

Effectiveness of Digital Learning in Primary School Science Education: A Conceptual Framework

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Abstract

Digital learning offers opportunities to support primary Science through visualisation, simulation, inquiry and collaboration, but technology use alone does not guarantee improved learning. This concept paper develops a process-oriented framework explaining how digital learning may become pedagogically effective in primary Science education. A structured literature search was conducted in Scopus, Web of Science and Google Scholar, yielding 548 initial records. Ten focal sources were purposively selected for the evidence map and conceptual synthesis; the 548 records are not the number of studies included. The main evidence window was 2022–2026, with foundational theoretical and policy sources retained where relevant. The proposed framework connects Technological Pedagogical Content Knowledge (TPACK) and the European Framework for the Digital Competence of Educators (DigCompEdu) with learner readiness and learning-ecosystem conditions. It proposes that outcomes depend on alignment among Science content, pedagogy and technology, teacher digital-pedagogical competence, and contextual readiness. These conditions shape learning processes such as prediction, visualisation, investigation, evidence recording and explanation, which may support engagement, conceptual understanding, Science process skills and achievement. The framework offers a Science-specific account of the conditions and mechanisms through which digital learning may create pedagogical value.

Keywords: Digital Learning, Science Education, Primary School, Tpack, Digcompedu, Educational Technology

Introduction

Digital transformation has expanded the ways teachers organise instruction and the ways learners access, process and communicate knowledge. In primary education, digital learning may include multimedia resources, simulations, interactive applications, mobile devices and learning platforms. However, the presence of technology does not in itself demonstrate educational effectiveness. The central issue is whether a digital resource supports the intended learning objectives and improves the quality of pupils' learning activity.

In Malaysia, the Digital Education Policy provides a national framework for digital education through six pillars, 18 strategies and 41 initiatives. It recognises the connected roles of

learners, educators, educational leaders, infrastructure, digital content and strategic collaboration (Kementerian Pendidikan Malaysia, 2023). This policy context indicates that effective digital learning depends not only on classroom tools, but also on teacher capability, equitable access, suitable content and school-level support.

Primary Science is a useful context in which to examine this issue because many scientific processes, structures and phenomena are difficult to observe directly. Simulations, animations, videos and interactive visualisations can help pupils examine representations, compare conditions and investigate relationships. Evidence from primary Science and inquiry-based learning suggests that digital resources can support visualisation, observation and interpretation of data when these resources are embedded in purposeful learning activities (Ariffin et al., 2023; Yun & Crippen, 2024).

The issue is particularly important for primary pupils, who are developing foundational scientific concepts, observational practices and early scientific reasoning. Digital environments can make some phenomena more visible and manipulable, but unfamiliar interfaces or complex displays may divert attention from the Science concept. Age-appropriate design, clear instructions, structured inquiry and teacher mediation are therefore necessary to help pupils use digital tools for scientific thinking rather than interaction alone. At the same time, technology use should not be assumed to produce higher academic achievement automatically. Outcomes may vary with the design of an intervention, classroom practice, the intended learning outcome and the fit between a tool and the Science content. Research and policy discussions emphasise the need to evaluate educational technology in relation to evidence and the conditions in which it is used, rather than treating access as a sufficient explanation of learning gains (Hall & Lundin, 2024; UNESCO, 2023). The specific problem addressed here is therefore how the conditions of digital implementation connect to the learning processes that matter in primary Science.

Two complementary perspectives help explain these conditions. Technological Pedagogical Content Knowledge (TPACK) emphasises the interaction among teachers' technological, pedagogical and subject-matter knowledge (Koehler & Mishra, 2009), while DigCompEdu describes broader educator competences for selecting digital resources, facilitating learning and using digital assessment (European Commission, 2017). These perspectives are valuable, but neither alone provides the complete Science-specific process explanation proposed here: how implementation conditions shape digital learning activities and how those activities support pupils' prediction, observation, evidence recording, interpretation and explanation.

This concept paper addresses that conceptual need by proposing a Science-specific, process-oriented framework connecting (1) technology–pedagogy–content alignment, (2) teacher digital-pedagogical competence, (3) learner readiness and (4) learning-ecosystem readiness. Its novelty is not the creation of a new standalone technology theory, but the explicit connection of these enabling conditions to the disciplinary work of primary Science: pupils predict, observe or manipulate phenomena, record and compare evidence, and develop reasoned explanations. This offers a context-sensitive contribution to educational and social-science discussions by linking teacher practice, learner participation and school conditions to the processes through which digital learning may support conceptual understanding, Science

Process Skills, engagement and achievement. The proposed relationships remain conceptual and require empirical examination.

Purpose and Conceptual Questions

This concept paper has three purposes. First, it synthesises literature concerning the benefits and learning outcomes associated with digital learning in primary Science education. Second, it identifies pedagogical, teacher, learner and ecosystem conditions that influence the effectiveness of digital learning. Third, it proposes a conceptual framework explaining how and under what conditions digital learning may support primary Science learning outcomes. The conceptual questions are:

- What forms of learning benefit are associated with digital technology use in primary Science education?
- What conditions influence the effectiveness of digital learning integration in primary Science?
- How can TPACK, DigCompEdu and contextual conditions be integrated to explain the pedagogical effectiveness of digital learning?

