student attitudes and motivation towards science: the inclusion of a range of digital tools, outdoor learning and fieldwork experiences, and teacher scaffolding for science learning. Almost all of the studies indicated positive effects, with the strongest case emerging for effects on self-efficacy, with some rather more mixed findings on impact on motivation and science learning, although still predominantly positive effects. The studies suggest that all three approaches are useful for building positive attitudes towards science learning and self-efficacy within this learning.

Theme 6: Interdisciplinary approaches and Integrated STEM

Interdisciplinary approaches

In the systematic literature review, eighteen articles were centred on interdisciplinary teaching, incorporating other subject areas into science lessons. An overview of these studies is provided in table 3.29.

Table 3.29

Studies with Interdisciplinary Approaches as a Theme

Author	Location	Sample	Age	Subject
Bakkaloglu 2021	Turkey	231	7-9	Drama
Boyraz 2017	Turkey	82	9	Games
Caiman 2019	Sweden	24 (focus on 2)	6-7	Art
Chen 2013	USA	835	9-10	Literacy
Fernandez Oliveras 2021	Spain	32	8-12	Games & Drama

Author	Location	Sample	Age	Subject
Fredagsvik 2022	Norway	96	10-12	Art
Hand 2018	USA	9963	8-12	Literacy
Kortam 2021	Israel	270	6-13	History
Kucuk 2022	Turkey	42	11-12	Drama
Mark 2020	USA	5	11-12	Poetry & Drawing
Preston 2019	Australia	20	8-11	Drawing
Sliogeris 2019	Australia	1 class: sample size not indicated	5-6	Play
Stagg 2019	UK	145	9-11	Drama
Taşkın-Can 2013	Turkey	60	10-11	Drama
van Dijk 2014	Netherlands	88	10-12	Drawing
Vitale 2012	USA	363	6-8	Literacy
Wilson 2021	USA	69	6-7	Drawing
Yeo 2021	Singapore	129	9-10	Drawing & Literacy

The literature illustrated interdisciplinary approaches being implemented across all age groups, from 5 - 13+. The studies also described how interdisciplinary teaching could be used across a variety of areas within science; for example, Physics (light and sound - Taşkın-Can, 2013), Chemistry (discovery of penicillin - Kortam, Hugerat, & Mamlok-Naaman, 2021), Biology (living things - Sliogeris & Almeida, 2019; Kucuk, 2022), and Environmental Science (climate change - Mark et al., 2020). The promotion and improvement of scientific skills and scientific thinking featured in the literature. In a Spanish study, Fernandez-Oliveras, Espigares-Gamezm, and Oliveras (2021) examined the use of games (traditional games from different cultures and geographical contexts) on students' learning of STEAM content. Three games were played over a four-month period which included the students becoming fully immersed in a dramatisation of the traditional board game through the use of role play, story and costume design. Findings indicated that scientific processes and thinking were activated through using traditional board games. Similarly, Taşkın-Can (2013) noted that the problem solving, critical thinking, creative thinking, linguistic and communicative skills of their participants improved during their study which involved integrating drama into the teaching of light and sound.

A number of studies examined science achievement scores after using a multidisciplinary teaching approach. For example, Boyraz and Serin (2017) indicated that the results from their integration of games and physical activities with the science content of forces showed improved science achievement scores and increased retention of science knowledge. For the studies where increasing science achievement scores was not the focus, authors reported that integrating other subject areas into the teaching of science attracted attention and enriched lessons (Kortam, 2021), allowed for collaborative project work and increased positive interactions with their classmates (Mark et al., 2020).

Kucuk (2022) highlighted the need for teacher intervention in their study which combined drama and the study of living things, with 11-12 year olds. In the study, students designed drama activities and presentations about the environmental problems faced by living things, but insufficient time for feedback resulted in misconceptions forming.

Integrated STEM

A further twelve studies focussed on an integrated STEM approach. These articles are summarised in Table 3.30.

Table 3.30

Studies with Integrated STEM as a Theme

Author	Location	Sample	Age
Anwar 2022	USA	1305	11-12
BozkurtAltan 2021	Turkey	24	13-14
Dasgupta 2019	USA	408	11-14
Dedeturk 2021	Turkey	40	11-12
Forsythe 2018	USA	45	12-13
Guzey 2019	USA	330	11-12
Kermani 2015	USA	58	4-6
Lamb 2014	USA	254	7 - 11
Magana 2019	USA	318	11-14
Munier 2013	France	22	9-11
Siew 2018	Malaysia	60	10-11
Wilhelm 2013	USA	194	12-13

Dasgupta, Magana, and Viera (2019) described integrated STEM approaches as the "seamless learning of disciplinary concepts infused with science inquiry, engineering design, mathematical reasoning, and technological skills" (p. 122). This was evident in the studies in this section which saw the integration of Biology, Physics, Chemistry and Earth and Space with Mathematics: e.g., data handling (Forsythe, 2018); measurement (Munier, Merle, & Brehelin, 2013); Engineering (e.g. design based tasks Bozkurt Altan & Tan 2020; Guzey et al, 2019) or Technology (e.g. computer simulation: Magana et al., 2019).

From Table 3.37 it is clear that the majority of integrated STEM approaches are aimed at upper primary classes. Kermani and Adlemir (2015) reported that implementing an integrated early childhood curriculum which focused on Maths, Science and Technology could bring a positive change in the students' overall learning of these subjects. Moreover, this approach increased teachers' awareness and confidence with integrating maths and science activities and concepts in their early year's classroom.

The inclusion of an integrated STEM curriculum produced improved results in a number of studies (e.g., Anwar et al., 2022; Dedeturk, Kirmuziul, & Kaya, 2021; Guzey, Rin-Whalen, & Peralta, 2019; Kermani & Aldemir, 2015; Lamb, Akmal & Petrie, 2015). Anwar et al. (2022) also noted that the retention of knowledge was improved in an intervention where ecology content was taught through an engineering design task. However, it is worth noting that the teachers in the control group (unlike those in the test) did not receive professional learning and followed the science textbook where the pedagogies underpinning the learning activities were unclear. There were also conflicting findings related to student interest and attitude, with Guzey (2019) reporting no significant effects from explicit engineering integration on participants' interest in science or engineering while Kermani and Aldemir (2015) claimed that students' awareness and interest increased as time went on. Although there were positive impacts on student learning in STEM in Lamb and colleagues' (2015) study they did acknowledge that the total time in the intervention with the test group, which was considerably more than that of the comparison group, could explain the increased gap in cognitive development between the comparison and the treatment group.

When implementing integrated STEM approaches, success was seen when technology, engineering or maths were fully intertwined with the science content. Wilhelm et al. (2013) outlined how their experimental groups used interactive technology, 3D modelling and mathematical measurement in lessons on the solar system, while the control group used a more didactic approach with worksheets and videos. Guzey (2019) noted the highest learning gains when engineering approaches were used throughout a unit of work, rather than including the engineering content at the end. Forsythe (2018) taught additional lessons on measures of centre and spread and displaying data, and noted that integrating maths and ecology resulted in more sophisticated approaches to sampling by their participants.

Implications for curriculum development

These studies commonly indicate interdisciplinary approaches being used across all classes, and across the Physical, Chemical, Biological and Environmental worlds. Moreover, the studies point to positive impacts on science achievement scores, as well as on scientific process and thinking skills. The need for careful teacher feedback in the course of student working is also flagged. Positive results are reported when Mathematics, Engineering and Technology are integrated into the science curriculum.

Theme 7: Early Years

Fourteen articles focused on learning science in early childhood were identified in the systematic literature review. Table 3.31 provides an overview of these.

Table 3.31

Overview of Studies with Early Years as a Theme

Author	Location	Sample	Age
Dejonckheere 2016	Belgium	57	4-6
Fleer 2019	Australia	26	3-5
Fridman 2020	Israel	215	4-6
Kalogiannakis 2018	Greece	30	3-5
Kermani 2015	USA	58	4-6
Kiriktas 2021	Turkey	27	5-6
Kos 2016	Slovenia	40	5-6
Leuchter 2014	Germany	244	4-9
López-Banet 2022	Spain	24	4-5
Panos 2022	Spain	72	3-6
Skalstad 2021	Norway	122	4-10
Tekerci 2017	Turkey	40	5-6
Üçüncü 2022	Turkey	198	4-6
Weber 2020	Germany	183	5-6

The studies highlight a range of methods and approaches utilised for learning science in early childhood. These include play-based pedagogies, inquiry and problem-based methods, and scientific process skills that promote questioning in early childhood education.

Three articles referred to play and game based pedagogies and involved playful interventions. Fleer's (2017) study that examined how imaginative play promoted scientific learning found that play based pedagogical practices supported children’s engagement and developed their scientific thinking. Using a playful intervention, Weber et al. (2020) investigated 5-6 year-old children’s theories about stability and whether these could be adjusted. Employing varying degrees of scaffolding including two types of guided play (verbal and material scaffolds, material scaffolds) and free play, they found that children in the playgroup with the highest degree of scaffolding (verbal and material scaffolds) gained better understandings of mass theory than the lesser supported playgroups.

Fridman, Eden, and Spektor-Levy (2020) examined 5-6 year-olds' nascent inquiry skills, metacognitive awareness and self-regulation during play-based scientific exploration tasks. They found that children exhibited inquiry capabilities and demonstrated higher levels of attention, persistence and autonomy during the structured task, but self-regulation scores were significantly higher during the open-ended, play-based, exploration task.

A further seven articles explored inquiry and problem-based methods, and scientific process skills in early childhood that resulted in positive outcomes regarding children's content knowledge and scientific skills. For example, Kirikatas, and Mehmet's (2021) study investigating the effects of the Predict-Observe-Explain (POE) method and critical thinking skills on preschool students in Turkey, noted the development of students' basic scientific, critical thinking and language skills and increase in motivation in science. Panos, Carrion, and Ruiz-Gallardo's (2022) study found that teaching children how to ask categorical questions on an information-seeking task resulted in improved learning that was maintained over time. While children aged 3-4 did not succeed in formulating categorical questions, this research highlights that this ability begins to develop from the age of 4-5.

