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Primary science teachers' perceptions of digital tools: a qualitative study of challenges and pedagogical implications

Wenlin Yang, Sirinapa Kijkuakul
Science Education Program, Faculty of Education, Naresuan University, Phitsanulok, Thailand

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ABSTRACT

This qualitative study investigates primary school science teachers' attitudes, experiences, and challenges in integrating digital tools into science instruction. Drawing on semi-structured interviews with 25 teachers from urban and rural schools in Meizhou City, Guangdong Province, China, thematic analysis explored how simulations, virtual labs, and multimedia platforms are employed, their perceived benefits, and systemic barriers to effective use. Findings indicate that digital tools support visualization of abstract concepts, supplement limited physical resources, and enhance student engagement through interactive experimentation. However, challenges such as misalignment with curriculum goals, insufficient technical support, and concerns about over-reliance on digital methods potentially diminishing hands-on learning were identified. Full-time and higher-grade teachers showed more consistent integration than part-time or lower-grade counterparts. The findings indicate a need to balance digital approaches with experiential learning, while reaffirming the continued importance of tactile, hands-on activities in science education. For educators and policymakers, the findings highlight priority areas for action, including professional development (PD) aligned with curricular goals, improved availability of digital resources across school contexts, and institutional mechanisms that guide teachers' use of digital tools in practice.

Corresponding Author:

Wenlin Yang
Science Education Program, Faculty of Education, Naresuan University
99 Moo 9, Thapo Sub-district, Muang District, Phitsanulok 65000, Thailand
Email: wenliny67@nu.ac.th

1. INTRODUCTION

Digital teaching tools are increasingly shaping instructional design and classroom interaction, altering how teachers plan science lessons and how students engage with learning activities. Digital tools, including simulation software, virtual laboratories, multimedia resources, online learning platforms, and educational applications, are widely regarded as instruments that can enrich instructional environments through interactivity, visualization, and multimodal representation [1]. In primary science education, where abstract scientific concepts and experimental processes often pose challenges for young learners, digital tools have demonstrated particular value in supporting conceptual understanding and learner engagement.

Across different national contexts, the integration of digital technologies has been recognized as a key strategy for improving educational quality and accessibility [2]. In China, this process aligns with broader national initiatives aimed at promoting educational equity and fostering 21st-century competencies [3]. Despite substantial investments in digital infrastructure, persistent challenges remain, especially in rural and economically disadvantaged regions, where disparities in access, teacher preparedness, and institutional support continue to affect classroom implementation [4]. Evidence from education systems such as Finland

and Singapore suggest that digital tools, when incorporated into science instruction, have been linked to stronger student engagement and more favorable learning outcomes [5].

From a theoretical perspective, research on technology integration has frequently adopted the technological pedagogical content knowledge (TPACK) framework to conceptualize how teachers combine subject content, pedagogy, and technology in classroom teaching [6]–[8]. Empirical studies suggest that teachers with higher TPACK demonstrate greater capacity to design technology-enhanced lessons that respond to disciplinary demands and students' learning needs [9]. However, existing studies suggest that possessing TPACK does not automatically lead to meaningful classroom application; its pedagogical value depends heavily on broader enabling conditions, including the availability of instructional resources, sustained forms of teacher learning, and supportive school-level arrangements. Moreover, teachers' beliefs, attitudes, and confidence regarding digital tools have been identified as key determinants of whether these tools are adopted in meaningful or superficial ways [10]–[13].

Despite a growing volume of studies on digital technology use in education, important gaps remain. The existing body of research has largely concentrated on secondary and tertiary science education, while empirical investigations of primary science classrooms, particularly within the Chinese context, remain relatively limited [14]. Furthermore, limited research has systematically explored how teachers' perceptions of digital tools interact with pedagogical strategies and contextual constraints, such as school location and access to professional development (PD), in shaping everyday instructional practice [15]–[17]. In under-resourced and rural primary schools, these challenges may be further intensified by limited training opportunities and tensions between digital instruction and traditional hands-on science learning approaches.

To address these gaps, this study reports a qualitative inquiry into how primary science teachers in China perceive and enact digital teaching tools in their everyday instructional practice, as well as the constraints they encounter in doing so. Drawing on teachers' experiences across varied school contexts and professional backgrounds, this study seeks to clarify how digital tools are understood, taken up, and shaped by constraints in primary science classrooms. The study is guided by the following research questions:

- What are primary school science teachers' attitudes and perceptions regarding the integration of digital tools in science teaching and learning? (RQ1)
- How do primary school science teachers utilize digital tools, such as simulations, virtual laboratories, and multimedia platforms, in their pedagogical practices? (RQ2)
- What challenges do primary school science teachers encounter when integrating digital tools into their teaching, particularly in urban and rural contexts? (RQ3)
- How do teachers' experiences with digital tools shape their perceptions of the role of traditional, hands-on learning in science education? (RQ4)

2. LITERATURE REVIEW

2.1. TPACK framework: conceptual lens for integrating digital tools

The TPACK framework, commonly referred to as TPACK, has been frequently used to examine how teachers bring digital tools into subject-specific instructional practices [6]. Rather than treating technology use as a stand-alone technical competence, the TPACK framework foregrounds how subject matter, pedagogy, and technological knowledge (TK) are mutually constituted in teachers' instructional decision-making [7], [8]. As such, TPACK has been extensively employed in educational research to interpret teachers' instructional decision-making in technology-enhanced learning environments.