Literature Review Approach

This manuscript is a concept paper informed by a structured literature search and focused conceptual synthesis. It is not presented as a full systematic literature review (SLR), and it does not claim that all records retrieved were screened through a PRISMA workflow. The purpose of the search was to identify a credible and relevant body of literature that could inform a conceptual explanation of digital learning effectiveness in primary-school Science. The approach therefore combines a transparent account of the initial search with purposive selection of focal sources for full-text conceptual analysis. Foundational theoretical and policy sources were considered separately from empirical studies because they serve different evidential purposes.

Databases and Search Strategy

The initial search was conducted using Scopus, Web of Science and Google Scholar. The counts supplied for the search were 198 records from Scopus, 200 from Web of Science and 150 from Google Scholar, giving 548 initial records in total. These figures represent records identified at the search stage, not the number of unique studies included in the conceptual synthesis. Because a complete duplicate-removal and screening log was not available for this concept paper, the manuscript does not report invented numbers for duplicates, records screened, exclusions or final included studies. This distinction is important: the initial retrieval total is reported as a search descriptor, not as evidence that 548 studies were analysed.

The principal search string combined four concept groups: digital learning or educational technology; Science education; primary or elementary education; and learning outcomes or learning processes. The search string was: ("digital learning" OR "digital technology" OR "educational technology" OR "technology-enhanced learning" OR "digital media") AND ("science education" OR "science learning" OR "science teaching" OR "primary science") AND ("primary school" OR "elementary school" OR "primary education") AND (effectiveness OR achievement OR engagement OR "conceptual understanding" OR inquiry OR collaboration). Search fields differed according to the database interface; terms were adapted to available

title, abstract and keyword fields. Google Scholar was used as a supplementary discovery source rather than treated as equivalent to a curated bibliographic database.

Search Period and Eligibility Considerations

The main evidence window was 2022–2026, with source checks conducted for this manuscript in October 2026. This period prioritises recent evidence on contemporary digital learning while allowing foundational theoretical and policy documents to be retained where needed to define the conceptual framework. The date limit applies to the main contemporary evidence, not to classic theoretical sources such as the original TPACK formulation or the DigCompEdu framework.

Sources were considered for the conceptual synthesis when they addressed digital learning or educational technology in primary/elementary education, or offered a directly relevant Science-education perspective, and when they informed at least one conceptual dimension: technology-pedagogy-content alignment, teacher digital-pedagogical competence, learner readiness, learning processes/outcomes, or ecosystem conditions. Priority was given to peer-reviewed journal articles, review studies, official policy documents and clearly identified research reports with traceable publication details. Studies focused solely on higher education or unrelated subject areas were not treated as direct evidence for claims about primary Science. Research on secondary-school teachers or AI was used only as contextual evidence about implementation challenges, not as direct evidence of primary-school Science outcomes.

Thematic Synthesis

The literature was organised thematically rather than statistically. The synthesis focused on recurring dimensions that were directly relevant to the conceptual questions: student engagement and learning experience; visualisation and conceptual understanding; inquiry and investigation; project-based learning; collaboration and communication; academic achievement; student readiness; teacher digital-pedagogical competence; and ecosystem readiness. Thematic synthesis was used to compare what the literature suggests about benefits with the conditions required for those benefits to occur. This distinction is central to the proposed framework because the same technology may support learning in one setting but produce limited value in another.

Because this is a concept paper, the analysis does not claim a PRISMA-compliant systematic review and does not calculate an effect size. The 548 records represent the initial search pool, not the number of studies analysed. Ten focal sources are presented in Table 1 to show how selected evidence informs the conceptual synthesis; this is a purposive, illustrative evidence map rather than a claim that a complete systematic-review screening process was undertaken. The paper therefore does not report unverified counts for duplicates, records screened, exclusions or a comprehensive final included-study set. Future work can operationalise the proposed framework through a full systematic review or empirical study with a formal screening protocol.

To clarify how the literature informs the framework, Table 1 summarises ten focal sources selected for their relevance to the conceptual questions. The table distinguishes empirical findings, review-level conclusions and contextual or theoretical evidence according to their

role in the argument. Other references in the manuscript provide theoretical foundations, policy context or supplementary discussion and should not be confused with the ten focal entries in Table 1.

