

Professional development for primary science teachers: a systematic literature review of international and Chinese research

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Article Info

Article history:

Received Feb 3, 2026
Revised May 22, 2026
Accepted Jun 8, 2026

Keywords:

Blended learning
Cross-cultural comparison
Digital competencies
Primary science teachers
Professional development
STEM education
Teacher learning

ABSTRACT

This study systematically reviews professional development for primary science teachers, emphasizing digital competencies and science, technology, engineering and mathematics (STEM)-oriented instruction. There were 30 peer-reviewed studies published between 2020 and 2024 analyzed from Scopus and China National Knowledge Infrastructure (CNKI) databases, integrating international and Chinese perspectives. Quality assessment considered research design, instrument validity, data transparency, and alignment between findings and conclusions. The review identifies four professional development orientations: system-driven, innovation-driven, sustainability-oriented, and capacity-building. Chinese programs are largely centralized and policy-aligned, whereas international programs emphasize teacher autonomy, collaborative innovation, and long-term sustainability. The COVID-19 pandemic accelerated online and blended professional development adoption, revealing both opportunities for digital competency development and inequities in access. Findings contribute a cross-cultural synthesis of professional development structures, strategies, and outcomes for primary science teachers. Implications include designing scalable, equitable, and context-sensitive professional development programs, particularly in resource-limited settings such as rural China and developing countries. Future research should focus on longitudinal evaluation, cross-cultural comparisons, and rigorous assessment of digital competency integration to enhance teacher professional learning and inform policy and practice globally.

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1. INTRODUCTION

Teacher professional development has long been recognized as a central mechanism for improving educational quality and strengthening teacher professionalism in global education systems [1]. It refers to sustained and structured learning opportunities designed to enhance teachers' disciplinary knowledge, pedagogical competencies, and reflective capacity. Effective professional development enables teachers not only to respond to curriculum reforms and policy changes but also to engage in evidence-informed instructional decision-making and adaptive teaching practices [2]. In science education, professional development plays a particularly critical role in supporting teachers to develop inquiry-based pedagogies and foster students' scientific literacy, problem-solving skills, and conceptual understanding.

Over the past two decades, professional development has evolved from short-term, workshop-based training toward more sustained, collaborative, and context-sensitive professional learning models. These emerging approaches emphasize teacher agency, professional collaboration, reflective practice, and knowledge co-construction within learning communities. Globally, such shifts are closely aligned with broader educational reforms driven by digital transformation, science, technology, engineering and mathematics (STEM) education expansion, and competency-based curriculum redesign. In parallel, China has experienced rapid growth in professional development initiatives supported by national policy reforms, increased educational investment, and large-scale digital learning infrastructure development. These developments have positioned professional development as a strategic priority in both global and Chinese education agendas.

Within this broader context, the professional development of primary science teachers has attracted increasing scholarly attention. Primary science education forms the foundation for students' scientific literacy and inquiry competence; however, primary teachers often function as generalists rather than subject specialists, particularly in developing or resource-constrained settings. As a result, professional development for primary science teachers must address multiple dimensions, including content knowledge (CK), pedagogical content knowledge (PCK), and the integration of digital technologies with inquiry-based and STEM-oriented instructional practices [3]. This multidimensional requirement further increases the complexity of professional development design and implementation across diverse educational contexts [4].

Despite this growing body of research, existing studies on teacher professional development remain fragmented across methodological, contextual, and theoretical dimensions [5]. Methodologically, research is divided between positivist approaches emphasizing measurable outcomes and interpretivist approaches focusing on experiential understanding, with limited integration between the two paradigms [6]. Contextually, professional development studies are often conducted within isolated national or regional settings, resulting in limited cross-cultural comparison and insufficient understanding of how governance structures and institutional conditions shape professional development practices [7]. Theoretically, there remains a lack of unified frameworks that integrate policy structures, teacher agency, and learning environments into a coherent analytical system. As a result, existing research on teacher professional development remains fragmented across methodological, contextual, and theoretical dimensions, with limited integration of policy structures, teacher agency, and learning environments.