Empirical studies have demonstrated that stronger TPACK is linked to teachers' enhanced capacity to design technology-rich lessons that are responsive to disciplinary demands and students' learning needs [9]. Two recurring insights can be identified in this body of research. First, the instructional relevance of digital resources, including simulations and virtual laboratories, is contingent on their alignment with subject-specific pedagogies, highlighting the central role of the content knowledge-pedagogical knowledge-technological knowledge (CK-PK-TK) intersection. Second, while TPACK provides a necessary foundation for meaningful technology integration, it alone does not guarantee effective classroom enactment. Prior studies consistently show that broader contextual factors, such as the availability of teaching resources, ongoing opportunities for professional learning, and support at the institutional level, are central to teachers' ability to enact TPACK in classroom practice [18]. Within primary science education, TPACK has therefore been applied not only to frame research inquiries but also to inform the design and evaluation of PD initiatives aimed at supporting teachers' digital integration.

2.2. Pedagogical affordances and classroom applications of digital tools

A substantial body of research has examined the pedagogical affordances of digital tools in primary science education, emphasizing their capacity to support inquiry-oriented and conceptually rich learning experiences. Digital resources such as simulation software, virtual laboratories, and multimedia materials enable the visualization of abstract or otherwise inaccessible scientific phenomena, thereby facilitating students' engagement, experimentation, and conceptual understanding [19]. Emerging applications of augmented reality/virtual reality (AR/VR) technologies and blended learning environments have further extended these affordances by offering learning experiences that are immersive and highly interactive, thereby supporting students' engagement and sustained interest [20].

However, the effective realization of these pedagogical affordances in classroom practice is not determined by technological availability alone. Prior studies consistently indicate that teachers' digital literacy, pedagogical beliefs, and confidence play a decisive role in shaping how and to what extent digital tools are incorporated into instructional activities [11]. In addition, persistent structural and contextual constraints, including inadequate infrastructure, misalignment between digital tools and curriculum requirements, and varying degrees of teacher resistance, continue to limit meaningful classroom integration [21]. As a result, despite the well-documented pedagogical potential of digital technologies, the literature points to an enduring gap between the possibilities afforded by digital tools and their routine enactment in primary science classrooms.

2.3. Teachers' beliefs, attitudes, and contextual influences

Teachers' beliefs and attitudes toward digital tools have been consistently identified as critical determinants of whether, how, and to what depth these resources are integrated into classroom practice [12]. Studies indicate that positive perceptions of digital technologies enhance teachers' willingness to experiment with new instructional approaches and to adapt pedagogical strategies in ways that support more meaningful technology integration [13]. Conversely, when teachers perceive digital tools as time-consuming, pedagogically misaligned, or burdensome in relation to curriculum demands, technology use tends to remain limited, superficial, or instrumental rather than transformative [14]. These divergent belief patterns highlight the need to attend to teachers' technological competencies alongside their pedagogical orientations and professional confidence when using digital tools.

Beyond individual beliefs, the use of digital tools is strongly mediated by contextual and institutional conditions. Research demonstrates that successful technology-enhanced instruction requires supportive environments, including access to sustained PD, reliable infrastructure, and organizational encouragement [17]. Persistent contextual constraints, such as insufficient technological resources, limited technical support, classroom management challenges, concerns about student distraction, and uneven levels of students' digital competence, continue to impede effective classroom implementation [18]. Taken together, these findings indicate that the effective use of digital tools in primary science classrooms is shaped by the interplay between teachers' beliefs and the wider educational context, pointing to the value of context-responsive strategies and system-level forms of support.

2.4. Professional development and systemic support for digital integration

Existing scholarship consistently points to PD as playing a central role in helping teachers incorporate digital tools into everyday classroom practice. Existing studies consistently indicate that short-term, skills-oriented training programs focusing primarily on technical operation are insufficient to support sustained and meaningful technology integration. Instead, effective PD initiatives are characterized by their integration of digital literacy with pedagogical content knowledge (PCK), enabling teachers to align technological tools with subject-specific instructional goals [22].

Empirical research further suggests that PD programs incorporating hands-on practice, peer collaboration, and opportunities for reflective learning contribute to enhanced teacher confidence and a greater willingness to experiment with digital technologies in instructional settings. Such design features are particularly important in primary science education, where many teachers have limited formal preparation in both advanced scientific content and technology-enhanced pedagogy. Without sustained and coherent PD support, teachers may struggle to translate technological affordances into pedagogically meaningful classroom practices.

In addition to program design, the effectiveness of PD is shaped by broader systemic and contextual conditions. Cross-cultural studies emphasize that PD initiatives must be sensitive to variations in infrastructure, curriculum demands, institutional expectations, and cultural attitudes toward technology use in education [23]. These findings suggest that PD functions not as an isolated intervention, but as part of a wider support system that mediates the relationship between technological potential and everyday classroom enactment. Overall, existing studies highlight the role of pedagogically embedded, context-sensitive PD in addressing the mismatch between the availability of digital tools and how they are used in primary science classrooms.

3. METHOD
3.1. Research design
This research employs a qualitative approach to examine primary science teachers' attitudes, perceptions, and lived experiences in relation to their use of digital teaching tools in classroom settings. Creswell [24] and Patton [25] emphasize that qualitative approaches are particularly suitable for examining the complexity of teachers' lived experiences and for developing a detailed understanding of how digital tools are integrated into classroom practices. Such an approach enables researchers to investigate not only what teachers do but also the reasoning, beliefs, and contextual factors shaping their pedagogical decisions.

Semi-structured interviews were chosen as the primary data collection method to provide both structure and flexibility, following the recommendations of Creswell [24] and Braun and Clarke [26]. The semi-structured format ensured that all participants addressed the central research questions while allowing the interviewer to probe further based on participants' responses. This flexibility is essential in exploratory research, as it facilitates in-depth insights into teachers' experiences, uncovers unanticipated perspectives, and captures the diversity of practices across different school contexts. The subsequent analysis was informed by the six-phase analytic procedures, which supported the systematic identification of patterns across participants' accounts. In summary, the use of semi-structured interviews allowed the study to balance consistency across interviews with the responsiveness needed to understand teachers' unique experiences, making it a suitable method for addressing the research objectives.