Table 1

Representative focal sources and their contribution to the conceptual synthesis

Focal source	Context/design stated in source	Relevant evidence or argument	Role in this paper
Ariffin et al. (2023)	Quasi-experimental study; 30 primary pupils; web-based visual media.	Reported significant pre/post achievement differences, improved Science Process Skills and positive pupil perceptions.	Supports the visualisation-to-scientific-practice pathway.
Abd Samad et al. (2022)	Needs analysis involving 188 Year Five pupils in rural national schools.	Identified access to mobile devices and a need for a Year Five Science mobile application.	Informs learner access, readiness and context-sensitive design.
Lam and Norman (2024)	One-group pre/post quasi-experiment; 29 primary pupils; metaverse-based Science learning.	Reported higher post-test scores and high interest in the intervention; findings are bounded by the sample and design.	Illustrates potential benefits while cautioning against broad causal generalisation.
Ambotang et al. (2024)	Survey of Year Six pupils on DELIMa 2.0 use.	Motivation was strongly associated with platform use; e-learning readiness showed a weaker positive association.	Informs learner readiness and engagement; not direct evidence of Science achievement.
Yun and Crippen (2024)	Systematic review of 22 empirical studies in inquiry-based elementary Science.	Technology was particularly used to support observation and data interpretation during inquiry.	Supports the Science inquiry-process pathway.
Aktaş and Özmen (2026)	Systematic content analysis of 90 TPACK-in-Science articles.	Found that domain-specific TPACK remains underexplored and called for more attention to content-specific pedagogy and tools.	Justifies the need for a Science-specific contribution beyond generic TPACK.
Murphy et al. (2023)	Research report including a systematic review of primary Science education.	Emphasises disciplinary learning, working scientifically and model-based learning in primary Science.	Supports focus on scientific practices and age-appropriate modelling.
Wulandari and Sumarno (2026)	Systematic review of 10 studies on digital media in elementary Science.	Synthesised evidence on motivation, conceptual understanding and active participation while stressing appropriate integration.	Supports the benefits-and-conditions argument.
Jekri et al. (2025)	Study of teachers' perspectives on generative AI in STEM; not direct evidence of primary Science outcomes.	Highlights teacher knowledge, confidence and implementation challenges associated with AI-supported STEM education.	Used only as adjacent contextual evidence about implementation conditions, not as direct evidence of primary Science outcomes.
Sarif et al. (2022)	Literature-based needs analysis for an animation-assisted teaching module in primary Science; eight full-text articles were analysed in the source study.	The paper identifies a need for animation-assisted materials to diversify primary Science teaching and support understanding of complex concepts.	Adds a Malaysia-based rationale for age-appropriate visualisation and purposeful material design.

Conceptual Basis of Digital Learning in Primary Science

In this paper, digital learning refers to the use of digital technologies to access resources, interact with content, conduct learning activities, communicate, collaborate and receive feedback. The concept is not restricted to online learning because digital technologies may be incorporated into face-to-face, blended or self-directed learning environments. This broader definition is useful for primary Science because technology can function as one component within an ordinary classroom lesson rather than as a separate mode of education. In primary Science, digital technology has pedagogical value when it expands learners' opportunities to observe phenomena, manipulate variables, record data, compare representations, construct explanations and receive feedback. A simulation, for instance, can provide an opportunity for learners to test predictions and observe changes that may be difficult, costly or unsafe to reproduce physically. However, its educational value may be limited if learners interact with the simulation without a clear scientific question, task or teacher guidance. The distinction between technological affordance and pedagogical use is therefore fundamental.

The conceptualisation also recognises that digital learning is not one uniform intervention. Video, simulation, digital games, learning management systems, interactive presentations, virtual laboratories and collaborative platforms provide different affordances. A video may support observation and explanation, whereas a simulation may support manipulation of variables and prediction. A collaborative platform may support communication and peer feedback, while a digital assessment tool may support formative feedback. Consequently, the question of effectiveness must always specify the technology, learning activity, Science content and intended outcome.

Literature-Based Perspectives on Digital Learning

Student Engagement and Learning Experience

Digital technologies can increase opportunities for learners to interact with content through simulations, videos, quizzes, visualisations and collaborative activities. Such interaction can make lessons more varied and provide immediate opportunities for learners to act on information. However, engagement should not be reduced to screen time or visible participation. A learner may spend considerable time using a digital device without engaging deeply with the underlying Science idea. Meaningful engagement occurs when digital activities require learners to predict, explore, explain, compare evidence, solve problems or respond to feedback. A review of digital learning media in primary education similarly identifies learner motivation, active participation and the quality of implementation as important considerations (Salam et al., 2024).

In this sense, engagement has behavioural, cognitive and affective dimensions. Behavioural engagement may involve participation in an activity; cognitive engagement involves sustained thinking and use of evidence; and affective engagement relates to interest, confidence or perceived relevance. Digital tools may support these dimensions when they provide manageable challenges and opportunities for active participation. Yet poorly designed digital activities may have the opposite effect by increasing distraction, cognitive overload or dependence on superficial interaction.

Visualisation and Conceptual Understanding

Visualisation is particularly relevant in Science because some concepts involve microscopic structures, rapid processes or phenomena that are difficult to observe directly. Interactive simulations and digital representations can help learners connect abstract ideas with observable representations. For example, dynamic representations can show change over time and allow learners to compare conditions that would be difficult to manipulate repeatedly in a physical setting. Such affordances are especially relevant to young learners who are still developing the ability to move between concrete observations and abstract scientific explanations. Recent work on multimodal technology-integrated Science teaching also highlights the potential of combining visual and digital representations to make early Science learning more interactive, while noting that the design must suit young learners (Salehi Gahrizangi et al., 2026). A Malaysian needs analysis for an animation-assisted primary Science module likewise identified the need for visual materials that can help pupils approach complex concepts (Sarif et al., 2022).