This fragmentation highlights the need for a systematic synthesis that can integrate dispersed findings and generate a more coherent understanding of professional development across contexts [8]. A systematic literature review is therefore necessary to consolidate existing evidence, identify dominant research patterns, and clarify how different professional development models operate under varying institutional and policy conditions. In particular, cross-national comparison between international contexts and China is essential for understanding how professional development systems respond to different governance logics, resource distributions, and educational development stages. To address these gaps, this study conducts a systematic literature review of 30 peer-reviewed studies (17 English and 13 Chinese) published between 2020 and 2024, retrieved from Scopus and China National Knowledge Infrastructure (CNKI) databases. By integrating evidence from international and Chinese contexts, this study aims to identify major professional development orientations, examine their design and implementation characteristics, and explore the contextual factors that shape their effectiveness.

Specifically, this study addresses the following research questions: i) RQ1: what are the major structural, methodological, and geographical patterns of research on professional development for primary science teachers in international and Chinese contexts? ii) RQ2: how do professional development design principles and implementation strategies differ across contexts? and iii) RQ3. What contextual constraints and systemic factors influence professional development effectiveness and sustainability, and what implications can be drawn for theory, practice, and policy? By synthesizing fragmented evidence across methodologies and contexts, this study contributes to the literature by developing a more integrated understanding of teacher professional development. It further aims to provide a conceptual foundation for interpreting professional development as a contextually embedded, systemically shaped, and multidimensionally interactive process, offering implications for future professional development design in both global and Chinese educational contexts.

2. METHOD

A comprehensive understanding of primary science teachers' professional development necessitates incorporating both international and Chinese literature. English-language studies provide global theoretical frameworks, comparative perspectives, and empirical evidence from diverse educational systems, whereas Chinese-language research offers context-specific insights into local policies, practices, and challenges [9]. Integrating both sources ensure a balanced perspective, bridging global scholarship with the realities of Chinese

primary science education. This approach aligns with best practices in systematic reviews that aim for geographical and cultural inclusivity [10]. Scopus and CNKI were selected as complementary bibliographic databases representing global indexed scholarship and regionally grounded Chinese academic outputs, respectively, ensuring methodological triangulation across international and local knowledge systems.

2.1. Data source and search strategy

Given the dual focus of this study capturing international perspectives on professional development and reflecting the Chinese context of primary science education two databases were selected for literature retrieval: Scopus and CNKI. The decision to use these two databases is supported by their complementary strengths in covering international and Chinese literature, respectively [11]. Scopus was chosen for its extensive coverage of high-quality, peer-reviewed international academic literature across disciplines, including education. Its inclusion ensured that the review incorporated internationally recognized research on teacher professional development [12]. The final Scopus search string used in this review was (“professional development” OR “teacher training” OR “teacher learning”) AND (“science education”) AND (“primary school” OR “elementary education”) AND (“in-service teacher”).

Meanwhile, CNKI was selected as the most authoritative and comprehensive Chinese academic database, providing extensive access to journal articles, dissertations, and research outputs published in China [13]. The inclusion of CNKI was particularly essential for two reasons. First, as a Chinese doctoral researcher conducting this study in an international doctoral program, it was important to bridge both global and local perspectives, a recognized strength in comparative education research [14]. Second, because this study focuses on the professional development of primary science teachers in China, incorporating Chinese-language research was necessary to capture locally grounded practices, policies, and challenges that might be absent from international databases. A parallel Chinese search strategy was developed using equivalent terms such as “教师专业发展”, “科学教育”, and “小学教师” or (teacher professional development, science education and primary/elementary school teachers), ensuring semantic equivalence across databases.

Following established practices in systematic reviews, comprehensive search strings were developed for both databases using a combination of keywords and Boolean operators [15]. For Scopus, search terms included combinations of “professional development,” “in-service teachers,” “science education,” and “primary schooling”, as shown in Table 1. For CNKI, equivalent Chinese terms were formulated through discussion with field experts to target literature on teacher professional development, in-service teachers, science teaching, and primary education. Searches were conducted in titles, abstracts, and keywords to ensure wide but focused coverage.