3.2. Participant selection
The sample included 25 primary science teachers whose participation was determined according to established inclusion criteria aligned with purposive sampling practices. The sample size was considered appropriate for qualitative research, enabling detailed exploration of teachers' experiences while maintaining manageability for thorough thematic analysis. Throughout the interview process, the research team tracked the development of emerging themes as a way to assess whether participants' accounts were being sufficiently explored. Following established qualitative research practices [24], [26], [27], thematic saturation was considered achieved when no new codes or themes appeared in successive interviews. In this study, after the 22nd interview, subsequent interviews did not yield additional themes, indicating that saturation had been reached and confirming that the final dataset adequately represented teachers' perspectives across different contexts. Based on prior qualitative studies on teacher technology integration, a sample of 20-30 participants is generally considered sufficient to achieve thematic saturation in a homogenous population.

The inclusion criteria were: a minimum of two years of teaching science at the primary level; at least one year of experience integrating digital teaching tools, such as interactive whiteboards, simulations, virtual labs, or online platforms; and representation from both urban and rural schools in Meizhou City, Guangdong Province, to capture regional differences in technology access and infrastructure. To enhance transparency, participants were recruited from several urban and rural primary schools in Meizhou City and surrounding counties, including Fengmian Primary School (Meijiang District), JinXiu School (Xingning City), Fengshun County Experimental Primary School, People's Primary School (Jiaoling County), Pingyuan County Experimental School, and Chayang Town Central Primary School (Dapu County). This selection ensured diversity in terms of school size, digital infrastructure, and student population.

The sample encompassed a diverse group of teachers in terms of age, teaching experience, digital tool usage, school location, and employment status, as summarized in Table 1. This diversity allowed for nuanced comparisons across different teaching backgrounds and levels of technological engagement. These teachers were known to the researcher through previous collaborations in PD workshops hosted by Jiaying University, a provincial hub for teacher training and in-service development. Many of the teachers had participated in PD programs related to digital pedagogy facilitated by the university in the past three years. This prior connection helped build trust and ensured meaningful engagement during the interviews.

3.3. Data collection instrument
Semi-structured interviews served as the main approach for collecting data on participants' perceptions and experiences of digital tool integration in science teaching. The interview guide was informed by key themes in the literature on digital pedagogy and primary science education and reviewed by two academic experts to ensure content relevance and clarity. The interviews addressed the following focal areas:
- The range of digital tools incorporated into primary science teaching;
- Teachers' reported benefits and challenges associated with the use of these tools;
- Teachers' views on how digital tools contribute to teaching and learning processes;
- Expectations regarding the future role and development of technology in primary science education.

Table 1. Characteristics of interviewed teachers

Pseudonym	Age	Region	Years of teaching	Digital tool experience	Full-time/ part-time	Science specialization	Access to digital tools	PD participation
T01	35	Urban	12	5 years	Full-time	Biology	High	Yes
T02	41	Rural	18	3 years	Full-time	Physics	Low	No
T03	29	Urban	6	4 years	Part-time	General science	Moderate	Yes
T04	33	Rural	9	5 years	Full-time	Chemistry	Moderate	Yes
T05	39	Urban	15	6 years	Full-time	Biology	High	Yes
T06	27	Rural	4	2 years	Part-time	General science	Low	No
T07	32	Urban	10	5 years	Full-time	Chemistry	Moderate	Yes
T08	36	Urban	13	6 years	Full-time	Physics	High	Yes
T09	30	Rural	7	3 years	Full-time	General science	Low	No
T10	45	Urban	22	4 years	Full-time	Biology	Moderate	Yes
T11	31	Rural	8	2 years	Full-time	Chemistry	Low	No
T12	38	Urban	14	7 years	Part-time	Physics	High	Yes
T13	29	Rural	6	2 years	Full-time	General science	Low	No
T14	34	Urban	11	6 years	Full-time	Biology	Moderate	Yes
T15	40	Rural	17	5 years	Full-time	Physics	Low	No
T16	26	Rural	5	2 years	Part-time	Chemistry	Low	No
T17	44	Urban	21	8 years	Full-time	Biology	High	Yes
T18	28	Urban	4	1 year	Part-time	General science	Moderate	No
T19	37	Rural	13	4 years	Full-time	Physics	Low	Yes
T20	42	Urban	19	6 years	Full-time	Chemistry	High	Yes
T21	33	Rural	10	3 years	Full-time	General science	Low	No
T22	31	Urban	9	5 years	Part-time	Biology	Moderate	Yes
T23	46	Rural	25	4 years	Full-time	Physics	Low	No
T24	30	Urban	7	3 years	Full-time	Chemistry	Moderate	Yes
T25	39	Rural	16	6 years	Full-time	Biology	Low	No

3.4. Interview protocol

An interview protocol was developed to guide conversations around teachers' experiences of using digital tools in primary science classrooms. Sample prompts included questions such as how teachers use digital tools in their classrooms, which tools they perceive as most effective and for what reasons, and what challenges they have encountered in integrating these tools into instruction. Teachers were also invited to reflect on whether and how digital tools influence students' learning in science.

Interviews were conducted in Mandarin, with each session lasting about 45 minutes. Interview data were digitally recorded and later prepared for analysis through transcription and translation into English. All personal identifiers were removed during data processing to ensure the confidentiality of participants. Given the expanded sample of 25 participants, the interview process was designed to maintain consistency across sessions while allowing for context-sensitive probing, particularly to capture variations between urban and rural teaching environments.