However, visual resources are most educationally useful when accompanied by questions, prompts and tasks that guide learners to interpret what they observe. Simply displaying an animation does not guarantee conceptual understanding. Teachers need to draw attention to relevant features, ask learners to make predictions, and require explanations that connect the representation to scientific concepts. Thus, visualisation is best understood as a mediating learning process rather than as an outcome in itself.

Inquiry, Investigation and Project-Based Learning

Digital technology can become part of inquiry when learners use it to formulate questions, search for information, manipulate variables, record observations and construct explanations. Yun and Crippen (2024) highlight the role of technology in supporting inquiry-based elementary Science while showing that its value depends on learning-activity design. This finding is conceptually important because inquiry shifts technology from a presentation tool to an instrument for doing Science.

Project-based learning offers another context in which digital tools can support extended learning. Learners may use digital resources to gather information, document observations, create representations and communicate project findings. The technology therefore supports several stages of the learning process. Nevertheless, project work can become technologically busy without being intellectually demanding. Effective design requires a clear Science problem, explicit criteria, opportunities for evidence-based reasoning and teacher feedback.

Collaboration and Communication

Digital platforms can enable learners to co-create products, share findings and respond to peers' ideas. Collaboration can be particularly valuable in Science because scientific understanding develops through explanation, argumentation and comparison of evidence. Digital tools can preserve learners' contributions and provide opportunities to revisit ideas. However, collaboration does not arise automatically from the availability of a digital platform. It depends on task structure, role allocation, interaction patterns and teacher guidance.

For primary learners, collaborative digital tasks also require explicit teaching of communication routines. Learners may need support to listen to peers, provide constructive

responses, identify evidence and reach agreement. Consequently, the digital platform is only an enabling condition. The pedagogical design determines whether technology becomes a vehicle for meaningful collaborative learning or merely a mechanism for sharing files and answers.

Academic Achievement and Learning Outcomes

Claims concerning achievement require particular caution because academic outcomes are influenced by multiple factors. Greater access to technology does not necessarily produce higher achievement. Learning outcomes may vary according to technology type, duration of use, learning objectives, teacher guidance and alignment between the digital activity and the Science curriculum. Hall and Lundin (2024) illustrate the importance of considering educational context rather than treating technology as an independent cause of learning.

Achievement should therefore be considered alongside intermediate learning processes. A digital activity may first influence engagement, exploration or conceptual understanding before any change becomes visible in formal assessment. This process-oriented view helps explain why short-term exposure to technology may not produce immediate achievement gains, while well-designed and sustained integration may contribute to learning over time. It also supports the framework proposed in this paper, where achievement is positioned as a potential outcome rather than as an automatic consequence of technology use.

Student Readiness

Primary learners differ in prior digital experience, self-regulation, language proficiency and ability to manage information. Digital tasks that are technically complex may divert attention from Science content to operating the technology. Clear instructions, age-appropriate interfaces, teacher support and reasonable duration of use are therefore important. Student readiness also includes the ability to interpret digital information critically, follow online safety practices and use digital resources responsibly.

The concept of readiness in the proposed framework is not intended to blame learners for implementation difficulties. Rather, it recognises that technology integration should be designed around the developmental characteristics of children. When a digital task is matched to learners' abilities, technology can reduce barriers to participation; when the task exceeds their technical or cognitive readiness, technology may become an additional barrier. This reinforces the need for teacher mediation and differentiated support.

Conditions Influencing Effectiveness

Technology-Pedagogy-Content Alignment

TPACK provides a basis for explaining why the same technology may be valuable in one context but less useful in another. The central principle is alignment among technological possibilities, pedagogical strategies and the disciplinary requirements of Science. Recent evidence indicates that TPACK should be understood as a contextual and dynamic construct rather than a static checklist of teacher skills (Schmid et al., 2024).

For primary Science, alignment requires teachers to consider what the learners need to understand, what scientific practices they need to perform and what technology can contribute. A simulation may be appropriate when the learning goal involves understanding relationships among variables. A video may be more appropriate when learners need to

observe a process that cannot easily be reproduced in class. A digital quiz may be useful for formative assessment but may be insufficient as the main learning activity. These examples illustrate that technology selection should follow the learning problem rather than determine it.

Teacher Digital-Pedagogical Competence

DigCompEdu complements TPACK by describing educator competences required to use digital technologies in educationally meaningful ways. Digital competence is more than technical operation; it includes selecting, adapting and using digital resources to support learning objectives, assessment and learner participation (European Commission, 2017). This distinction is important because a teacher may be highly competent in operating an application but less prepared to design a learning sequence that uses the application effectively.

Professional development should therefore combine technical knowledge with pedagogical design. Teachers need opportunities to evaluate digital resources, anticipate learner difficulties, design inquiry questions, integrate formative assessment and reflect on the quality of learning produced. Walan and Enochsson (2024) further indicate that teachers' experiences of digital tools are influenced by contextual obstacles and support needs. Teacher competence should thus be developed together with organisational conditions rather than treated as an individual responsibility alone.