Table 1. Search string used in Scopus database for selecting relevant studies

Topics	Search string
Professional development	“professional development” OR “teacher training” OR “teacher learning” OR “professional learning”
In-service teachers	“in-service teacher” OR “practicing teacher” OR “experienced teacher”
Science	“science teaching” OR “science learning”
Elementary	“elementary school” OR “primary school” OR “primary education” OR “elementary education”

2.2. Inclusion and exclusion criteria

To ensure rigor, consistent inclusion and exclusion criteria were applied across both databases [16]. The criteria were developed based on the population, intervention, comparison, outcomes, study design (PICOS) framework commonly used to formulate research questions in systematic reviews [17]. For Scopus, only English-language, peer-reviewed journal articles and conference papers published between 2020 and 2024 were considered. For CNKI, Chinese-language core journal articles and master’s/doctoral dissertations published in the same period were included. Across both databases, studies were selected if they explicitly focused on the professional development of in-service primary school science teachers (population), with particular attention to the intervention of developing digital competency, digital literacy, or information and communication technology (ICT) integration in science teaching. Excluded were studies published before 2020, non-English/Chinese publications, research unrelated to primary school science teacher professional development, or literature types such as commentaries, and grey literature to maintain a focus on primary empirical research, as shown in Table 2. These criteria also contributed to reducing potential selection bias and ensuring the inclusion of high-quality and relevant studies.

Table 2. Inclusion and exclusion criteria

Criteria type	Inclusion criteria	Exclusion criteria
Publication year	Studies published between January 2020 and December 2024	Studies published before 2020
Document type	Peer-reviewed journal articles and conference papers	Reviews, book chapters, editorials, dissertations, and grey literature
Source type	Indexed journals and conference proceedings (e.g., Scopus and Web of Science)	Books, trade publications, book series, and non-indexed sources
Language	English (Scopus) and Chinese (CNKI)	Other language
Educational level	Studies focusing on primary education	Studies focusing on secondary, tertiary, or early childhood education
Target population	In-service primary school science teachers	Pre-service teachers, and other grade teachers
Focus and context	Studies addressing professional development related to digital competency or digital literacy for science teaching in primary schools	Studies not related to digital competency or professional development in science education, or not targeting primary school level

2.3. Screening and selection process

The screening and selection process adhered to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines, ensuring transparency and replicability [18]. For both Scopus and CNKI, the process involved four stages: identification, title and abstract screening, full-text eligibility assessment, and final inclusion. The screening and coding processes were independently conducted by two researchers. Any discrepancies were resolved through discussion to reach consensus. An acceptable level of agreement was achieved, ensuring the reliability and consistency of study selection. By combining Scopus and CNKI, this study ensured that both global perspectives and Chinese local practices were adequately represented, which was particularly critical given the researcher’s academic positioning as a Chinese doctoral student in an international doctoral program. Figures 1 and 2 present the PRISMA flow diagram illustrating the detailed process of identification, screening, eligibility assessment, and final inclusion of studies in this review.