3.5. Data analysis

Thematic analysis primarily employed an inductive approach, allowing themes to emerge from the data rather than imposing pre-existing codes, while some deductive elements guided by TPACK-related constructs were considered during coding. The data were analyzed using thematic analysis, following Braun and Clarke's six-phase framework, a widely recognized and robust method for qualitative research [24], [26]. This approach was chosen to ensure a systematic, transparent, and rigorous process of identifying patterns and themes in participants' narratives. The six phases included:

- Familiarization: immersing in the transcripts through repeated reading to develop an in-depth understanding of the dataset.
- Generating initial codes: highlighting meaningful segments of text and assigning descriptive codes reflecting participants' statements.
- Searching for themes: grouping related codes into candidate themes that capture overarching patterns in the data.
- Reviewing themes: iteratively examining candidate themes to ensure they accurately represent the dataset, merging or refining themes as needed.
- Defining and naming themes: clearly specifying the scope, focus, and label of each theme to reflect its meaning and significance.
- Producing the report: illustrating each theme with representative statements from participants while linking them to the research objectives.

To enhance transparency and trustworthiness, the coding process was conducted manually and reviewed independently by a co-researcher. Discrepancies were discussed until consensus was reached, ensuring confirmability. Member checking was employed, whereby a subset of participants verified the accuracy of interpreted meanings. Peer debriefing sessions further supported credibility by critically examining emerging themes and assumptions. An audit trail was maintained to document all coding decisions, theme development, and analytical memos, providing a clear trace of the analysis process. The final themes, summarized in Table 2, represent the outcome of this systematic coding and iterative review process. Each theme is illustrated with representative codes and participant statements, providing rich contextualized evidence of teachers' experiences with digital tools in primary science classrooms.

Table 2. Examples of themes, codes, and representative statements

Theme	Codes	Representative statement
Perceived pedagogical benefits	Enhanced concept visualization; student engagement	"*Using simulations really helps my students understand abstract science concepts*." (T03)
Resource limitations	Inadequate equipment; limited digital access	"*Our rural school has only one working projector, and it's shared*." (T02)
Teacher beliefs about integration	Skepticism about overuse; preference for balance	"*I prefer hands-on experiments, but digital tools can supplement when materials are limited*." (T08)
Training and competence	Lack of training, need for PD	"*I've never had formal training in using these tools; I just try to learn on my own*." (T06)
Policy and curriculum constraints	Rigid curriculum structure; lack of digital tool guidelines	"*We have to strictly follow the textbook, and there's little room to integrate digital tools*." (T10)
Contextual and cultural factors	Community attitudes; local digital literacy	"*Some parents don't think using tablets in class is real learning*." (T15)

This thematic analysis facilitated a more fine-grained account of the ways in which digital tools are perceived and used in primary science classrooms, as shaped by contextual factors such as region, teacher experience, and institutional support. Table 3 presents the distribution of six key themes across teacher subgroups according to location (urban versus rural), teaching experience (less than five years versus five or more years), and participation in PD training. The values indicate the number and percentage of teachers reporting each theme within the respective subgroups.

Table 3. Cross-tabulation of themes by teacher subgroups

Theme	Urban teachers (n=13)	Rural teachers (n=12)	<5 years teaching (n=2)	≥5 years teaching (n=23)	Received PD training (n=14)	No PD training (n=11)
Perceived pedagogical benefits	11 (85%)	7 (58%)	1 (50%)	17 (74%)	12 (86%)	6 (55%)
Resource and infrastructure limits	5 (38%)	11 (92%)	1 (50%)	16 (70%)	6 (43%)	10 (91%)
Teacher beliefs on integration	8 (62%)	6 (50%)	1 (50%)	14 (61%)	9 (64%)	5 (45%)
Training and professional competence	7 (54%)	10 (83%)	1 (50%)	17 (74%)	13 (93%)	4 (36%)
Policy and curriculum constraints	4 (31%)	9 (75%)	0 (0%)	14 (61%)	8 (57%)	5 (45%)
Contextual and cultural factors	3 (23%)	8 (67%)	0 (0%)	12 (52%)	5 (36%)	6 (55%)

The analysis revealed variations in reported pedagogical benefits associated with teachers' school location and frequency of participation in PD training. In contrast, rural teachers and those without PD experience tended to emphasize resource and infrastructure limitations. Participants with at least five years of teaching experience emphasized the role of teacher beliefs in technology integration, professional training, and perceived competence. This cross-tabulation illustrates how contextual factors, including school location, teaching experience, and access to PD, are associated with teachers' perceptions of digital tools. The analysis identified themes related to PD needs and resource conditions that shape teachers' integration of digital tools in primary science teaching.

In addition to the methodological determination of saturation during data collection, evidence of data saturation is further reflected in the analytical outcomes. As shown in Table 2, all six themes were consistently identified across the dataset and supported by multiple participants' accounts. Moreover, the cross-tabulation in Table 3 demonstrates that each theme recurred across different teacher subgroups (urban and rural contexts, varying levels of teaching experience, and PD participation), indicating that the thematic patterns were not isolated to a small number of participants. The recurrence and stability of themes across interviews and subgroups suggest that additional data collection was unlikely to yield substantively novel themes, thereby supporting the claim of thematic saturation. These patterns are further illustrated in the results section, where thematic findings are presented with representative quotations and subgroup distributions.

3.6. Trustworthiness, reliability, and validity

This study employed multiple methodological strategies to address key dimensions of trustworthiness, including credibility, dependability, confirmability, and transferability, with close attention to participants' lived experiences and the authentic context of primary science teaching.