Learning Ecosystem Readiness

Digital learning also depends on devices, internet connectivity, quality digital content, technical support and school leadership. The Malaysian Digital Education Policy positions infrastructure, content, educators and strategic collaboration as important elements of the digital education ecosystem (Kementerian Pendidikan Malaysia, 2023). This perspective is important because a pedagogically sound lesson cannot be implemented consistently when connectivity is unreliable, devices are unavailable or technical support is absent. Malaysian research on AI/STEM implementation further identifies teacher knowledge, skills, confidence and infrastructure as practical constraints, although findings from secondary-school teachers or AI-focused settings should be treated as contextual rather than direct evidence for primary Science (Jekri et al., 2025; Hasmadi & Zaini, 2026).

Ecosystem readiness also includes institutional culture. School leaders influence whether teachers have time to experiment, collaborate and reflect on digital practice. Access to technical assistance can reduce lesson disruption and increase teachers' confidence. Quality digital content reduces the time required for teachers to locate suitable resources. Therefore, school-level readiness should be viewed as a support structure that enables pedagogical decisions rather than as a separate administrative issue.

Equity, Inclusion and Responsible Use

Effectiveness should also be evaluated in relation to equity. If some learners have reliable devices and internet access while others do not, a digital intervention may widen rather than reduce learning differences. UNESCO (2023) emphasises the importance of equity and inclusion when considering educational technology. For primary schools, teachers may

therefore need alternative access arrangements, shared-device strategies, downloadable resources or non-digital alternatives so that learning objectives remain accessible.

Responsible use is another consideration. Young learners require guidance concerning privacy, digital citizenship, appropriate communication and the evaluation of online information. These issues are connected to the quality of learning because students cannot participate effectively in digital Science learning if they are unable to navigate digital information safely and critically. Thus, digital competence is relevant to both teachers and learners. Recent Malaysian work on AI in primary Science also discusses the potential of digital tools to support 4C skills alongside infrastructure, teacher-training and ethical concerns (Puspanathan & Mahmud, 2026); these findings are relevant to emerging technologies but should not be generalised to every form of digital learning.

From Technology Availability to Pedagogical Value

A central issue emerging from the literature is the distinction between access to technology and the educational value obtained from that technology. The presence of computers, tablets, internet connectivity or digital platforms does not by itself constitute effective digital learning. Educational value is generated when a digital resource changes the quality of an activity in a way that is aligned with the intended learning outcome. In primary Science, this distinction is particularly important because technology can easily become an attractive presentation tool without creating opportunities for pupils to observe evidence, manipulate variables, explain relationships or construct scientific meaning. The conceptual position adopted in this paper is therefore that effectiveness should be judged by the learning process created through technology rather than by the technology itself.

This distinction also explains why findings on academic achievement may be inconsistent. When a device merely replaces a worksheet or a teacher presentation, the underlying learning process may remain substantially unchanged. In contrast, a simulation can permit pupils to manipulate variables repeatedly, visualise invisible processes and compare outcomes in ways that may be difficult to achieve with physical materials alone. Likewise, collaborative digital tasks may extend discussion and representation of ideas, but only when pupils are given meaningful roles and clear intellectual tasks. The literature therefore supports a conditional interpretation: digital learning can be effective, but its effectiveness depends on the relationship between technological affordances, pedagogical design, content characteristics and learner needs.

Digital Affordances in Primary Science

Digital technologies offer several affordances that are particularly relevant to Science learning. First, visualisation enables pupils to represent processes that are too small, too large, too fast, too slow or otherwise inaccessible to direct observation. Second, simulation enables controlled manipulation of variables and repeated experimentation without consuming physical materials. Third, multimedia resources can combine text, image, sound, animation and demonstration to provide multiple representations of a phenomenon. Fourth, digital platforms can support immediate feedback and formative assessment. Fifth, collaborative tools can make pupils' reasoning visible through shared documents, presentations, discussion boards or digital products. These affordances should not be

interpreted as universal benefits; rather, they identify possibilities that teachers can exploit when they correspond to curricular and pedagogical purposes.

For primary Science, the value of these affordances is closely associated with the nature of the content. Topics involving systems, cycles, forces, electricity, matter, the human body and environmental processes often include relationships that pupils cannot easily observe directly. Digital representations can make such relationships more accessible, while physical activities remain important for developing practical skills and connecting abstract ideas to tangible experiences. A balanced approach therefore treats digital learning as an extension of the learning environment. The strongest conceptual proposition is not that digital technology should replace hands-on Science, but that it should be selected when its affordances complement or extend what can be achieved through other teaching resources.

The Role of Teacher Mediation

Teacher mediation is a recurring condition in the proposed framework. Digital environments can provide pupils with opportunities to explore, but exploration alone does not guarantee conceptual understanding. Pupils may focus on superficial features of an animation, manipulate a simulation without recording evidence, or select information without evaluating its credibility. The teacher consequently remains responsible for framing the task, establishing learning intentions, sequencing activities, questioning pupils' reasoning and interpreting evidence of learning. This position is consistent with TPACK because effective integration requires teachers to connect technology with both subject matter and pedagogy (Koehler & Mishra 2009).