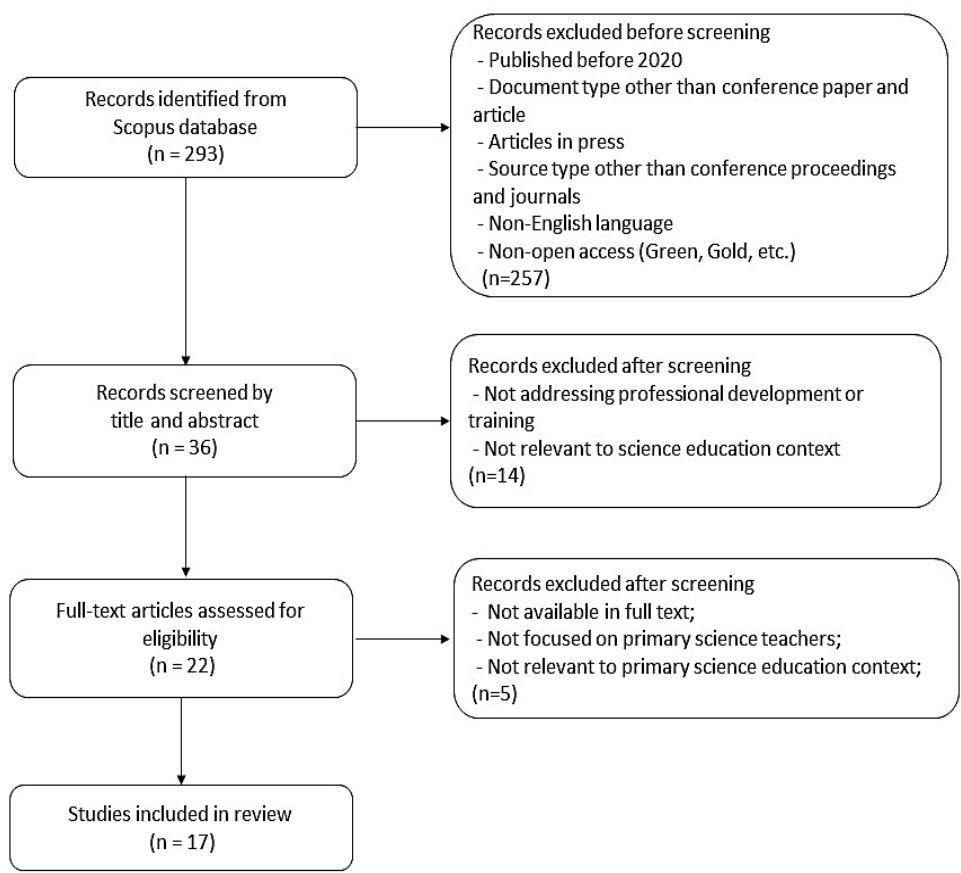


Figure 1. PRISMA flow diagram (Scopus)

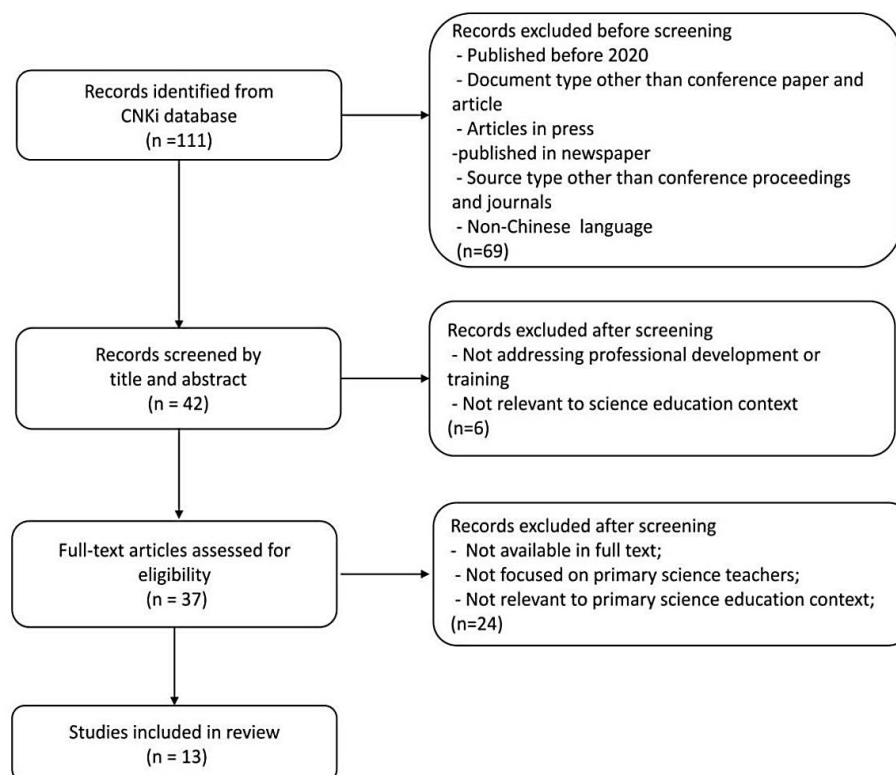


Figure 2. PRISMA flow diagram (CNKI)

2.4. Quality assessment and risk of bias

To ensure the methodological rigor and credibility of the included studies, a systematic quality assessment was conducted following established practices in systematic review [19]. First, all studies that met the inclusion criteria were further evaluated based on predefined quality indicators, including: i) clarity of research objectives; ii) appropriateness of research design; iii) validity and reliability of data collection instruments; iv) transparency of data analysis procedures; and v) alignment between findings and conclusions.