- Member checking: after transcription, a subset of participants reviewed their interview transcripts and the preliminary interpretations of their responses. Participant feedback was used to review the researcher's coding and theme development, supporting closer alignment between the analysis and participants' intended meanings. Member checking directly supports credibility by grounding the findings in participants lived experiences.
- Peer debriefing: throughout the data analysis process, regular discussions were conducted with colleagues experienced in qualitative research. These debriefing sessions critically examined coding decisions, theme development, and interpretation of data, helping to identify potential biases, assumptions, or blind spots. Peer feedback strengthened both the confirmability and transparency of the thematic analysis.
- Audit trail: a detailed audit trail was maintained, documenting all steps of data handling, including participant selection, coding procedures, initial code lists, theme refinement, and analytical memos. This systematic documentation ensures that the analysis process is traceable, replicable, and transparent, allowing external reviewers to follow the reasoning from raw data to final themes.
- Thick description: rich, contextualized descriptions of classrooms, teaching practices, and interactions with digital tools were provided to facilitate transferability. By providing detailed accounts of participant experiences, readers are better positioned to judge how the findings may be relevant across comparable educational settings.
- Ethical considerations: ethical rigor was strictly maintained throughout the study. All participants voluntarily consented to take part in the study in writing, with assurances that their identities would remain protected and that participation could be discontinued at any point without consequence. Data were securely stored and destroyed following study completion. Ethical adherence not only protects participants' rights but also reinforces the reliability and trustworthiness of the research process.
- Integration with coding and thematic analysis: these trustworthiness strategies were embedded in the coding and theme generation procedures. For instance, coding was independently reviewed and iteratively refined through peer debriefing and member checking, ensuring that the identified themes were credible, coherent, and reflective of participants' experiences. The audit trail and detailed analytic memos document the decisions made at each stage, enhancing transparency and methodological rigor. Collectively, these strategies demonstrate that the study's findings are credible, dependable, and transferable, providing a transparent and systematic account of primary school science teachers' perceptions and practices regarding digital tool integration.

4. RESULTS

The analysis of interview data revealed several key themes regarding primary school science teachers' experiences with and perceptions of digital teaching tools. These themes encompass the diverse functional roles of digital tools, pedagogical utilization, challenges in integration, and the interplay between digital and hands-on learning. Within each theme, subthemes were identified to capture nuanced patterns across participants' responses, providing interpretative depth and clear links between raw data and derived themes.

4.1. Diverse functional roles of digital tools

These perceptions were shared by the majority of participants across both urban and rural schools, and were reported by both full-time and part-time teachers, as reflected in the thematic distribution presented in Table 3. The following analysis examines primary science teachers' attitudes and perceptions related to digital tool integration in science teaching. Participants generally expressed positive attitudes toward digital tools, highlighting their contribution to lesson quality, student engagement, and conceptual understanding. Thematic analysis revealed three subthemes reflecting the functional roles of digital tools.

4.1.1. Enhancing concept visualization

Teachers frequently described digital tools as enabling the visualization of abstract or unobservable scientific phenomena, particularly those that cannot be directly accessed through traditional classroom experiments. Simulations of molecular structures, chemical reactions, and biological processes enabled students to grasp concepts that could not be directly observed in a traditional classroom. For example, T03 (urban, part-time) described:

"*I use Yuejiao Xiangyun to show students models of molecules and reactions, which they can't see in the lab. It really helps them understand abstract concepts.*"

4.1.2. Facilitating interactive and engaging learning

Digital tools were reported to increase interactivity and engagement in lessons. Video resources and multimedia presentations helped students observe long-duration or invisible processes, such as plant growth or chemical reactions. T15 (rural, full-time) explained:

"*We use videos to show processes that take days or even weeks, like plant growth or the cooling of hot objects. This helps students visualize what we're learning about over time.*"

Beyond supporting conceptual visualization, teachers emphasized that digital tools also transformed students' modes of engagement by enabling extended observation over time and repeated interaction with learning materials, rather than one-time exposure in traditional lessons. This subtheme reflects the role of digital tools in supporting students' active engagement with content, enabling visualization and exploration beyond traditional classroom limitations.

4.1.3. Supplementing limited physical resources

In schools with constrained laboratory facilities or equipment, digital tools provided essential alternatives. NB Laboratory software, for instance, allowed students to simulate complex experiments safely. T06 (rural, part-time) noted:

"*The NB Laboratory is great for simulating chemical reactions and biological processes. It allows students to see things that we can't easily demonstrate in real life due to safety concerns or equipment limitations.*"

Teachers emphasized that digital tools could compensate for gaps in physical resources, ensuring equitable access to scientific experiences across diverse school contexts. Collectively, these subthemes illustrate that teachers perceive digital tools as multifunctional resources that enhance conceptual understanding, engagement, and instructional flexibility. The integration of these tools reflects thoughtful pedagogical decisions that align with curriculum goals while addressing contextual constraints.

4.2. Pedagogical utilization of digital tools

This section presents findings on how primary science teachers integrate digital tools into their pedagogical practices. Thematic analysis revealed three subthemes that characterize patterns of pedagogical utilization: frequency and consistency of use, contextual influences on integration, and strategic support for abstract concepts.

4.2.1. Frequency and consistency of digital tool use

Many full-time science teachers described integrating digital tools as a regular component of their instructional practice, particularly when explaining abstract concepts. These teachers leveraged simulations, multimedia, and interactive platforms to support explanation and visualization of abstract concepts. T01 (urban, full-time) described:

"*I use digital tools in almost every lesson. They are an essential part of my teaching strategy, especially when explaining abstract concepts.*"

In contrast, several part-time teachers described more selective and situational use of digital tools, often constrained by time and teaching load. T03 (urban, part-time) explained:

"*I teach science alongside other subjects, so I don't have enough time to fully integrate digital tools. I mostly use them when I have a lesson that particularly benefits from the visual aids.*"

These differences underscore how employment status shapes the consistency and frequency of digital tool usage in classrooms. This pattern was consistently observed across participants, with more frequent and sustained use reported predominantly by full-time teachers, while part-time teachers more often described selective or situational integration, a trend also reflected across multiple interviews.