DigCompEdu adds a complementary perspective by emphasising teachers' competence in selecting digital resources, designing learning activities, facilitating learner engagement and using digital assessment. The two frameworks therefore address different but connected dimensions of the same problem. TPACK explains the knowledge needed to integrate technology with content and pedagogy, while DigCompEdu describes broader professional competencies needed to use digital technologies effectively in educational practice. Their integration strengthens the conceptual explanation because a teacher may understand the Science content and possess technical skills, yet still require pedagogical competence to transform those resources into a meaningful learning experience.

Student Agency, Readiness and Self-Regulation

Effectiveness is also influenced by pupil characteristics. Primary pupils differ in prior knowledge, digital familiarity, language proficiency, confidence, attention and ability to regulate their learning. Digital learning environments can increase agency because pupils may control the pace of interaction, revisit explanations and explore alternative representations. However, greater choice can also create cognitive and behavioural demands. Younger learners may require explicit instructions, visual cues, modelling and structured reflection. Consequently, student readiness should be treated as a moderating condition rather than an assumed benefit of digital learning.

In Science, self-regulation is particularly relevant when pupils are asked to investigate a question using a digital resource. They need to identify what they are trying to find out, determine which variables are relevant, record observations, compare evidence and

formulate an explanation. These processes can be scaffolded through worksheets, guiding questions, prediction tables, teacher prompts and structured discussion. The conceptual framework therefore places student readiness alongside teacher competence and ecosystem readiness. This avoids a technology-centred explanation in which outcomes are attributed solely to the tool.

Evidence on Achievement: A Cautious Interpretation

The literature suggests that digital learning may contribute to academic achievement, conceptual understanding and engagement, but the evidence should be interpreted cautiously. Achievement is an outcome of multiple interacting factors, including prior knowledge, instructional time, assessment design, teacher quality and the degree of alignment between learning activities and curriculum standards. A digital intervention may improve engagement without producing a measurable achievement gain, or it may improve conceptual understanding that is not captured by a narrow test. Conversely, an attractive digital activity may produce high participation while contributing little to the intended learning outcomes. A recent review of digital media in elementary Science similarly reports promising patterns for motivation, conceptual understanding and active participation, while emphasising the need for appropriate integration (Wulandari & Sumarno, 2026).

This distinction is important for conceptual work because it prevents the paper from making a deterministic claim that digital learning is inherently effective. Hall and Lundin (2024), for example, illustrate the importance of distinguishing access to computers from demonstrable learning gains. The implication is that future empirical studies should specify what type of technology is used, what pedagogical strategy accompanies it, which Science outcomes are measured and under what implementation conditions. Such specificity can strengthen the evidence base for primary Science education and help explain why effects differ across settings.

Propositions Derived from the Conceptual Framework

Based on the integrated analysis, five propositions are advanced for future empirical examination. Proposition 1: digital learning is more likely to produce positive Science learning outcomes when technology is aligned with the content and pedagogical strategy represented by TPACK. Proposition 2: teacher digital-pedagogical competence strengthens the relationship between technology use and the quality of learning experiences. Proposition 3: student readiness and self-regulation moderate the effectiveness of digital learning activities, particularly when tasks require independent exploration. Proposition 4: infrastructure, technical support, digital content and school-level leadership constitute enabling conditions for sustained implementation. Proposition 5: engagement, conceptual understanding and Science process skills function as important intermediate learning processes through which digital learning may influence achievement.

These propositions extend the discussion beyond a descriptive list of benefits and challenges. They provide a basis for future empirical studies to examine not merely whether digital learning works, but how and under what conditions it works. For example, a quasi-experimental study could examine achievement differences while also measuring engagement and conceptual understanding. A mixed-methods study could examine how

teacher competence and infrastructure influence implementation fidelity. In this way, the conceptual paper provides a bridge between existing literature and future research design.

Integrated Conceptual Proposition

The literature suggests that digital learning effectiveness should not be represented as a direct relationship between technology use and student achievement. Instead, effectiveness can be conceptualised as a process in which implementation conditions shape the quality of digital learning experiences, which then influence learning processes and potential outcomes. This proposition is consistent with the observation that digital technology has affordances, but the educational value of those affordances depends on pedagogical mediation and context.

Three interrelated conditions are proposed. The first is technology-pedagogy-content alignment, represented by TPACK. The second is teacher digital-pedagogical competence, represented principally through DigCompEdu. The third is learning ecosystem readiness, incorporating infrastructure, digital content, technical support, school leadership and learner readiness. Together, these conditions influence learning experiences such as simulation, visualisation, inquiry, project work, collaboration and feedback.

These experiences are expected to shape learning processes including engagement, exploration, conceptual understanding, scientific reasoning and self-regulation. Potential outcomes include Science achievement, Science skills, communication and digital literacy. The framework therefore explains effectiveness as conditional rather than automatic. It also allows different digital interventions to be compared conceptually because the same outcome can be reached through different technology-pedagogy combinations.