Each study was reviewed against these criteria to ensure that only methodologically sound and empirically robust research contributed to the synthesis. Studies that lacked sufficient methodological transparency or failed to provide clear evidence supporting their findings were carefully examined and interpreted with caution during the analysis phase. In addition, particular attention was given to the assessment of instrument validity and reliability, especially in survey-based studies, which constitute a significant proportion of the reviewed literature. When available, indicators such as pilot testing, reliability coefficients (e.g., Cronbach's alpha), and validation procedures were considered to evaluate the robustness of the research instruments.

To address potential risk of bias, several strategies were adopted [20]. First, the use of explicit inclusion and exclusion criteria helped reduce selection bias. Second, the screening process involved consultation with a second reviewer in cases of uncertainty, which enhanced the reliability of study selection. Third, the inclusion of studies from both international (Scopus) and Chinese (CNKI) databases mitigated geographical and publication bias, allowing for a more balanced and comprehensive representation of the field. Despite these efforts, it is acknowledged that some degree of bias may remain, particularly due to the reliance on published literature and the predominance of self-reported data in many empirical studies. These limitations were taken into account when interpreting the findings and drawing conclusions.

3. RESULTS

3.1. Temporal and geographical trends

This review synthesized 30 core publications, comprising 17 in English and 13 in Chinese, focusing on professional development for primary science teachers. Temporal analysis revealed a steady increase in research output from 2020 to 2023, peaking at 11 publications in 2023, followed by sustained activity in 2024. The increasing research output from 2020 to 2023 may be attributed to the acceleration of digital transformation

policies in teacher education and the post-pandemic expansion of online professional development initiatives, which intensified scholarly attention to technology-enhanced professional development models [21]. Notably, in 2024, the volume of Chinese research exceeded international contributions, reflecting intensified national investment in educational research under post-pandemic recovery strategies, as well as the expansion of policy-driven teacher professional development initiatives supported by centralized funding mechanisms [22]. As shown in Figure 3, publication output increased steadily from 2020 to 2023 before stabilizing in 2024.

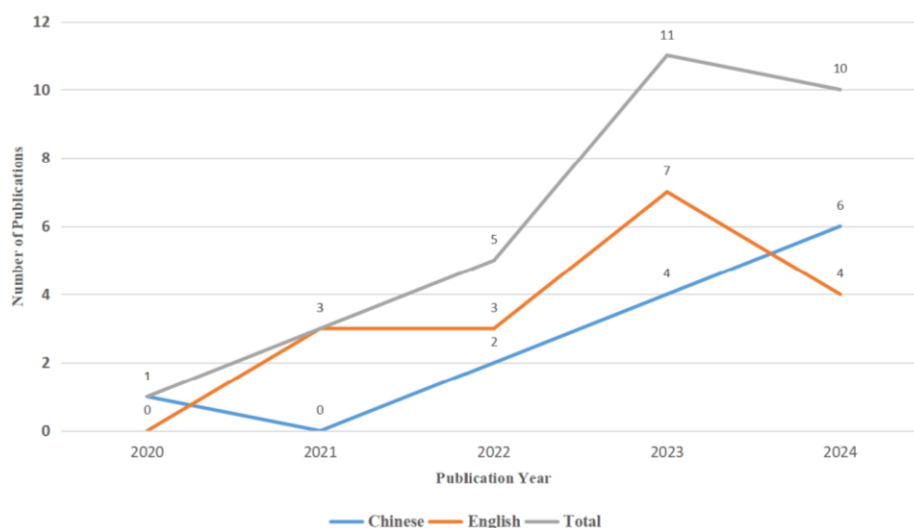


Figure 3. Annual publication trend

Geographically, the reviewed studies were concentrated primarily in the United States, China, and Europe, collectively accounting for approximately 90% of publications. United States studies, largely urban and qualitative, emphasized equity-oriented STEM curricula, small-scale workshops, and teacher identity reconstruction initiatives [23]. This emphasis reflects the decentralized governance structure of the United States education system, where teacher autonomy and school-level decision-making foster innovation-oriented and qualitative professional development research.