4.2.2. Contextual influences on integration

Teachers highlighted that the integration of digital tools was influenced by class level and curriculum demands. Higher-grade classes were more likely to incorporate simulations to explain complex scientific processes, reflecting the advanced cognitive demands of the content. T08 (urban, full-time) noted:

> "*In the higher grades, we do more advanced science, and digital tools are invaluable for explaining things like chemical bonding or energy transfer. These are difficult to grasp without visual aids or simulations.*"

Conversely, lower-grade classes used digital tools more selectively, often emphasizing engagement and visualization over procedural complexity. This finding suggests that pedagogical integration is context-dependent, shaped by both student developmental levels and curricular objectives.

4.2.3. Strategic support for abstract concepts

Across all participants, teachers emphasized using digital tools strategically to support understanding of concepts that are abstract, invisible, or otherwise challenging to demonstrate hands-on. Teachers consistently described aligning tool use with specific learning goals, ensuring that digital resources complemented rather than replaced traditional teaching methods. For example, T05 (urban, full-time) reflected:

> "*I plan each digital activity carefully. The tool must clarify the concept or demonstrate something students cannot see directly. Otherwise, it is just a gimmick.*"

This strategic approach indicates that teachers consider pedagogical purpose and learning outcomes when integrating digital tools, rather than using technology indiscriminately. Collectively, these subthemes illustrate that teachers' pedagogical use of digital tools is deliberate, contextually influenced, and strategically aligned with curricular goals. Integration varies according to employment status, class level, and the cognitive demands of science content, highlighting the nuanced decision-making underlying technology-enhanced teaching.

4.3. Challenges in digital tool integration

This section presents findings on the challenges encountered by primary science teachers when integrating digital tools, with particular attention to differences between rural and urban contexts. Thematic analysis revealed three interconnected subthemes: curriculum alignment and instructional relevance, infrastructure and technical constraints, and pedagogical balance and over-reliance.

4.3.1. Curriculum alignment and instructional relevance

Teachers frequently highlighted the challenge of aligning digital tools with prescribed curriculum objectives. Several teachers reported that while digital resources enhanced interactivity, they often required modification to fit lesson goals. T02 (rural, full-time) explained:

> "*The tools are great for making lessons more interactive, but sometimes they don't directly align with the curriculum. I often need to modify the content to make sure it fits with the lesson objectives.*"

Similarly, T14 (urban, full-time) noted:

> "*Even when I find a great simulation, I must adapt it to match the concepts we are teaching. Otherwise, students might get distracted or confused.*"

These comments indicate that effective integration requires deliberate adaptation, suggesting that pedagogical decision-making is critical to ensure tools support, rather than disrupt, instructional coherence.

4.3.2. Infrastructure and technical constraints

Infrastructure limitations were more prominently described by teachers working in rural schools, where unstable networks and limited access to devices constrained consistent digital tool use. Network instability, limited access to devices, and hardware shortages frequently hindered lesson delivery. T09 (rural, full-time) reported:

> "*In our school, the internet connection is very unstable, and this makes it difficult to rely on online tools during class. Sometimes the video won't load, or the simulation won't run properly.*"

T16 (rural, part-time) further emphasized limited resources:

> "*We have only one projector in our lab, and it's shared among multiple classes. This makes it hard to plan lessons that rely on digital demonstrations.*"

These experiences illustrate how technical and infrastructural constraints directly shape the feasibility and consistency of tool integration, highlighting disparities between urban and rural settings. Reports of infrastructure and technical constraints were predominantly voiced by teachers from rural schools, while urban teachers mentioned these issues less frequently, indicating a clear contextual pattern rather than isolated cases.

4.3.3. Pedagogical balance and over-reliance

Teachers also expressed caution against over-reliance on digital tools, emphasizing that hands-on experiments remain essential for scientific inquiry and conceptual understanding. T06 (rural, part-time) explained:

> "*Digital tools are helpful, but I'm always careful not to rely too heavily on them. Students need to experience hands-on science to really understand the concepts. Otherwise, they just become passive recipients of information.*"

T10 (urban, full-time) added:

> "*Sometimes I worry that students focus too much on simulations and videos, and forget to develop practical skills. Balancing digital and physical experiments is critical.*"

These reflections indicate that teachers described integration as involving both technical operation and pedagogical considerations, particularly in relation to visualization, interaction, and experiential learning. Collectively, these subthemes demonstrate that challenges in digital tool integration are multidimensional. They encompass the need for alignment with curriculum objectives, reliable infrastructure, and careful pedagogical planning. Importantly, the analysis reveals that teachers' decisions are informed by both contextual constraints (e.g., rural vs. urban schools) and instructional priorities, highlighting the complex interplay between technology, pedagogy, and environment.

4.4. Interplay between digital tools and hands-on learning (RQ4)

This section addresses RQ4, exploring how primary school science teachers perceive the relationship between digital tools and traditional, hands-on learning in science education. Thematic analysis identified two interrelated subthemes: complementarity between digital and hands-on approaches and risk of over-reliance on digital tools.

4.4.1. Complementarity between digital and hands-on approaches

Many teachers reported that combining digital tools with physical experiments enhanced learning outcomes by linking conceptual understanding with practical experience. Digital tools provided theoretical scaffolding, visualization of abstract concepts, and extended opportunities for observation beyond classroom limitations, while hands-on experiments allowed students to apply and consolidate knowledge. T03 (urban, part-time) explained:

> "*The best results come when we combine digital tools with physical experiments. Students get the theory from the digital tools and then apply it in a real experiment, which helps them solidify their understanding.*"

T12 (urban, part-time) further emphasized this synergy:

> "*Simulations help students understand what happens at a molecular level, but the hands-on activity lets them see it in action. Without both, understanding is incomplete.*"

These insights indicate that teachers view digital and hands-on strategies as mutually reinforcing, suggesting that pedagogical planning should intentionally integrate both modes rather than treating them independently.