Two articles focused on pre-school children's understanding of pro-environmental behaviours and learning outdoors (Kos et al., 2016; Skalstad & Munkebye, 2021). Both studies revealed positive outcomes from children's direct experiences and explorations of nature: Kos et al. reported greater knowledge of pro-environmental behaviours and Skalstad and Munkebye reported children's posing of subject matter-related questions, while also flagging the need for teachers to follow up on children's explorations and provide answers to their questions in order to elicit higher level cognitive questions.

One study found that the use of picture books support children's understanding about magnets Kalogiannakis, Nirgianaki, and Papadakis (2018). Finally, Kermani and Aldemir's (2015) study reported an increase in pre-kindergarten children's scientific skills and awareness and interest in science as a result of engaging with a content-specific and purposeful maths, science and technology curriculum project.

Implications for curriculum development

The studies highlight the range of methods and approaches utilised for learning science in early childhood. These include play-based pedagogies, inquiry and problem-based methods, along with scientific process skills concerning the promotion of questioning in early childhood education. Important outcomes include potential for better scientific concepts and explanations, increased awareness of and interest in science and in environmental issues.

Theme 8: Playful Approaches and Picture Books

Playful Approaches

Six studies in this systematic literature review centred on playful pedagogies or play-based pedagogies - see Table 3.32 for an overview.

Table 3.32

Overview of Studies with Playful Approaches as a Theme

Author	Location	Sample	Age
Akerblom 2019	Sweden	22	6
Fernandex-Oliveras 2021	Spain	32	7-12
Fleer 2019	Australia	26	4.6 (mean age)
Fridman 2020	Israel	215	5-6
Sliogeris 2019	Australia	No sample size given	5-6
Weber 2020	Germany	183	5-6

Four of the six studies were situated in early childhood settings. Akerblom et al. (2019) reported that children's conceptualisations of water, molecules and chemistry were enhanced after their participation in a playfully enacted, drama-based chemistry lesson. However, they caution that playful approaches may also enhance scientific misconceptions as some children in the study found it difficult to interpret the science content in the drama. Similarly, Weber et al.'s study (2020) reported that children's conceptualisations of mass theory were enhanced through playful interventions. Fridman and colleagues (2020) also reported positive findings when pre-schoolers implemented nascent inquiry skills, metacognitive awareness and self-regulation capabilities during play-based scientific exploration tasks. Fleer's (2017) study focused on the impact of a number of play-based pedagogies on the scientific engagement and thinking of young children. The study argued that play-based interventions promote scientific understanding and thinking.

The final two studies were situated in a primary context. Sliogeris and Almeida's study (2019) examined the effects of teacher-guided play and child-guided play (such as creative and imaginative play) on the development of children's scientific conceptual understanding. The study revealed that play-based approaches allowed teachers to explicitly introduce scientific concepts and supported children to make sense of these scientific concepts using familiar, everyday knowledge and activities. Sliogeris and Almeida (2017) provide empirical data to support their assertion that play enhances primary children's learning and deserves merit and space in the school science curriculum. Taking a different approach, Fernandex-Oliveras, Espigares-Gamezm, and Oliveras' (2021) Spanish study examined the impact of playing games on students' learning of STEAM content. Three games, played over a four-month period, involved students becoming immersed in a dramatisation of the traditional board game through the use of imagination, role play, story and costume design. Findings indicated development in students' scientific processes and thinking through this approach.

Implications for curriculum development

The evidence suggests strongly that playful approaches offer effective pedagogies for science learning across early years into upper primary level. These approaches are shown to enhance conceptual understanding and scientific thinking. They have proven to be effective for developing children's understanding of complex concepts.

Picture Books / Story

Eight articles in the SLR focused on the use of picture books and story on children's learning in science. The studies, based in six different countries, are overviewed in Table 3.33.

Table 3.33

Studies with Picture Books / Story as a Theme

Author	Location	Sample Size	Age range
Basar 2022	Turkey	36	8 - 9
Browning 2015	UK	62	5-8
Brunner 2020	USA	184	9-11
Emmons 2018	USA	37	5-8
Kalogiannakis	Greece	30	3-6
Larsen 2020	Canada	102	5
Okay 2021	Turkey	52	4-6
Yuliana 2021	Indonesia	58	12-13

Across the studies, digital stories, read-alouds and narratives were used to support children's learning. The use of story as primary (experienced directly) and secondary (experienced indirectly) evidence, and the effects of picture books on scientific literacy were also studied. The broader evidence notes that digital stories offer multimedia with multisensory appeal for learners (Özkaya, 2020), while stories generally encourage students to formulate their own interpretations of meaning (Doyle & Carter, 2003).

Two articles focused on the effects of reading stories aloud in science using an adapted science trade book, aided by educational curriculum materials in Brunner and Abd-El-Khalick's (2020) study, and by custom-made read-alouds and storybooks in Emmons, Lees, and Kelemen's (2018) study. Brunner and Abd-El-Khalick found that students and teachers further developed their views on NOS following the intervention, and Emmons et al. (2020) highlighted early years' students self-generating accurate explanations of adaptation by natural selection.

Additionally, second graders successfully generated the logic of natural selection through their engagement with the read-aloud storybooks.

In a Turkish study, Basar (2022) explored the effect of digital stories on 3rd grade students' achievement, attitudes and motivation in science. Following their engagement with digital stories in science, students' achievement, attitudes and motivation were higher among those in the experimental group.

Browning and Hohenstein (2015) explored the use of narratives or expository texts (ET) about evolution with students in Year 1, Year 2 and Year 3 in a British primary school. They found that narratives about evolution were more effective in supporting students' learning about evolution than ETs. Larsen, Venkadasalam and Ganea's (2020) examined 5-year olds' understanding of balance through primary (a guided activity) and secondary sources (picture books). They found students learned equally well from both primary and secondary sources of evidence. Kalogiannakis et al. (2018) examined the picture story reading method on children's learning about magnetism through an empirical case study in two Greek kindergarten classrooms. They found enriched knowledge about magnetism after engagement with the picture books, with students defining magnets and correctly identifying the material of magnets, as well as their attraction and repulsion properties. Finally, Yuliana et al. (2021) investigated the effect of ethno-science theme picture books in context-based learning (EthCBL) on fifth grade students' scientific literacy in a public elementary school in Indonesia. Findings highlighted that EthCBL was more effective in promoting scientific literacy than traditional teaching, with the experimental group demonstrating significantly higher post-test scores in all sub-scales of scientific literacy than the control group.

Implications for curriculum development

There is consistent evidence that the use of story and picture books encourage students to formulate their own interpretations of phenomena, but the need for purposefully adapted or custom-made stories and picture-books that are tailored for science learning is also flagged. Also important to note is the usefulness of these approaches across pre-school and early primary classes.

Theme 9: Digital Learning and Technology

There were a significant number of studies that used digital supports, tools and technologies to enhance students' learning and/or motivation and attitudes in science. Thirty four studies, from 13 countries, with the most from Taiwan and the USA, are captured here. This does not include the studies considered within inquiry (theme 4), attitudes, values and motivation (theme 5) or in other themes. Of note, is that all but one of these 34 studies reflect interventions with mid-upper primary grades. A range of digital learning and technology is included from immersive learning to interactive multimodal online learning environments, digital game-based learning to programming.

Table 3.24

Overview of Studies with Main Focus on Digital Learning and Technology

Author	Location	Sample	Age
Åhman 2020	Sweden	45	12-13
Ajlouni 2020	Jordan	50	10-11
Balım 2013	Turkey	51	11 - 12
Beyoglu 2020	Cyprus	42	11
Boda 2020	USA	400+	10-11
Boda 2020	USA	400	10-11
Chen 2020	China	100	9 - 10
Cheng 2019	Taiwan	50	9-10
Chou 2021	Taiwan	56	8 - 9
Epstein 2016	USA	244	Av age 12.3
Hanif 2020	Indonesia	54	9 - 10
Herga 2015	Slovenia	225	Av age 11.4
Hodges 2020	USA	482	7-11
Hsu 2013	Taiwan	58	8-9
Hsu 2016	USA and Taiwan	68	11-13
Huang 2020	Taiwan	40	10-11
Hu 2019	Taiwan	100	10-11
Jaakkola 2018	Finland	127	9-12
Jaakkola 2015	Finland	52	11-12
Kamarainen 2013	USA	71	11-12
Lai 2019	Taiwan	46	10-11
Lin 2018	Taiwan	55	10 - 11
Lin 2018	Hong Kong	61	10-12
Lin 2020	Taiwan	146	10-11
Liu 2020	China	90	11
Merkouris 2019	Greece	56	10-11

Ntourou 2021	Greece	33	10 - 11
Okyay 2021	Turkey	52	4-6
Rappolt-Schlichtmann 2013	USA	621	9-10
Saez-Lopez 2019	Spain	93	10 - 11
Silva, MJ	Portugal	72	9 - 10
Tsai 2020	Taiwan	69	10 - 11
Wahyu 2020	Indonesia	516	8 - 9
Winarni 2020	Indonesia	36	8 - 9

Interactive multimodal online learning environments featured most commonly across the digital learning and technology studies included here, encompassing a broad range of technology and tools including instructional videos, instructional games, interactive PowerPoint presentations, assessment tools (Ajlouni & Jaradat, 2020), technology enhanced concept maps and mind maps (Balim, 2013), graphic video media (Hanif, 2020), a virtual lab (Herga, Glazar, & Dinevski, 2015), an online Universally Designed for Learning Science Notebook (Rappolt-Schlichtmann et al., 2013), an interactive digital storybook (Okyay & Kandir, 2021), a Graph-Orientated, Computer Assisted Programme (Hsu et al., 2016) and a computerised inquiry-stage-dependent argumentation assistance programme (Lin et al., 2018). Some studies explored different strategies within learning environments such as differing question-stem prompts (Hu, Chiu, & Chiou, 2019) and simulations with concrete versus abstract and concrete fading representations (Jaakkola & Veermans, 2015; 2018).