Chinese studies, predominantly rural and survey-based, focused on centralized professional development programs, school-based research groups, and structured, policy-aligned interventions [24]. In contrast, China's system-driven and survey-based professional development research reflects a centralized curriculum governance model that prioritizes large-scale policy implementation and accountability-oriented evaluation of teacher development. European research emphasized sustainability-oriented, multi-year professional development initiatives, incorporating mentoring, communities of practice, and reflective practice cycles [25]. This orientation is closely linked to long-term professional learning policies and the institutionalization of collaborative teacher learning communities within school systems.

Studies from emerging contexts, including Thailand, Saudi Arabia, and Nigeria, concentrated on capacity-building, foundational skill development, and Sustainable Development Goals (SDG)-linked programs [26]. These patterns reflect structural constraints in educational infrastructure and the need to address foundational teacher competency gaps under resource-limited conditions. Overall, these patterns suggest that professional development research distributions are shaped not only by policy priorities and institutional structures, but also by underlying governance logics, resource availability, and educational development stages across different regions.

3.2. Research methodologies

Analysis of the methodological approaches revealed that quantitative methods were predominant (43.3%), followed by qualitative (33.3%) and mixed-methods approaches (23.3%). This distribution reflects a broader positivist orientation in primary science teacher professional development research, where emphasis is placed on measuring outcomes, comparing groups, and identifying statistically generalizable patterns of effectiveness. Quantitative studies primarily employed cross-sectional surveys, pre/post assessments, and standardized tests, aiming to identify trends, measure prevalence, or test associations. The dominance of such designs suggests a tendency within professional development research to prioritize accountability-oriented

evaluation and observable instructional outcomes, often driven by policy demands for measurable evidence of teacher effectiveness. While these studies provide a broad overview of professional development implementation at scale, they frequently reduce complex professional learning processes to isolated variables, with limited consideration of instrument validity or contextual and cognitive dimensions of teacher learning [27]. This reflects an underlying methodological assumption that professional development impact can be adequately captured through quantifiable indicators.

Qualitative studies employed case studies, semi-structured interviews, classroom observations, and document analyses, offering rich, context-specific insights into teacher experiences and instructional practices. Their use indicates a complementary interpretivist orientation aimed at understanding how teachers experience and enact professional development in real classroom settings. Nevertheless, these studies frequently encounter challenges in transferability, reflexivity, and cross-contextual comparison, which limits their ability to inform large-scale professional development policy design [28].

Mixed-methods research sought to triangulate quantitative and qualitative findings to generate more comprehensive insights, yet in many cases the integration remained partial, with quantitative and qualitative strands operating in parallel rather than being fully integrated. This indicates an emerging but still underdeveloped effort to bridge measurement-oriented and meaning-oriented research traditions in professional development studies. Overall, these methodological patterns suggest that current professional development research is characterized by a dominance of positivist and measurement-driven paradigms, alongside a growing but still limited interpretivist and integrative methodological shift. This imbalance highlights the need for research designs that more effectively integrate generalizability with contextual depth in order to capture the multidimensional and situated nature of teacher professional learning [29]. Table 3 summarizes the distribution of research paradigms, objectives, data collection methods, and analytical strategies across the reviewed studies.

Table 3. Methodological paradigms, data collection, and analysis in primary science professional development research

Paradigm	Frequency	Research objectives	Common designs/data collection	Typical analysis approaches
Quantitative	13 (43.3%)	Identify trends, measure prevalence, and test associations	Cross-sectional surveys, pre/post assessments, standardized tests, and institutional records	Descriptive statistics (frequencies and means) and inferential statistics (t-tests, analysis of variance (ANOVA), and regression)
Qualitative	10 (33.3%)	Explore experiences, uncover mechanisms, and contextualize practices	Case studies, phenomenology, grounded theory, semi-structured interviews, classroom observations, and document analysis	Thematic analysis, content analysis, and discourse/interaction analysis
Mixed methods	7 (23.3%)	Triangulate findings, explain relationships, and develop context-sensitive insights	Explanatory sequential/convergent parallel designs, hybrid surveys/interviews, and multi-source triangulation	Joint displays, data transformation (quantitizing/qualitizing), and narrative weaving

3.3. Structural characteristics and implementation strategies

Analysis of program designs revealed four interrelated professional development orientations—system-driven, innovation-driven, sustainability-oriented, and capacity-building—which should be understood as interacting analytical dimensions rather than mutually exclusive or country-specific categories [30]. These orientations emerge differently across contexts depending on policy configurations, institutional arrangements, and resource availability.