4.4.2. Risk of over-reliance on digital tools

While recognizing the benefits of digital tools, teachers cautioned that excessive dependence could undermine conceptual understanding and practical skill development. T08 (urban, full-time) noted:

> "*If students only watch simulations or videos, they might understand the concept theoretically but fail to apply it in practice. Hands-on experiments remain essential.*"

Similarly, T15 (rural, full-time) observed:

> "*Digital tools are great for visualization, but they can't replace the tactile experience of conducting an experiment. Over-reliance can make students passive learners.*"

These reflections highlight the need for teachers to balance instructional strategies, ensuring that digital tools enhance rather than substitute experiential learning.

Collectively, the findings demonstrate that teachers strategically integrate digital and hands-on approaches to optimize student engagement and learning outcomes. The analysis also reveals context-sensitive decision-making: urban teachers often leveraged digital tools for complex visualizations, whereas rural teachers emphasized using both modes to compensate for limited laboratory resources. This nuanced understanding was evident in teachers' descriptions of flexible pedagogical approaches and deliberate instructional design in technology-enhanced science lessons.

4.5. Summary of findings

The analysis of the interview data revealed several interrelated aspects of primary school science teachers' experiences with digital tools. Across the findings, teachers described the use of digital technologies in science teaching as beneficial for lesson preparation, making abstract concepts more accessible, and supporting students' conceptual understanding. The ways in which teachers employed digital tools varied according to employment status, teaching load, and student grade levels. Patterns of digital tool integration varied according to teaching roles, instructional demands, and classroom contexts. Teachers with heavier teaching loads or responsibility for higher-grade content often described more deliberate and planned uses of digital tools, while others reported more selective or context-dependent integration. Teachers encountered multiple challenges that constrained effective integration. These challenges included misalignment between available digital resources and curriculum objectives, unstable network connectivity particularly in rural schools, and the need to balance digital instruction with hands-on experimental activities. Teachers highlighted the complementary nature of digital tools and hands-on experiments, noting that combining theoretical visualization with practical engagement produced the most meaningful learning outcomes for students. Collectively, these findings demonstrate how teachers' perceptions, pedagogical practices, contextual constraints, and integration strategies are intertwined. They provide a coherent foundation for interpreting the educational implications and for guiding targeted PD and resource support. Across all themes, the findings were not limited to a small number of individuals but recurred across participants from different school locations, employment statuses, and levels of PD experience, supporting the representativeness of the identified patterns.

5. DISCUSSION

The present study offers a more differentiated understanding of how digital tools are integrated into primary science education, contributing to ongoing scholarly discussions and extending prior research. Teachers highlighted both the benefits and challenges associated with digital tool use, revealing the complex interplay of pedagogical, technological, and contextual factors. By connecting these findings to prior research and the TPACK framework, this discussion demonstrates how digital tools influence instructional practices, teacher decision-making, and context-sensitive pedagogical strategies. The analysis offers insights relevant for both local and international educational contexts.

5.1. Teachers' attitudes and perceptions toward digital tools

Teachers' generally positive orientations toward digital tools appear to be closely linked to their perceptions of how such tools can foster student involvement and support the development of scientific concepts. They emphasized that simulations, virtual labs, and multimedia resources helped students visualize abstract, dynamic, or otherwise invisible phenomena, such as chemical reactions, energy transfer, and plant growth [28]. Teachers reported that digital tools fostered curiosity and inquiry, motivating students to ask questions and explore underlying scientific principles, rather than passively receiving information. This finding adds qualitative evidence to the existing literature by illustrating how daily classroom practices leverage digital tools not only for content delivery but also for cultivating scientific inquiry and critical thinking, consistent with prior observations on student-centered and interactive learning. Furthermore, teachers highlighted the capacity of digital tools to support differentiated learning. Students with varying cognitive styles and learning preferences benefited from multimedia explanations and interactive simulations, reinforcing prior research that digital technology can cater to diverse learners. The current study contributes additional empirical detail, documenting how teachers strategically select digital tools to scaffold learning for students at different proficiency levels, thereby promoting equity and inclusivity within the classroom.

5.2. Utilization of digital tools in pedagogical practices

The study revealed a range of practices for integrating digital tools into science teaching. Teachers used digital platforms to prepare lessons, access multimedia content, and conduct simulations of experiments that might otherwise be unsafe, impractical, or time-consuming. Integration strategies varied by teacher role, school context, and grade level: full-time science teachers and higher-grade classrooms generally featured more frequent and intensive use of digital tools, while part-time teachers with broader teaching responsibilities integrated tools less consistently. These variations suggest that teachers' use of digital tools is influenced by both pedagogical orientations and situational factors that shape opportunities for engaging with technology in classroom practice.

Teachers emphasized the importance of blending digital tools with hands-on experiments, using simulations to illustrate concepts followed by real experiments to consolidate learning. This blended approach was perceived as enhancing conceptual understanding and metacognitive awareness, illustrating how digital tools are employed in context-sensitive ways to support inquiry-based learning and active engagement. In this sense, context sensitivity refers to teachers' adaptive decision-making in response to instructional goals, time constraints, and classroom realities, rather than to the mere adoption of specific technologies.