A number of studies reported significant science learning in terms of conceptual knowledge (Ajlouni & Jaradat, 2020; Cheng, Hwang, & Chen, 2019; Hanif, 2020; Herga et al., 2015; Hsu et al., 2016, Lin & Chan, 2018; Rappolt-Schlichtmann et al., 2013). Additionally, Okyay and Kandir (2021), exploring the use of an interactive digital storybook intervention with early years learners (age 4-6), found that the scientific vocabulary acquisition among the children in the experimental group was significantly stronger than that among the children in the control group. While two studies showed no significant positive difference in science learning outcomes as a result of their technology based intervention, they reported other positive outcomes such as the experimental group who used concept maps reported that learning was useful and engaging (Balim, 2013) and the detailed stem group having better questioning quality in the intervention exploring different question stem prompts (Hu et al., 2019). Other studies showed a positive impact on argumentation skills (Lin et al., 2018), environmental attitudes (Cheng, Hwang & Chen, 2019), motivation (Rappolt-Schlichtmann et al., 2013) and students' language and scientific literacy (Winarni et al., 2020).

Seven studies investigated various forms of immersive learning, virtual and augmented, and generally showed positive impacts on student learning (Lai et al., 2019; Liu et al., 2018; Wahyu et al., 2020), attitudes and motivations (Chen, 2020; Lai et al., 2019; Boda & Brown, 2020a & b), scientific literacy (Wahyu et al., 2020) and on learning through representations (Ahman & Jeppsson, 2020). Two studies highlighted the importance of context in the learning environments (Boda & Brown, 2020a; Chen, 2020). Lai et al. (2019) reported that students' perceptions of extraneous cognitive load were significantly reduced in the AR multimedia learning environment compared to a traditional multimedia learning environment.

Five studies investigated the impact of digital game-based learning on science learning, skills and motivation. Epstein et al., (2016) and Hodges et al (2020) both reported increases in students' science conceptual learning following a game-based intervention. However, Hodges et al. (2020) reported that learning gains were less evident for 3rd grade (compared to 4th and 5th grade). While Huanga, Juoa, and Chen (2020) reported no difference in learning they did report increases in motivation and problem-solving ability. Epstein et al., (2016) also explored collaborative versus competitive game models and found that learning gains were significant only for the competitive model for males. Hsu and Tsai (2013) also explored the use of game-based learning on 3rd grade students' learning in science, focussing on the self-explanation aspect in a game. They reported no learning gains for the self-explanation aspect. Finally, Tsai, Lin and Liu (2020) reported the positive effect of a digital game which incorporated the gamification, assessment, modelling, and enquiry (GAME) model, on 6th grade students' scientific competencies. Both high-and low-performing students in the experimental group had positive perceptions of the game.

Three studies explored programming and robotics with conflicting results. Ntourou, Kalogiannakis, and Psycharis (2021) reported significant increases in 5th grade students' science learning and computational thinking but not on motivation, whereas Sáez-López, Sevillano-García and Vazquez-Cano (2019) reported positive outcomes for 6th grade students in mathematics and computational thinking, but not in science. Merkouris, Chorianopoulou, Chorianopoulos, and colleagues (2019) explored the effects of touch and gestural interaction with a tablet and a robot with students aged 10-11 and reported that students' knowledge of friction was enhanced significantly in all groups. However, students with misconceptions gained a better understanding of friction through the opportunity to use a physical, rather than virtual, agent and learning gains were higher in the physical conditions than in the virtual conditions.

One study investigated digital media web searches towards improving Scientific Epistemological Beliefs (Lin et al. 2020) reporting positive outcomes. Only one study included here (Chou & Wang 2021) reported on the impact of hand-held devices, in this case mobile microscopes, on students' learning. While no significant difference in science learning between the two groups was observed, the experimental group performed significantly higher in the non-standardised test and demonstrated positive learning attitudes and behaviours throughout the experiment.

Implications for curriculum development

These studies reveal mixed results relating to learning outcomes, but often balanced by other positive outcomes as seen under the inquiry and attitudes themes. There is evidence of science learning, and of improved problem-solving, but the mixed findings on learning suggest the need for careful and well-planned choices to be made to ensure the best chances for supporting learning through the use of digital technologies.

3.6.2 Discussion

It is apparent from the research that, for scientific literacy students need to develop their knowledge of and about science and a range of science process and inquiry skills.

Evidence from curriculum implementation indicates that engagement with scientific content (including NOS) across all science disciplines is yielding positive results in terms of developing students' science knowledge and their ability to explain their scientific inquiries, predictions and results using scientific terminology (Estyn, 2017; ERO, 2012). However, there are also concerns regarding: children holding naive conceptual understanding even after engaging in science inquiries (Bianchi et al., 2021); teachers not having sufficient conceptual knowledge to effectively implement science curricula or to address children's naive scientific conceptions (ETI, 2014; ERO, 2012; Ofsted, 2021).

On the curriculum specifications themselves, concerns have been raised about science content lacking depth and breadth (Bianchi et al., 2021); the need to reduce content and to re-sequence content in some year levels to be more age appropriate (ACARA, 2021). Furthermore, lack of clarity and detail on scientific content learning outcomes results in teachers not implementing the intended curriculum content (ACARA, 2021; ETI, 2014). Fundamentally, when science curriculum policy is unclear and where individual teachers are afforded too much choice in deciding how often pupils carry out investigative work, pupils in different classes have inconsistent opportunities to develop their science inquiry skills (Estyn, 2017).

The question of what scientific content should be included in the new STE curriculum specifications is therefore a challenging one. On the one hand it is important that children's naive scientific conceptions are addressed as they progress through primary school. It is also important that students begin to develop their understanding of key scientific concepts to enable them to make sense of the world around them. Learning outcomes related to children's conceptual understanding of Biological, Physical, Material and Environmental sciences are therefore important and indeed are commonplace in most curricula, including the current Irish primary Science Curriculum (DES, 1999). These are also reflected in the systematic review. Supporting the development of children's understanding of the NOS and SSIs are further elements for scientific literacy that should be included in STE curriculum specifications.

Then, on the other hand, there is the challenge posed by curriculum overload as a key issue in primary science curricula not being implemented in schools (ERO, 2012). While the research base does not indicate what science content to prioritise within curricula, there is general agreement on the need to include the 'big ideas' and 'guiding principles' of science (e.g., Harlen, 2010; 2015) in STE curricula specifications. These have been broadly accepted as best practices in science education that afford deep and more meaningful engagement with science in ways that enable students to begin understanding and making sense of the world in which they live and can inform the development of conceptual learning outcomes in the proposed STE specifications.

There is overwhelming evidence that science process, critical thinking, argumentation and problem-solving skills are essential skills for scientific literacy and that all primary students should be afforded frequent opportunities to apply and develop these skills in meaningful ways during school science. However, while evidence suggests children are being afforded some opportunities to develop their science skills, in many cases the core science skills are not being developed in meaningful ways (ETI, 2014). The literature highlights that explicit instruction of key science skills may be required to enable students to apply them in new scenarios and investigations and that teachers should at times monitor specific skills during scientific investigations (Shclatter et al., 2022).

It is important therefore, that in the proposed STE specifications that there are clear learning outcomes regarding key science skills and how they should be applied. This is particularly the case given the evidence that teachers do not focus on science processes due to lack of clarity regarding what they entail. The importance of explicitly teaching science skills, and focussing both implicitly and explicitly on particular skills during scientific inquiries has also been highlighted in the literature (e.g. Kruit, 2019). This is deemed essential if children are to develop the ability to apply a range of science skills in new and unfamiliar contexts (Lazonder & Egberink, 2014; Kruit, 2019).

The evidence is clear, hands-on, child-centred, inquiry-based pedagogies, model-based learning, engagement with SSIs, design-based learning and engineering processes and inquiries within a digital framework, are highly effective in supporting children's learning in, engagement with and attitudes towards science. However, research on implementation of these methodologies yields mixed results. On the one hand there is evidence of students leading their own investigations, using scientific language and skills effectively, having positive attitudes towards science, and engaging in meaningful learning (ERO, 2012; ETI, 2014; Estyn, 2017).

However, there are shortcomings including, superficial learning, over-reliance of teacher directed approaches, over-emphasis on content knowledge to the detriment of skill development, limited building on prior learning, prescriptive practical work and more able students not being challenged (Bianchi, 2021; Ofsted, 2021; ERO, 2012; Estyn, 2017). Other inhibiting factors that emerged in the research include: insufficient instructional materials (including digital technologies); lack of whole school approaches to science; inadequate time for science; science being squeezed out of the primary school curriculum due to assessment-led dominant focus on core subjects (e.g. English and mathematics) and / or being integrated with other subjects; low confidence and competence amongst teachers; inadequate professional learning for teachers (ACARA, 2021; Bianchi et al., 2014; ETI, 2014; Ofsted, 2021; Spring 2017; Wellcome Trust, 2016). These all have implications for curriculum development and implementation.

Finally, the literature highlights the role science education has to play in supporting our young people in developing positive attitudes and values towards science and to ensure they have an appreciation of the role of scientific knowledge in addressing the range of complex societal and global issues. It is also apparent that science education has a critical role in supporting pro-environmental behaviours. While the literature review provides insights into the impact of engagement with various interventions on students' attitudes, values and self-efficacy in science, guidance on the specific attitudes and values to promote in science class is restricted to pro-environmental attitudes.