Proposed Conceptual Framework

The framework can be represented as a four-stage process:

The framework proposes that implementation conditions operate as enabling or constraining factors. They do not directly produce achievement. Instead, they influence the design and quality of the digital learning experience. For example, strong infrastructure without appropriate pedagogical alignment may increase technology access without improving learning. Conversely, a teacher with strong pedagogical knowledge may design an effective digital activity but face implementation constraints if learners cannot access the required technology. Effectiveness therefore depends on interaction among the components.

The second stage, digital learning experience design, is the immediate pedagogical mechanism. This stage asks what learners actually do with technology. A simulation is not considered effective merely because it is interactive; it becomes pedagogically meaningful when learners use it to investigate a scientific relationship, test a prediction or interpret evidence. Likewise, collaboration becomes meaningful when learners explain ideas, compare evidence and construct shared understanding. The framework therefore places learning activity between implementation conditions and learning outcomes.

The third stage represents learning processes. Engagement, exploration and conceptual understanding are positioned as mechanisms through which digital experiences may influence outcomes. This stage is important because learning is not instantaneous. Learners

need opportunities to attend to information, manipulate ideas, receive feedback and revise their understanding. The final stage includes potential outcomes that can be observed through assessment, performance tasks, scientific practices and digital literacy measures.

Input / Condition	Pedagogical Mechanism	Learning Experience	Expected Outcomes
TPACK alignment	Technology is matched with Science content and pedagogy	Purposeful use of simulation, visualisation, inquiry and modelling	Conceptual understanding and Science process skills
DigCompEdu competence	Teacher selects, designs, facilitates and assesses digital learning	Guided interaction, feedback, differentiation and digital assessment	Engagement, participation and improved learning quality
Student readiness	Tasks are scaffolded according to prior knowledge and self-regulation	Active exploration, reflection and independent learning	Confidence, agency and sustained engagement
Ecosystem readiness	Infrastructure, content, technical support and leadership enable implementation	Reliable and equitable access to digital learning	Sustainable implementation and learning opportunities

Discussion: What This Conceptualisation Adds

The framework's contribution is not the claim that TPACK, DigCompEdu or school readiness is new. Its contribution is a Science-specific process explanation connecting these dimensions to what primary pupils must do to learn Science: move from an initial prediction, through observation or manipulation, to interpretation of evidence and a reasoned scientific explanation. This is more specific than a general technology-integration model because it identifies the disciplinary work that digital tools should support.

The framework distinguishes four analytically different levels: (a) enabling conditions—teacher knowledge, digital competence, pupil readiness and school support; (b) pedagogical design—alignment of the Science objective, representation and inquiry task; (c) learning mechanisms—prediction, observation, variable manipulation, evidence recording, comparison and explanation; and (d) outcomes—conceptual understanding, Science Process Skills, engagement and achievement. This distinction explains why access or interactivity alone may not produce learning gains. It also generates testable propositions: if a digital tool does not support a relevant Science practice, its contribution to conceptual understanding should be limited even when pupils report enjoyment.

A further contribution is the treatment of pupil development as a boundary condition. Primary pupils may need explicit scaffolding to interpret a simulation, stay focused on the learning question and regulate exploration. The framework therefore treats pupil readiness and teacher scaffolding as conditions shaping the transition from digital interaction to evidence-based reasoning. This is relevant to primary Science, where digital representations should complement concrete observation and hands-on activity rather than replace them.

Finally, the framework separates a tool's affordance from the quality of its pedagogical use. A visual simulation can make an unseen process visible, but its learning value depends on

whether pupils are asked to predict, vary a factor, record changes, compare outcomes and justify a conclusion. This mechanism-oriented contribution responds to the underexplored nature of domain-specific TPACK in Science education identified by Aktaş and Özmen (2026), and is consistent with evidence that educational technology in inquiry-based primary Science often supports observation and data interpretation (Yun & Crippen, 2024).

The principal contribution of this concept paper is the integration of three dimensions that are often discussed separately: technology-pedagogy-content alignment, teacher digital-pedagogical competence and learning ecosystem readiness. TPACK explains the knowledge required to align technology with pedagogy and content, while DigCompEdu provides a practice-oriented account of educator competence in digital resources, teaching, assessment and learner empowerment. The ecosystem dimension extends the explanation beyond individual teacher capability to include the conditions in which digital teaching occurs.

This integrated perspective changes the central question from whether digital learning is effective in general to a conditional question: what technology is used, by whom, for which Science content, through what pedagogical design, under what ecosystem conditions, and for which learning outcomes? Such a question is more consistent with heterogeneous educational-technology evidence and avoids technological determinism. It also creates a clearer basis for empirical testing because each component can be operationalised as a variable or contextual condition.

The framework also contributes by distinguishing technology affordances from learning processes. Visualisation, simulation and interactivity are affordances; engagement, exploration and conceptual understanding are learning processes; achievement and Science skills are potential outcomes. Keeping these levels separate helps avoid the common assumption that an engaging digital activity must automatically improve achievement. A lesson may be highly engaging but conceptually weak, or conceptually strong but difficult to access. The proposed framework allows these possibilities to be examined rather than collapsed into one general measure of effectiveness.