Importantly, differences in digital tool utilization were shaped less by teachers' willingness to adopt technology and more by institutional role expectations and workload distribution. This finding aligns with prior research suggesting that teachers' capacity to innovate pedagogically is strongly influenced by time allocation, role differentiation, and access to organizational support, rather than by individual attitudes alone. From this perspective, the less consistent integration reported by part-time teachers reflects structural constraints embedded in school organization and staffing arrangements, underscoring the need to interpret teachers' pedagogical choices within their broader institutional contexts. The analysis highlights the need for PD to move beyond standardized training approaches and to better accommodate teachers' differentiated role expectations and workload constraints in supporting digital pedagogical practices.

5.3. Challenges in integrating digital tools

Despite positive perceptions, several challenges emerged in the effective use of digital tools. Curriculum misalignment was a common concern, requiring teachers to modify digital resources extensively to meet learning objectives [29]. Infrastructure gaps, especially in rural schools, limited the use of online tools, with unstable internet and limited hardware increasing teacher workload and creating stress. Teachers also expressed caution about over-reliance on digital tools, emphasizing that hands-on, tactile learning remains critical for developing scientific inquiry skills. These findings underscore the necessity of considering both pedagogical and contextual factors in technology integration, as access and alignment issues directly affect how tools are utilized and how effectively they enhance learning [30].

5.4. Influence of digital tool experience on views of traditional learning

Teachers' experiences with digital tools shaped their perceptions of hands-on learning. While digital simulations facilitated visualization and conceptual exploration, teachers consistently stressed that these tools are complements rather than replacements for physical experiments. The combination of digital and traditional methods allowed students to first engage with abstract representations and then apply knowledge concretely, strengthening conceptual understanding and fostering critical thinking. This interplay highlights teachers' deliberate reasoning about how to balance innovation and tradition in science education, reflecting both practical constraints and pedagogical goals [31].

5.5. Professional development and institutional support

Sustained PD and institutional support were identified as essential for effective integration of digital tools. Teachers highlighted the value of PD programs that combine technological skills with pedagogical content knowledge, fostering context-sensitive strategies aligned with curriculum objectives. Peer collaboration and practice-based learning in PD initiatives further enhanced teachers' confidence and efficacy. However, PD alone was insufficient without adequate institutional support, including reliable infrastructure, technical assistance, and funding. These findings reinforce the literature emphasizing that systemic and structural factors are critical determinants of successful technology integration in classrooms [32].

5.6. Limitations and future research

This study relied on teacher self-reports from a purposive sample in selected Chinese regions, limiting generalizability. Because the study employed a cross-sectional approach, the findings reflect teachers' perceptions at one moment in time rather than changes or effects observed over an extended period. Subsequent research may employ longitudinal or mixed-methods approaches to explore sustained digital tool use and its influence on scientific inquiry skills, conceptual understanding, and learning motivation. Comparative research across cultures and educational systems could reveal contextual moderating factors, informing policymakers and educators on tailoring digital tool integration strategies. Additionally, student perspectives on digital learning remain underexplored; understanding how student engagement and perceptions align with teachers' views would provide a more holistic picture of technology-enhanced science education.

5.7. Implications for an international readership

Although based in the Chinese primary school context, the findings have transferable lessons. For example, research in Spain has shown that primary teachers perceive digital teaching materials as valuable for enhancing instructional practices but face ongoing challenges related to professional competence and contextual factors, which resonates with our findings regarding the need for targeted training and sustained support in digital tool integration [33]. Similarly, comparative evidence from primary classrooms in Estonia highlights that sustained integration of digital technologies depends on national frameworks for teacher digital competence and targeted PD, reinforcing the role of systemic support in equitable implementation [34]. These international studies lend support to the interpretation that practice-based, context-sensitive PD, equitable infrastructure investment, and strategic implementation are important considerations for teacher training, curriculum design, and educational policy in diverse primary science education contexts.

6. CONCLUSION

This study offers three central insights regarding how digital tools are incorporated within primary science education. First, context-sensitive PD is essential, as teachers are most effective when training programs build both technical competence and pedagogical strategies aligned with curriculum objectives. Second, reliable infrastructure and systemic support, including stable internet connectivity and institutional backing, are critical for enabling meaningful classroom use, particularly in contexts with uneven resource distribution. Third, blending digital tools with hands-on, experiential learning enhances students' conceptual understanding, inquiry skills, and motivation, illustrating the pedagogical value of complementing digital innovations with traditional practices. These findings have practical implications for instructional policy, curriculum development, and teacher training: educational leaders can design targeted PD programs, allocate resources strategically, and create curricula that support equitable and effective technology integration. Overall, addressing these factors can help educators improve learning outcomes, foster student engagement, and advance science education in diverse primary school contexts.

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Wenlin Yang	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Sirinapa Kijkuakul		✓		✓			✓			✓	✓	✓	✓	✓

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research involving human participants was conducted in compliance with all relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration, and was approved by the Medical Research Ethics Committee of Jiaying University (Approval No. JUMREC-2025-001).

DATA AVAILABILITY

The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author(s).

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BIOGRAPHIES OF AUTHORS

Wenlin Yang is a Ph.D. candidate in Science Education at the Faculty of Education, Naresuan University, Thailand. He earned his master's degree from South China Normal University, China, in 2016 and subsequently taught at Jiaying University, Meizhou, Guangdong, China. In 2024, he began his doctoral studies in Science Education at Naresuan University. His research focuses on teacher professional development and the integration of information technology with subject teaching. He can be contacted at email: wenliny67@nu.ac.th.

Sirinapa Kijkuakul received her Ph.D. in Science Education from Kasetsart University, Thailand. She has over 17 years of experience as a senior lecturer, teaching undergraduate and graduate students at the Faculty of Education, Naresuan University, Phitsanulok, Thailand. Her research focuses on science education, particularly in STEM education, scientific literacy, teacher professional development, and qualitative action research. She can be contacted at email: sirinapaki@nu.ac.th.