3.7 Recommendations for Science curriculum development

Based on the findings from the curriculum content analysis and the systematic literature review, the following key recommendations for the development and implementation of the STE curriculum are proposed:

1. There is strong evidence that hands-on, inquiry-based pedagogies are instrumental for effective teaching and learning in science and therefore, should underpin the STE specifications. Clear descriptions and exemplars of different types of hands-on, structured, guided and open inquiry pedagogies should therefore be explicitly outlined in the STE specifications.

2. It is evident from both the curriculum analysis and systematic literature review that content knowledge in terms of Biological, Physical, Material and Environmental

science and the Nature of Science are essential for scientific literacy. A list of key learning outcomes related to all science disciplines and the Nature of Science should be included in the STE curriculum specifications. However, these should appear as a set of key ideas to help children understand the world around them, linked to key 'big ideas' and 'principles' in science (e.g. Harlen, 2010: 2015) rather than as an exhaustive list of specific learning objectives.

3. Science content in isolation is not sufficient. Students should be afforded opportunities to connect this content knowledge to their everyday lives if they are to become informed future citizens. In this manner, the science content with which children engage becomes relevant to their lives. The proposed STE curriculum specifications should explicitly state the importance of linking scientific content to students' everyday lives and should include specific learning outcomes related to Sustainability and Climate Change.

4. The importance of explicitly teaching science skills and focussing both implicitly and explicitly on particular skills during scientific inquiries is highlighted in the literature. This is essential if children are to develop the ability to apply a range of science skills in new and unfamiliar contexts. Succinct learning outcomes explicitly related to scientific skill development should be included in the STE curriculum specifications so that teachers can provide students with opportunities to apply and develop these skills in meaningful ways. Clear descriptors of the working scientifically (process), and related skills including argumentation, reasoning, critical thinking and design/ engineering skills should also be provided in the STE specifications. Furthermore, rubrics for assessment of these skills should be provided to ensure they are applied and developed appropriately.

5. Science is a core discipline within the STEM curriculum area. Alongside engagement in iSTEM inquiries and projects, it is essential that students are afforded frequent opportunities to engage in science as a discipline in its own right. Within this, there is strong evidence that engaging with science specific pedagogies is instrumental to the development of fundamental science knowledge, skills and attitudes. To this extent, as is the case for mathematics, another core discipline of STEM, dedicated time for science as a subject in its own right must be allocated within the overall curriculum framework. This is particularly the case given the evidence that engagement with hands-on, inquiry-based approaches to teaching and learning of science takes more time than traditional teacher-directed didactic approaches.

6. The benefits of utilising digital technologies to support and enhance hands-on scientific inquiry are highlighted in the literature. Digital technologies should be used to support and enhance students' learning and engagement with science; they cannot replace hands-on science inquiries. Exemplars of effective use of digital technologies to enhance hands-on science inquiries should be provided. These could include exemplars of how digital technologies can be used, for example, to gather, analyse and represent scientific data or to scaffold argumentation.

7. While the literature review provides insights into the impact of engagement with various interventions on students’ science attitudes, values and self-efficacy, with the exception of pro-environmental attitudes, the studies did not explicitly focus on what attitudes and values should be promoted in science class. However, the importance of supporting the development of positive attitudes, values and dispositions in science for active citizenship cannot be overlooked. The STE specifications should therefore

include specific learning outcomes related to the development of positive attitudes and values towards science to ensure that this is an explicit feature rather than a by-product of engagement with science. These learning outcomes should include outcomes related to pro-environmental attitudes.

8. It is widely accepted that scientific literacy is essential for active citizenship. If scientific literacy is to be an overarching aim of the STE specifications, a clear definition of scientific literacy in the context of the STE curriculum needs to be provided. This definition should take cognisance of the different visions of scientific literacy and how these translate into more specific content so that these visions become achievable.

9. There is widespread evidence that primary teachers, in Ireland and worldwide, do not feel confident or competent in implementing more child-centred, inquiry-based approaches to teaching science due to inadequate conceptual and pedagogical content knowledge. There is also a dearth of professional learning opportunities in science for primary teachers. It is thus essential for effective implementation of the STE curriculum that professional learning opportunities to support teachers in developing their science content and pedagogical knowledge are made available.

10. If these more child-centred inquiry-based approaches to teaching and learning science are to be effectively implemented in all primary schools throughout Ireland resources will be required. Ring-fenced funding for these resources should therefore be provided.

Section 4

What is the relationship between Technology/Engineering and Science and Mathematics? (What content is in focus in overviewed curricula presenting a Technology strand?)

4.1 Introduction

As noted in the opening section of this report, while the learning of disciplinary concepts is important, a 'siloed' approach can impede learners' understanding of the connections and interdependencies that exist between disciplinary concepts in science, technology, engineering and mathematics (Katehi et al., 2009). Understanding the synergies between these concepts is important (NRC, 2014) not least because the world we live in daily is not compartmentalised into neat 'subject' areas; knowledge from different disciplines is frequently used to inform decisions and actions. In an increasingly technological world, this imperative for real-world problem-solving feeds into the international interest in understanding what is meant by iSTEM and how to design learning environments for students that develop these integrated skills and processes.

The design of curriculum and learning experiences to enable the seamless learning of core STEM disciplinary content and practices, and iSTEM skills and practices is a challenge faced by policy makers and curriculum designers. As noted in the curriculum analysis presented in Section 3, many countries have begun to publish curricula that detail the relationship between technology/engineering and science and mathematics. Later in this chapter, we overview differences in the ways in which the relationship is configured across key curricula, but begin here by noting key features that are common across these curricula:

- Technology and engineering skills, viewed dually as both content and tools that support STEM working, are commonly structured under the headings of **design thinking** and **computational thinking/coding**.

- Second, the importance of **digital competence** is incorporated into most curricula, including the Irish primary curriculum, as an essential key competence.

Further emerging areas of interest are **data literacy** and **artificial intelligence**. In considering curriculum development, it is therefore useful to anticipate and prepare for these emerging areas. 'Being mathematical' is also highlighted in the *Primary Curriculum Framework* and in the STEM reports as an underpinning key competency for STEM working that is to be developed across the curriculum. From the perspective of technology/engineering and their role in supporting STEM working, we do not focus here on the 'being mathematical' feature but acknowledge its fundamental importance.

In the next section, we revisit the curricula analysed in Section 3 with a focus on how the technology/engineering core features listed above are described and configured. We draw also from the literature base on how these features relate to, and support, mathematics and science learning.

4.2 Technology/Engineering key components: Revisiting international curricula

Revisiting the national curricula of the countries previously analysed from the perspective of science, the curricula were also analysed in relation to approaches adopted towards iSTEM. Specifically, the Technology curricula were analysed for this purpose. Nine of the countries had dedicated Technology curricula; of these, five have a separate Technology curriculum (Australia/ New Zealand/ England/ Scotland/ Sweden), two have a Science and Technology curriculum (Ontario and Wales) and two have an integrated curriculum (Hong Kong & Northern Ireland).

Each of the curricula was analysed for structural organisation, aims and common iSTEM skills and processes. Processes identified include: design (design thinking and engineering design thinking), computational thinking and coding, digital competence and data literacy. These were present in all of the curricula albeit in different ways with varying degrees of specificity.

4.2.1 Design Thinking

Design thinking is a method of problem solving that focuses on developing solutions for authentic problems and provides students with opportunities to engage in analysis, synthesis and evaluation activities (Lawson, 2006). It involves multiple steps which provide space for students to learn and apply their disciplinary knowledge while working towards solving the design problem:

1) Identifying a problem
2) Researching possible solutions
3) Picking the best solution
4) Building a prototype
5) Testing the prototype
6) Repeating any steps needed to improve the design

Students' active involvement in authentic learning design processes and practices provides them with opportunities to make sense of concepts [across the disciplines], helps them construct knowledge and apply concepts to solve real-world problems; thus reflecting how science, mathematics and engineering are practiced in the real world (Anwar et al., 2022). However, "design is not just about how a product or service looks. At its simplest, design is a process to find and understand the needs of people and to find creative ways to solve problems to meet those needs" (GoI, 2022, p. 3). It is a process that fosters empathy, a deeper awareness of the needs and feelings of people, which Liu Sun (2017) claims is a recognised deficit in traditional STEM education. Engaging in an empathy-focused pedagogical approach is believed to encourage young people to become more actively engaged with issues around them (Kijima et al., 2018), helping them to be socially aware and responsible, and is particularly important for preparing K-12 students to effectively tackle many of the complex, human-centred, and STEM-related issues of the 21st century (Liu Sun, 2017 as quoted in Kenna, 2022). In addition, as documented in Kijima et al (2018) research indicates that "under-represented students, such as first-generation, minority, and female students, show greater motivation to pursue STEM topics if they believe that science advances pro-social goals, such as improving the lives of others and serving their communities" (p. 10).

The research literature also highlights that by engaging in design thinking a clear relationship can be established with Science, Mathematics and Technology. The specific supports for science learning linked with engineering design tasks have already been highlighted in Section 3. Additionally, we note here that the research emphasises the mutually reinforcing nature of science and design - for example, Marulcu et al., (2013) suggest that inquiry and design can support each other to accomplish both science and technology learning. In particular, "design could support inquiry and science learning once it is used as a context for science teaching. Also, science education research supports the view that design activities help students gain many abilities that are needed to understand science content and to perform inquiry" (p.1829). Additionally, design justification is one way to require the students to apply disciplinary understandings (e.g., scientific and mathematical concepts) to the engineering design. As Anwar et al., (2022) suggests students should make recommendations for design decisions supported by the background information, content, data, and results from tests. The justification of design choices resembles the argumentation practices in science education (Hand et al., 2009; Llewellyn, 2014; Toulmin, 2008). Furthermore, the collaborative nature of design provides opportunities for teamwork (Kolodner, 2002) and involves people working together to solve real-life problems that address societal as well as personal needs (Atman et al. 2008).