For example, a simulation may have strong pedagogical value when a teacher uses it to enable learners to test hypotheses, manipulate variables and interpret evidence. The same simulation may provide limited learning value if learners simply explore the interface without a cognitive task or connection to the Science learning objective. The technology is therefore not the independent explanation of learning. Instead, it is embedded within a designed experience in which teacher decisions, learner readiness and contextual support interact.

The framework further highlights the importance of the teacher as a designer of learning experiences. Digital competence should not be viewed only as the ability to operate devices. Teachers need to make decisions about sequencing, questioning, assessment, differentiation and feedback. This interpretation aligns DigCompEdu with TPACK: DigCompEdu clarifies what educators need to do with digital technologies, while TPACK explains the importance of connecting those actions to pedagogy and disciplinary content.

Finally, the framework has relevance for the Malaysian primary-school context because it connects classroom-level practice with the broader digital education ecosystem described in

the Digital Education Policy. Rather than assuming that digital transformation can be achieved through equipment provision alone, the framework emphasises content, educator capability, learner readiness and institutional support. This provides a more balanced basis for discussing implementation and for designing future empirical research.

Implications for Practice

For teachers, digital lesson planning should begin with the intended Science learning objective and learning problem rather than with the digital application itself. Teachers can ask whether learners need to observe, manipulate, compare, explain, communicate or practise a particular skill, and then determine whether technology adds value to that activity. This approach can reduce the tendency to use technology simply because it is available.

Professional development should combine technical skills with pedagogical design, assessment and digital-resource selection. Training can include opportunities for teachers to redesign existing Science lessons, evaluate digital resources against curriculum objectives, develop inquiry questions and use formative assessment data. Such professional learning is more closely aligned with the integrated TPACK-DigCompEdu perspective than one-off training focused only on application functions.

School leaders should treat infrastructure, digital content and technical support as part of the pedagogical ecosystem. Reliable access, technical assistance and opportunities for teacher collaboration can reduce barriers to implementation. Leadership can also support teachers by recognising time needed for lesson preparation and reflection. These conditions matter because pedagogical innovation is difficult to sustain when teachers are expected to manage digital implementation without organisational support.

For curriculum planners, the framework suggests that digital learning should be embedded in curriculum expectations as a means of supporting scientific practices rather than as an isolated technology objective. Curriculum materials can include examples of appropriate digital representations, inquiry tasks, simulations and formative assessment strategies. At the same time, non-digital alternatives should remain available where technology does not add meaningful value or where access conditions differ across schools.

For researchers, the framework provides a basis for future empirical testing. Researchers can examine whether TPACK alignment, teacher digital competence and ecosystem readiness predict the quality of digital learning experiences and whether those experiences are associated with engagement, conceptual understanding and achievement. Such studies can use quasi-experimental, mixed-methods or longitudinal designs to test the proposed pathways in specific Science topics and primary-school contexts.

Limitations

This concept paper has several limitations. First, the framework is derived from existing literature and theoretical perspectives rather than primary empirical data. The proposed relationships should therefore be treated as conceptual propositions rather than established causal effects. Second, the literature on digital learning includes heterogeneous technologies, pedagogical designs, learner populations and outcome measures, limiting direct comparison across studies. Third, the initial database counts reported in this paper represent records

identified during the structured search and do not constitute a PRISMA flow or a claim of exhaustive systematic-review screening.

A further limitation concerns the use of foundational theories alongside recent evidence. TPACK and DigCompEdu are older conceptual sources, but they are retained because the framework depends on their established definitions. Their inclusion should not be interpreted as evidence that older studies are representative of current digital learning conditions. Future research should examine how these frameworks operate alongside newer technologies and contemporary primary-school practices.

The proposed framework also requires empirical validation. Future studies should operationalise each component and examine whether the hypothesised relationships hold across different schools, Science topics and learner groups. In particular, empirical research in Malaysian primary schools can help determine how infrastructure, teacher competence, student readiness and technology-pedagogy alignment interact in real classroom conditions.

Conclusion

Digital learning has considerable potential to support primary Science education through visualisation, interaction, inquiry, collaboration and access to learning resources. However, the presence of technology does not by itself guarantee effective learning. The literature reviewed in this concept paper indicates that effectiveness is better understood as a conditional process shaped by pedagogical design, teacher competence, learner characteristics and the surrounding educational ecosystem.

By integrating TPACK and DigCompEdu with student readiness and ecosystem conditions, the proposed framework provides a process-oriented explanation of how digital learning may contribute to Science learning outcomes. The framework moves beyond the question of whether technology is effective and instead asks how technology is designed, how teachers use it, how learners engage with it and what contextual conditions support or constrain its use. This conceptualisation can guide teacher planning, professional development, school-level digital implementation and future empirical research.

The framework is particularly relevant to primary Science because digital technologies can provide representations and experiences that are difficult to reproduce through conventional instruction alone. Nevertheless, technology should complement rather than replace concrete experiences, scientific discussion and teacher guidance. The ultimate criterion for effectiveness is therefore not the amount of technology used, but the extent to which technology helps learners observe, explore, reason, communicate and construct meaningful scientific understanding.

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