A range of understandings and models of design thinking are included across the curricula analysed. Designing, building and testing computing solutions is one of 13 key concepts in the Scottish Technologies curriculum where the **"**application and interpretation of designing, offering learners opportunities to become independent in designing solutions to meet real-life needs and challenges, and adept at solving problems of increasing scale and complexity" (CfE, p4). A framework has been developed as part of the Scottish Technologies curriculum to provide clarity on the lines of progression in the five categories of the curriculum across the school stages. In addition, a range of practical supports and resources are provided through the Curriculum for Excellence website.

In Wales, design thinking and engineering is one of six underpinning curriculum goals and the descriptions of learning in design thinking and engineering are laid out across five developmental steps (Figure 4.1).

Figure 4.1

Descriptions of Learning: Design Thinking (Wales)

Design thinking and engineering offer technical and creative ways to meet society's needs and wants.

Progression step 1	Progression step 2	Progression step 3
I can design while I make and communicate about what I am making.	I can produce designs to communicate my ideas in response to particular contexts.	I can draw inspiration to design from historical, cultural and other sources.
I can safely use simple tools, materials and equipment to construct and deconstruct.	I can make design decisions, using my knowledge of materials and existing products, and suggest design improvements.	I can creatively respond to the needs and wants of the user, based on the context and on the information collected.
I can explore the properties of materials and choose different materials for a particular use.	I can explore how different component parts work together.	I can identify and consider factors when developing design proposals.
I can identify, follow and begin to create sequences and patterns in everyday activities.	I can safely use a range of tools, materials and equipment to construct for a variety of reasons.	I can use design thinking to test and refine my design decisions without fear of failure.
	I have experienced using basic prototyping techniques to improve outcomes.	I can apply my knowledge and skills when making design decisions in order to produce specific outcomes.
	I can identify things in the environment which may be harmful and can act to reduce the risks to myself and others.	I can consider how my design proposals will solve problems and how this may affect the environment.
	I can explore and describe the properties	

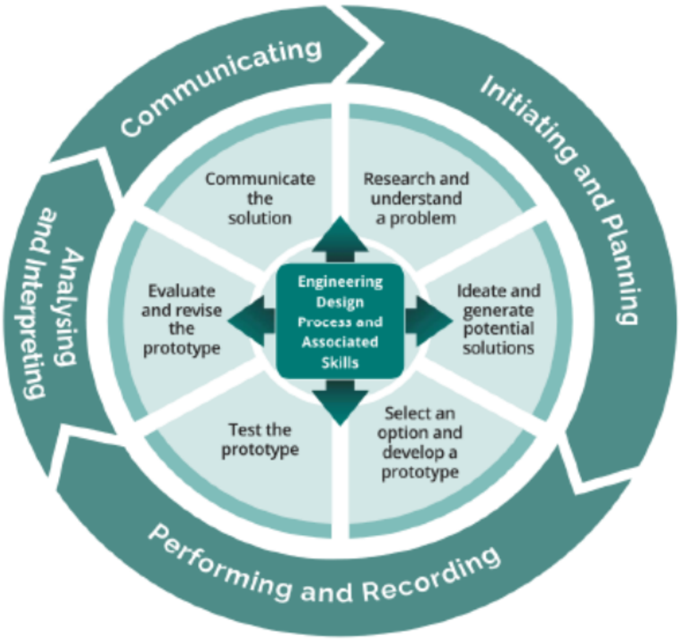
In addition, teachers are provided with a set of key considerations to guide planning in epistemic, procedural and content knowledge, for example:

- develop conceptual and procedural knowledge of a range of materials and techniques through practical experiences to inform learners' design thinking and support their capacity for engineering and making.
- engage in iterative design processes, including continual testing and evaluating. Using low-fidelity and high-fidelity prototyping and high-quality making also supports the iterative design process.
- create software solutions that are fit for purpose. Knowing how to design, create, test and use software that is functional, robust and considerate of diverse audiences.

In Australia, the Design and Technologies curriculum places a strong focus on design thinking, the application of the design process and producing (making) solutions to design products, services and environments. It includes using design thinking strategies in order to understand design problems, generate creative and innovative ideas, and analyse and evaluate these ideas to find the best solution. Across primary and post primary school, students are provided with multiple opportunities to produce at least three types of designed solutions (product, service and environment) which have been specified to give students opportunities to engage with a broad range of design thinking and production skills. Curriculum content is supported by exemplars.

Figure 4.2

Engineering Design Process and Associated Skills (Ontario)



In Ontario, an engineering design process (EDP) is employed as an underpinning framework in the strand STEM Skills and Connections (See Figure 4.2 on previous page) to enable students and teachers to plan and build solutions to problems or develop ways to address needs that connect to the curriculum and the world around them. As illustrated in Figure 4.2, it involves students initiating and planning solutions, performing tests and recording data, analysing and interpreting results, and communicating those results using appropriate vocabulary and forms for a variety of purposes. The end product of the EDP might not be a tangible object; it might instead be a computer simulation or a model, or even a new scientific or technological process or system. Each component of the EDP is described in detail in the curriculum.

4.2.2 Computational thinking

The main rationale for introducing computational thinking (CT) in most countries is to foster 21st century skills, which are understood as essential for an active life in the digital world. (Bocconi et al., 2022). Computational thinking represents a way of thinking about solving complex, open-ended problems and is considered a fundamental skill for everyone, not just for computer scientists (Wing, 2006). It can be generally defined as a way of thinking that includes skills and practices that are part of computer programming, such as algorithmic thinking, abstraction, generalisation, decomposition, and debugging (Brennan & Resnick, 2012).

Computational thinking is recognised as a foundational competency for problem solving in STEM contexts (Grover & Pea, 2018). Recent studies that look at integrating

CT and science focus on computational modelling - using computational tools to develop models of scientific phenomena, and promoting learning through the creation, testing, and manipulation of these models (Weintrop et al., 2016; Aksit & Wiebe, 2020; Wagh et al., 2017).

Computational thinking and related concepts (e.g., coding, programming) have received growing consideration for almost two decades. By 2019, approximately half of European education systems had engaged in the reform of curricula related to digital competence and, computational thinking had been introduced, or made more prominent (EC, 2020) and there is a growing movement across Europe towards the inclusion of informatics (computing or computer science) as a fundamental discipline (Caspersen et al., 2022).

Three main approaches tend to be followed when it comes to integrating CT into curricula (Bocconi et al., 2016, Caspersen et al., 2022):

- as a cross-curricular theme – basic computer science concepts are addressed in all subjects, and all teachers share responsibility for developing computational thinking skills.
- as part of a separate subject – basic computer science concepts are taught in a computing related subject (e.g., Informatics).
- within other subjects – basic computer science concepts are integrated within other curriculum subjects (e.g., Maths and Technology).

Conducted on behalf of the European Commission's Joint Research Centre; Bocconni et al.'s study (2022) found that a combination of these three approaches is commonly adopted. At primary level, CT skills are developed (i) as part of a cross-curricular theme and within other subjects such as Mathematics and Technology; (ii) as part of a separate subject but also as a cross-curricular theme or (iii) as a purely cross-curricular theme. Similar approaches were observed in the curricula examined for this report although varying levels of guidance were provided.

Computational thinking (CT) and coding learning expectations have been integrated into the Ontario Math grades 1-8 (2020), Math grade 9 (2021), Science and Technology grades 1-8 (2022), and Science grade 9 curricula (2022). The Grades 1-8 Science and Technology curriculum includes a focus on 'Coding and the Impact of Coding and Emerging Technologies' where students engage with a wide variety of science and technology concepts and contexts through coding; and the engineering design process (EDP) used in the development of a coding project. In addition, a teacher's guide, 'Effective Computational Thinking (CT) and Coding Instruction - A Teacher's Guide' has been published to help teachers deliver effective instruction in computational thinking and coding across the wider STEM curriculum. Ways that CT and coding can be implemented in the Science & Technology curriculum are also included in the guide (Figure 4.3).

Figure 4.3

Ways Computational Thinking can be Implemented (Ontario)

<table>
<tr><th>Scientific Research Process and Associated Skills</th><th>Scientific Experimentation Process and Associated Skills</th><th>Engineering Design Process and Association Skills</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><th>Possible Student Activities</th><th>Possible Student Activities</th><th>Possible Student Activities</th></tr>
<tr><td>Research impact of coding and emerging technology on an industry (e.g. healthcare, transportation, retail, agriculture, etc.)</td><td>Use sensors and code to collect data to support a scientific experiment. Coding techniques could also be used to analyse and summarize the data.</td><td>Build and test a prototype of an automated system using coding and sensors.</td></tr>
</table>

When applying coding and computational thinking skills in science and technology classroom teachers need to consider what it looks like within the following phases:

- initiating and planning (e.g., asking questions, clarifying problems, planning procedures)
- performing and recording (e.g., following procedures, accessing information, recording observations and findings)
- analysing and interpreting (e.g., organizing data, reflecting on the effectiveness of actions performed, drawing conclusions)
- communicating (e.g., using appropriate vocabulary, communicating findings in a variety of ways)

In contrast, frameworks have been designed and included as part of the curricula in Australia, Scotland and Wales so that students develop and use increasingly sophisticated computational thinking and coding skills as they progress through school. Computational thinking tends to be presented as predominantly algorithmic in nature and includes problem solving techniques and strategies, such as organising data logically, breaking down problems into components, and the design and use of algorithms, patterns and models.

Finally, Wales positions computational thinking and related concepts as part of the national Digital Competence Framework and in the Science and Technology curriculum. Computation is one of the underpinning goals in the Science and Technology curriculum which leverages plugged and unplugged approaches to computational thinking. This is complemented by the Digital Competence Framework which places emphasis on coding.

4.2.3 Digital Competence

Drawing on the EU (2018) definition, digital competence involves 'the confident, critical and responsible use of, and engagement with, digital technologies for learning, at work, and for participation in society'. Fostering the development of digital competence of citizens and learners of all ages is recognised as a cornerstone of EU Digital Education Action Plan (DEAP), 2021-2027 (EC, 2020).

Digital competence is regarded as a core concept in many international policy documents (Ilomäki et al., 2016) and has been a priority for the European Commission for some time in policies, actions, and communications (e.g., European Commission, 2010; 2013). Internationally, there has also been an increasing interest in the development and use of digital competence frameworks in education settings; some have been developed as international or national initiatives and others in the context of national curriculum development. Previous work carried out by Butler & Leahy (2021, 2022) has analysed how digital competence is framed in a range of national curricula, finding a similarity in approach and areas of competence identified. Most present competence as a broad concept that encompasses skills, dispositions, and values; and while they differ in the terminology using terms such as 'ICT capabilities', 'digital literacy' and 'ICT standards', these terms reflect similar content and there are strong similarities in the areas of competence identified across countries (See Table 4.1)

Looking across the curricula included in this report, digital competence is included as a 'transferable skill' (Ontario), 'general capability' (Australia) and 'cross-curricular skill' (Wales). In this way, it is embedded across all other areas of the curriculum including the Technology curricula. This is so that students develop digital competence as part of their learning in all curricular areas and the skills and knowledge developed in one curriculum area will be supported in other areas.

Table 4.1

Comparison of how Digital Competence is framed in a Range of National Curricula (Butler & Leahy, 2022)

Country/ Region	**Framework**		**Areas of competence**
Australia	ICT Capability learning continuum	ICT capabilities	• Applying social and ethical protocols/practices using ICT • Investigating with ICT • Creating with ICT • Communicating with ICT • Managing/operating with ICT

Toronto, Canada	Toronto District School Board ICT Standards	ICT standards	• Technology operations & concepts • Research & information fluency • Critical thinking & problem solving • Communication & • Collaboration • Digital citizenship • Creativity & innovation
Wales, UK	Digital Competence Framework[3]	Strands	• Citizenship • Interacting and collaborating • Producing • Data/computational thinking
New Zealand	Technology-Curriculum	Strands	• Technological practice, • Technological knowledge • Nature of technology
Netherlands	National Curriculum	Digital literacy: Big ideas	• Data and information • Safety and privacy • Communication/ cooperation • Digital citizenship • Digital economy • Applying and designing • Sustainability
Finland	National Curriculum	Transversal Competence	• Working with data, information • programming
Estonia	National Curriculum	Digital Competence models	• Information/Data Literacy • Problem-Solving • Digital Content Creation • Communication & Collaboration • Safety
Denmark	Trial programme (2018-2021)	Technology comprehension	• Digital Empowerment • Digital Design/Design process • Computational Thinking • Technological Knowledge & Skills

4.2.4 Artificial Intelligence and Data literacy

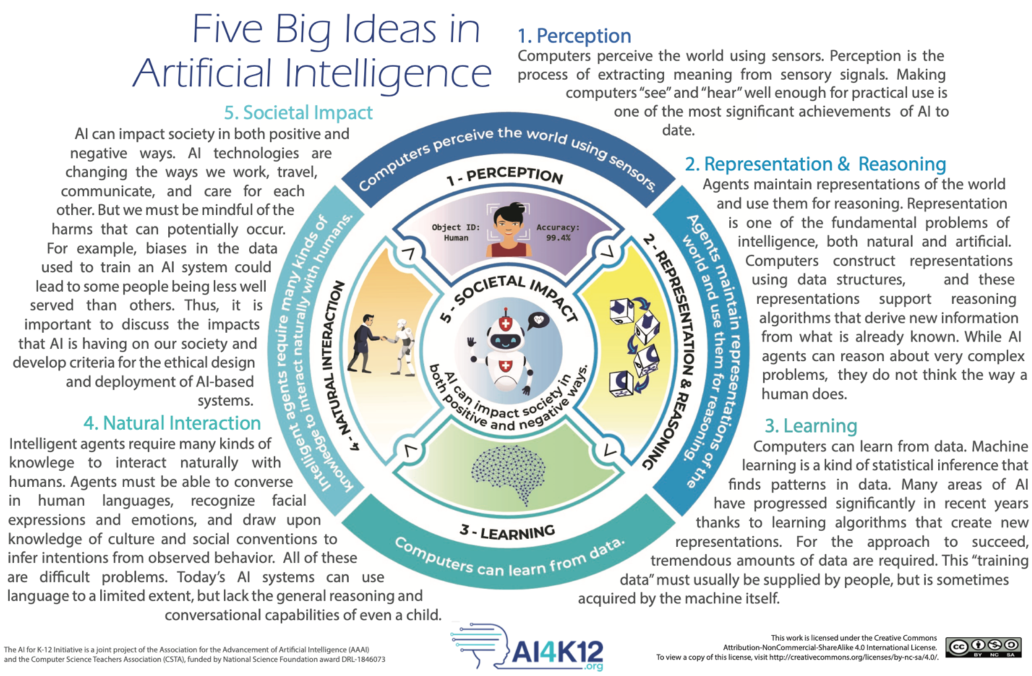
Artificial Intelligence

The continued adoption of artificial intelligence (AI) into mainstream education throughout the 2020s will initiate datafication on an unprecedented scale (Selwyn, 2019). Tackling the myriad of complex issues surrounding the use of data and AI and how it relates to schools is becoming increasingly more relevant and urgent.

Research suggests that since experts' knowledge is built around core concepts and big ideas the curriculum should be organised in the same way (Bransford et al., 2000). Drawing on the seminal paper produced by Touretzky et al. (2019), AI big ideas are framed for K-12 students around five main concepts: Perception, Representation and Reasoning, Learning, Natural Interaction, and Societal Impact (See Figure 4.4). In other words, how a robot (also called "agent") uses sensors to take information on the environment, how AI systems analyse data, find patterns and make predictions, how this software relates to humans, and what is the impact on our lives.

Figure 4.4

Five Big Ideas in Artificial Intelligence (David Touretzky et al., 2019)



Currently, AI is not included in primary school curricula although some interesting work has been done in engaging children in AI key ideas and competencies. Very young children can teach a machine learning model to recognise feelings while learning about emotions themselves (Vartiainen et al., 2020); primary and middle school children have engaged in projects on AI ethics and creativity using social robots and bespoke software (Ali et al., 2019) There are unplugged activities that allow students to engage with AI key ideas without the need of screens (Lindner et al., 2019). Undoubtedly, there are many questions that still need to be investigated such as how software and robots can be inclusive and accessible and how AI technology will impact students' learning and metacognition (Kahn & Winters, 2021). AI is a complex area but it is a critical competence that students need to develop in order to engage in our ever increasing complex digital world.

Data Literacy

Data literacy is becoming increasingly more important, with increasing and ready access to vast amounts of data requiring that all learners be able to critically assess inputs, understand the basis of information presented as fact, and make informed judgements that impact their own behaviours and values. Data literacy is vital for both STEM and non-STEM fields as every individual must be able to synthesise data to support decision-making, make sense of the world, and prepare for the future (NCTM, 2019; NCTM, 2020). Data literacy is beginning to appear in school curricula and it is included in two of the curricula analysed: Wales (published in 2018) and Ontario (published 2022).

Similar to computational thinking, data literacy is included in both the Science and Technology curriculum and the national Digital Competence Framework in Wales. Again, this is a complementary relationship where learners engage with the collection, representation and analysis of data and develop an understanding of how data drives our computational world. In addition, they use a range of software tools to create, manage and interrogate datasets to investigate lines of inquiry.

In Ontario, Data Literacy is included as a strand of the mathematics curriculum where data literacy includes data collection and organisation, data visualisation and data analysis as well as probability and statistics. A key focus in this strand is to support learners in developing critical thinking skills so that they can analyse, synthesize, understand, generate, and use data, both as consumers and producers.

4.3 Curriculum Approaches to Configuring the Core Features

The literature, as noted in the first section of this report, suggests that attention to the development of models for incorporation of iSTEM is required in the primary school curriculum along with exemplars of iSTEM projects for use across the primary grades. Curricula that include attention to STEM integration, as noted in Section 3, are relatively recent implementations. A useful starting point is therefore to look at the approaches adopted elsewhere.

Example A: National Curriculum for Wales

Science and Technology are grouped together as one of six learning areas in the National Curriculum for Wales; it pertains to the disciplines of Biology, Chemistry, Computer Science, Design and Technology, and Physics to enhance learners' knowledge and understanding of the world. The overarching goal is:

> Through robust and consistent evaluation of scientific and technological evidence, learners can become ethical, informed citizens of Wales and the

world, who will be able to make informed decisions about future actions. Healthy, confident individuals, ready to lead fulfilling lives as valued members of society, are informed by knowledge of their bodies and the ecosystems around them, and of how technological innovations can support improvements in health and lifestyle.

Included in the curriculum are statements of what matters, principles of progression, and description of learning. Two of the statements of what matters explicitly call out the transversal STEM skills of design thinking and computation:

- Design thinking and engineering offer technical and creative ways to meet society's needs and wants.
- Computation is the foundation for our digital world.

Each statement is supported by a framework or description of learning which lays out five progression steps from the perspective of learners. For example, Figure 4.1 illustrates the progressive steps for design thinking for P1, P2 and P3 (3-5 years, 5-8 years and 8-11 years).

A defining feature of the curriculum is that schools have autonomy to develop their own curriculum to meet the needs of their students. Teachers are expected to design and plan their curriculum and are advised to facilitate learning through active and practical experiences in a specific, thematic or multi-disciplinary nature. A set of key considerations to guide planning through three aspects of knowledge; procedural, epistemic and content is provided.

Example B: Ontario Science and Technology Curriculum

The aim of the Ontario Science and Technology curriculum is for students to acquire and develop the skills and knowledge they need to thrive in today's rapidly changing world. The curriculum focuses on fundamental science and technology concepts and on science, technology, engineering, and mathematics (STEM) skills. It is designed to help students develop an understanding and appreciation of each of the core subjects of Mathematics, Science, and Technological education while at the same time, supporting a more holistic understanding and application of skills and knowledge related to engineering design and innovation.

A central component of the curriculum is practical, hands-on, experiential learning that will support students in becoming scientifically and technologically literate. Throughout the primary science and technology programme, students apply scientific and engineering design processes to investigate problems relating to Science, Technology, Society, and the Environment. Students are encouraged to consider what practical steps they themselves can take to help solve some of these problems.

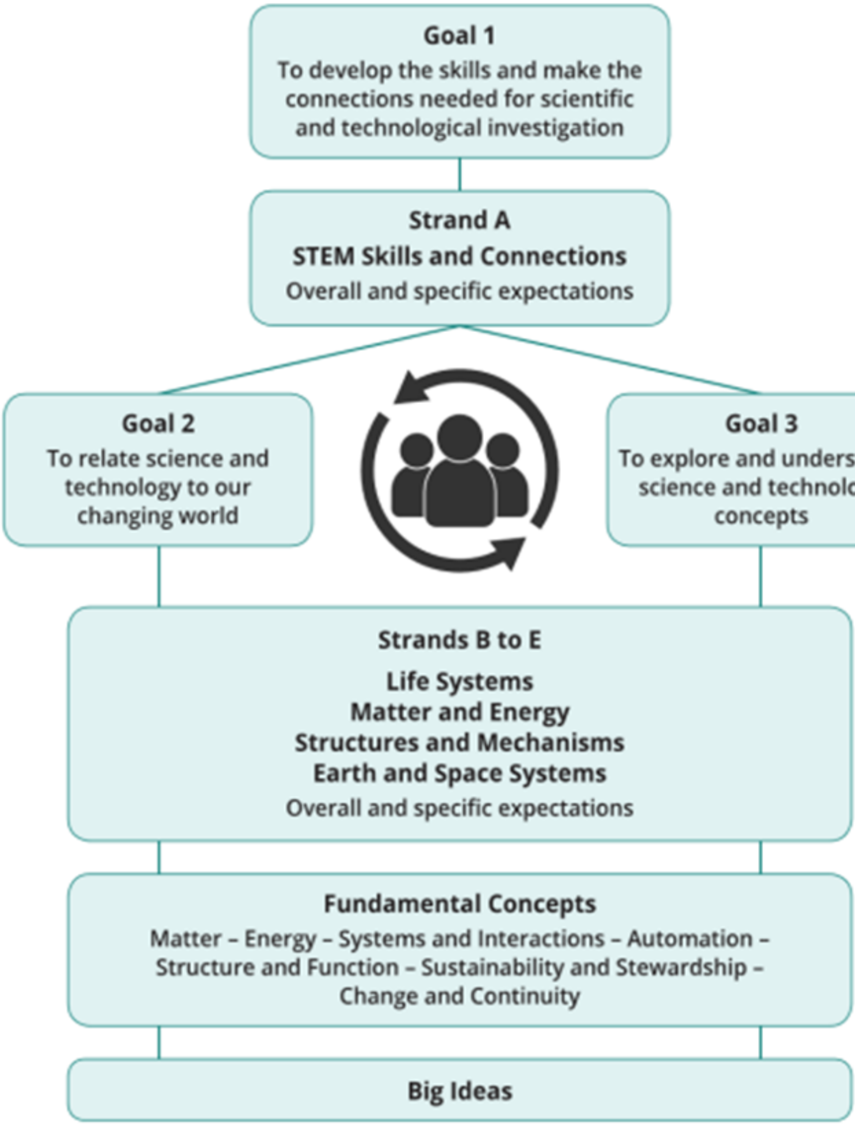
This curriculum recognises that approaches to STEM education may vary across Ontario schools whereby STEM subjects may be taught (i) separately, but with an effort to make cross-curricular connections a part of student learning (ii) problem-solving application projects may be designed to combine two or more STEM subjects, and (iii) content from all four STEM subjects might be fully integrated to reinforce students' understanding of each subject, by enhancing their understanding of the interrelationships among them, and by providing the opportunity to apply a spectrum of knowledge and skills in novel ways in real-world contexts.

- ‘Big ideas’ describe the aspects of the fundamental concepts that are addressed at each grade level. Developing an understanding of the big ideas requires students to consider and apply STEM skills as they engage in investigative processes and make connections between related science and technology concepts, between science and technology and other disciplines, and between science and technology and everyday life.
- Strand A is an overarching strand that focuses on the foundational STEM skills and connections that will enable students to investigate concepts and integrate knowledge from each of the other strands and to make practical connections between science and technology and other subject areas.

The relationship between the fundamental concepts, STEM skills and connections, big ideas, goals of the science and technology program, and overall and specific expectations of this curriculum are illustrated in Figure 4.5.

Figure 4.5

Overall Framework for Ontario Science and Technology Curriculum



The curriculum is accompanied by a supporting website that contains the specific expectations for each grade level and a range of resources including long range plans for Grades 1-8.

Example C: Australia Technologies Curriculum

Technologies is included as one of eight learning areas and comprises two mandatory subjects: Design and Technologies and Digital Technologies. Among the aims of the technologies curriculum is that:

> Students will develop the technologies knowledge, understanding and skills to engage purposefully in the process of creating preferred futures. They will use a range of thinking skills, including futures and systems thinking, to generate and communicate creative ideas. These ideas will be enacted through the practical application of design and computational thinking along

with traditional, contemporary and emerging technologies. The end products students produce (make) will be effective, meaningful and culturally authentic solutions to identified problems or opportunities in personal, family, community and global settings.

Each of the two subjects specify the distinct knowledge, understanding and skills of the subject area and, where appropriate, also highlight their similarities and complementary learning. This is to allow for connections to be made and provide the flexibility for developing integrated teaching programmes. The key difference between Design and Technologies and Digital Technologies is the relative emphasis on design thinking and computational thinking. While both are utilised in each subject, Design and Technologies has a strong focus on design thinking, the application of the design process and producing (making) solutions in the form of products, services and environments. In Digital Technologies the focus is on the use of digital systems, information and computational thinking to create solutions for identified needs and opportunities (See Figure 4.6).

Figure 4.6:

Technologies Curriculum: Design and Technologies and Digital Technologies

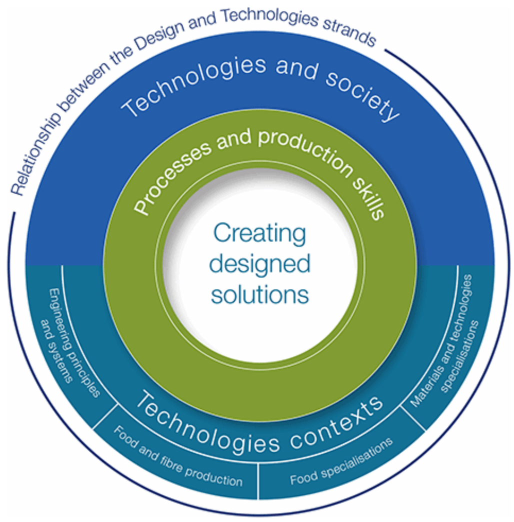


Figure 4.6a Relationship between the Design and Technology strands

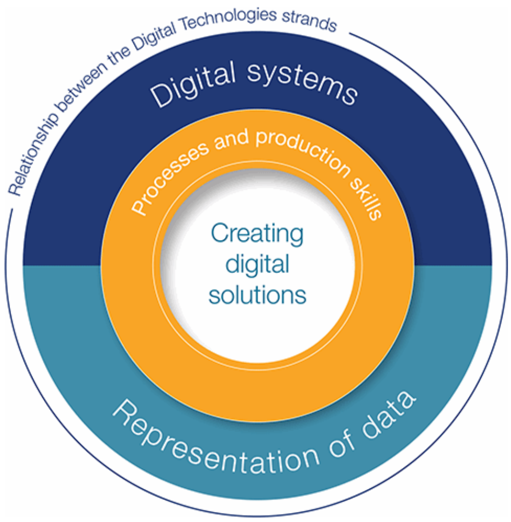


Figure 4.6b Relationship between the Digital Technologies strands

Like all other areas in the Australian curriculum, the Technologies Curriculum is supported by a guiding framework in which curriculum content is presented as content descriptions which specify the knowledge, understanding and skills that young people are expected to learn and that teachers are expected to teach across the years of schooling. The content descriptions are accompanied by content elaborations which provide illustrations and/or examples that teachers may choose to use in the classroom or as inspiration for their own activities.

Example D. Swedish Technology Syllabus

Among the overall goals of the national curriculum in Sweden is that upon graduating compulsory schooling, students will be able to use both digital and other tools and media for attaining knowledge, processing information, problem-solving, creation, communication and learning. This goal is further clarified as part of the core content in each of 21 syllabi of the curriculum, one of which is Technology. Technology has been included as a subject in the Swedish National Curriculum since 1994 with the goal of helping students develop knowledge and skills needed for orienting and acting in a technology intensive world. With curriculum revision in 2017, increased attention was accorded to digital technologies within the core content and knowledge requirements of the Technology syllabus. This is set out across three areas: (i) Technological solutions, (ii) Working methods for developing technical solutions, and (iii) Technology, man, society and the environment. Core content in each of these areas is presented as a series of learning outcomes for each of the three stages (years 1-3, years 4-6, and years 7-9), and knowledge requirements (assessment criteria) for awarding students either A, B, C, D, or, E grades at the end of years 6 and 9.

Schools have autonomy in the delivery of each subject from a pedagogical perspective. Provided teachers address the core content in the syllabi, they can structure the organisation of learning however they wish.

Implications

Looking across the curricula, a number of observations can be made; in Sweden, while the Technology syllabus outlines the core content and knowledge requirements, it is lacking in detail. Moreover, schools have autonomy both in how they structure the organisation of learning and the pedagogical approaches adopted. A consequence is that there is no consensus relating to the content and implementation of the subject (Fahrman, Gumaelius, & Norstrom, 2015) - a practice which leads to insecure teaching (Norström, 2014). There is also a risk of inequality amongst schools and of the students' STEM experiences becoming fragmented.

schools and teachers design their own curriculum represents a significant culture shift for Irish teachers and would demand significant teacher professional learning and support if it were to be successfully implemented in primary schools in Ireland. In contrast, the models, frameworks, supports and resources contained in the Technology curricula of countries such as Ontario and Australia provide useful points of reference.

Section 5

What aspects of the curriculum area (knowledge, skills, values and dispositions) support integration in stages 1 and 2, and what aspects of the subjects support integration in stages 3 and 4?

Before the aspects of the STEM disciplines that can support integration are considered, it is important to reiterate a number of key messages emerging from the literature on effective iSTEM. First, it is apparent that for effective integration of STEM, students must be afforded opportunities to engage with both the individual STEM disciplines and iSTEM projects. Time therefore must be allocated for Mathematics and Science as disciplines (see Mathematics curriculum and Science recommendations in this report) and for interdisciplinary STEM projects. A balance needs to be struck between disciplinary and integrated STEM.

Additionally, as the literature notes, iSTEM projects also need dedicated time. Our survey of the literature and the various curriculum documents and reports suggests the inclusion of an iSTEM project per term, with projects planned purposely to surface or draw from a range of different mathematical, scientific, technology and design components across different projects. Planning for synergies between disciplinary and integrated STEM teaching requires careful planning, as this supports the building of, and progression in, disciplinary learning and transversal skills. More haphazard inclusion of topics can provide access to useful experiences, but they tend to involve inefficient use of time as teachers need to 'side-step' into the teaching of particular topics in the course of integrated project working.

While we see nothing wrong with this kind of 'side-stepping' into disciplinary teaching as concepts arise in the course of iSTEM project working, doing this in unplanned ways tends to contribute to greater risks of uneven experiences afforded to children by different teachers, and offers too little support for teachers with fragile confidence in their own STEM disciplinary and interdisciplinary teaching.

Clarity is essential for effective iSTEM implementation. To this extent frameworks / models of iSTEM and what progression within iSTEM can look like need to be developed and supported by exemplars of iSTEM projects for use across all stages. The STEM education curriculum area is a new curriculum area for primary teachers in Ireland and while some are already integrating the STEM subjects to varying degrees, iSTEM methodologies and projects are not commonplace in Irish primary schools. To avoid poor iSTEM methodologies being adopted, or teachers becoming overwhelmed, iSTEM frameworks, models and project exemplars should be made available to teachers with the publication of the curriculum specifications. Several iSTEM frameworks already exist (e.g., Butler et al., 2020) which in turn can inform the design of key stages and learning trajectories.

It was apparent from the literature review that the positive impacts of Science and STEM interventions on students' learning are dependent on teachers' support, appropriate scaffolding and structured curricula (Anwar et al., 2015). If teachers are to design authentic learning experiences which integrate core STEM competences within real-world contexts, we believe it is essential that they have first-hand experience of working in this way themselves, in order to be in a position to inspire truly innovative STEM learning in their classrooms. This view is supported by the research literature which illustrates the strong connections between teacher professional learning and successful learning outcomes for students (Anwar et al., 2022; Cunningham et al., 2020; Marulcu & Barnett, 2013). However, professional learning opportunities, which are already described as limited in relation to Mathematics and Science, need to be improved, and expanded to include examples of, and spaces to try out, integrated STEM projects. These opportunities must not be 'once off, one size fits all' type approaches; they need longitudinal timelines of ongoing, sustained and customised support, tailored to suit the individual needs and contexts of schools.

Effective iSTEM requires careful planning and therefore dedicated time for planning iSTEM projects should be earmarked / prioritised in schools. Schools could also be supported in their planning and implementation of iSTEM projects via Oide, the new support service for professional learning of teachers and school leaders in Ireland. Furthermore, as recommended in the STEM Education 2020 report, if STEM education is to be effective, it needs to be situated within the school self-evaluation process. This would enable schools to pose questions that challenge their approaches and by self-evaluating their STEM education practices, schools would be well placed to identify strengths and weaknesses and then proactively address areas for development (DES, 2020).

5.1 Areas of Mathematics that Support Integration

The draft *Primary Mathematics Curriculum* (NCCA, 2022) and the reports that fed into the development of this curriculum (in particular, Dooley et al., 2014; Dooley, 2019) flag areas of mathematics that particularly lend themselves to STEM integration. Among these are modeling projects involving real-world phenomena, with the mathematics curriculum citing the work of Lesh and Doerr's (2003) writing on design principles for eliciting modeling activity (e.g., NCCA & Nic Mhuirí, n.d.), and problem-solving projects involving mathematical processes and practices, with this kind of mathematizing described as a core feature of the *Primary Mathematics Curriculum*. As noted in the Science recommendations below, ensuring a focus on 'big ideas' in mathematics is viewed as a way of dealing with both important mathematical concepts in teaching and learning and supporting integrated STEM, given that these ideas often underpin the structure of phenomena in the world. Multiplicative reasoning is one example of a mathematical big idea that underlies a whole swathe of mathematical topics (fractions, ratio, linear patterns, trigonometry among others), and several real-world situations.

Across all stages, interdisciplinary/real-world investigations and problem-solving that lead to the emergence of mathematical concepts (e.g., developing approaches for fair sharing in Stages 1 and 2), alongside projects that involve applications of content and reasoning linked to curricular content in these years can be incorporated.

5.2 Aspects of Science that support integration

5.2.1 Knowledge

Content from all the sciences (Biological, Physical, Material, Environmental) is appropriate and should be used to support iSTEM. As suggested in the science recommendations (Section 3), iSTEM inquiries should draw on content related to 'Big Ideas' in science. It is important that this scientific content is relevant and applicable to children's everyday lives and that while students in primary school are capable of engaging in the more 'difficult' science knowledge, teachers need to be cognisant of addressing children's existing naive conceptions in the first instance.

5.2.2 Working Scientifically

The literature notes that engaging with iSTEM projects supports the development of scientific knowledge and skills. It is also apparent that there are further positive impacts on children's learning in and engagement with science when iSTEM projects afford students opportunities to conduct hands-on scientific inquiries using both concrete resources and digital technologies to address questions, solve a problem or propose a solution (Lamb et al., 2015).

In this regard all scientific process skills, including higher order skills like reasoning and argumentation, can and should be applied in iSTEM projects at all stages in primary school. At a very basic level students could, for example, be asked to carry out a scientific investigation to answer a particular question or solve a problem, using digital technologies and mathematical knowledge and processes to enhance their investigations, for example, to gather, observe, measure, analyse data or to report findings from the investigation. Such inquiries can be carried out in all stages of primary school and different levels of teachers' scaffolds can be provided as required, depending on the age of children and/ or their experience of engaging with inquiry. Children in younger classes, for example, could do more structured or guided inquiries moving to more open inquiries as children progress through the different stages. Following on from this, students might be asked to design an artefact /model/ prototype that would solve a problem or propose a solution to a problem. In this instance students would use their scientific and mathematical knowledge and skills and engage in the engineering design / design and make processes to plan and build a prototype or an artefact. This could be extended by asking students to develop their prototype / model further, incorporating digital technologies (e.g., via robotics, animations or computer simulations). Through this type of integration children use their scientific, mathematical, technological, and design knowledge and skills and apply them to new situations to solve problems, thus supporting the development of science and STEM literacy.

5.2.3 Model based learning

The literature also suggests that engaging in model-based practices have positive impacts on science learning and can support effective engagement in iSTEM.

Affording children opportunities to develop scientific models in different forms, including physical models, mathematical models, computer simulations, visual diagrams and analogies seamlessly integrates the STEM disciplines. Model based practices afford children opportunities to apply and develop a range of STEM competencies, including, creativity, problem solving, critical thinking and reasoning.

5.3 Aspects of Technology/Engineering that support integration

As detailed in Section 4, a set of core transversal processes are identified across international curricula that support integration as: design thinking, coding/ computational thinking, digital competence and data literacy. In the Irish context, the NCCA has engaged in research (Millwood et al., 2018; NCCA, 2019) and also commissioned reports (Butler & Leahy, 2022; Kenna, 2022; Waite & Quill, 2022) on these transversal processes and concepts which can be leveraged to inform the development of future iSTEM curricula. Across the literature, these skills are recognised as foundational competencies for critical thinking and problem solving in STEM contexts. Disciplinary relationships can be established with Science, Mathematics and Technology.

5.4 Concluding comments

We believe that teachers are the catalyst to realising the potential of STEM in disciplinary and integrated forms, and to ensuring that effective, sustainable systematic change happens. However, for many educators achieving the vision will require a sea-change in how they understand STEM teaching, learning and assessment and will require making adjustments to long-term established schooling models. Integrated STEM is new for many teachers, so it is imperative that they are supported during their pre-service education and ongoing professional learning to increase their knowledge and understanding of STEM in action in real-world contexts.

There is a symbiotic relationship between the development of STEM teaching and learning, underpinned by frameworks, key stages and learning trajectories, and the design of teacher professional learning. Work with teachers on developing these frameworks and exemplars informs the common language which enables opportunities for identifying / making STEM connections across and between the disciplines explicit to students and educators. In addition, it supports the framing and clear articulation of learning goals and learning progressions that are fundamental to seeing improved STEM experiences for children in primary schools.

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