In China, professional development programs exhibit a stronger emphasis on system-driven orientation, characterized by centralized workshops, tiered mentoring systems, school-based research groups, and the “1+2+X” teaching-research model. These structures reflect a governance logic prioritizing policy coherence, large-scale coordination, and equity in resource distribution. While such system-driven mechanisms are effective in addressing rural-urban disparities and teacher workforce imbalances, they may also constrain teacher autonomy and limit opportunities for collaborative innovation and pedagogical experimentation [31]. This indicates a high degree of structural alignment, but relatively constrained space for localized innovation.

In the United States, professional development practices demonstrate a stronger innovation-driven orientation, reflected in small-scale, curriculum-linked workshops, blended learning environments, and initiatives aimed at supporting teacher identity reconstruction. This orientation is closely associated with decentralized governance structures that prioritize teacher autonomy and school-level decision-making, thereby fostering creativity and equity-oriented STEM integration [32]. However, the fragmentation of initiatives across institutions suggests that innovation without sufficient systemic coordination may limit scalability and coherence of professional development implementation [33].

European professional development systems are characterized by a sustainability-oriented orientation, embedded in multi-year professional learning programs, mentoring systems, communities of practice, and reflective practice cycles. This reflects a policy emphasis on long-term professional growth and institutionalized collaboration among teachers. These structures support sustained instructional improvement and professional continuity, yet challenges remain in maintaining participation over time and ensuring scalability across diverse educational settings [34].

In emerging educational contexts, professional development initiatives primarily reflect a capacity-building orientation, focusing on foundational teacher competencies, community-based support mechanisms, outdoor STEM learning, and SDG-aligned programs. These approaches are strongly shaped by resource constraints and structural limitations in educational infrastructure, aiming to address foundational gaps in teacher knowledge and instructional capacity. However, their effectiveness is often constrained by limited scalability and long-term sustainability [35].

Overall, these findings indicate that the four professional development orientations do not operate as isolated national models, but rather as interdependent dimensions of a broader professional development system. Their relative prominence is shaped by governance structures, institutional capacity, and resource conditions, leading to observable trade-offs among scalability, innovation, sustainability, and contextual responsiveness. These trade-offs are not inherent limitations of specific countries, but structural outcomes of how professional development systems balance centralization, teacher autonomy, and resource allocation mechanisms [36]. Table 4 provides a detailed summary of implementation strategies and associated challenges across regions.

Table 4. Key implementation strategies and challenges in primary science teacher professional development across regions

Region	Implementation strategies	Key challenges
China	Policy-aligned tiered professional development programs; mentor-led guidance; centralized workshops; school-based research groups; and “internet+” blended learning	Rural-urban disparities; limited computational thinking integration; and minimal community-based inquiry
United States	Teacher-centered innovation projects; curriculum-linked workshops; small-scale practice-oriented professional development; teacher identity reconstruction; and blended/online professional development	Fragmented STEM integration and limited cross-disciplinary coherence
Europe	Multi-year longitudinal professional development; mentoring and peer coaching; communities of practice (CoPs); reflective practice sessions; and evidence-informed methods	Maintaining participation; institutional alignment; and scaling professional development programs
Emerging contexts	Foundational capacity building; outdoor STEM activities; and community-based teacher networks; SDG-linked initiatives; local resource leveraging	Resource constraints; limited scalability; and foundational skill gaps

4. DISCUSSION

4.1. Methodological critique

The predominance of quantitative research in studies of primary science teacher professional development reflects its effectiveness in generating large-scale diagnostic evidence and identifying generalizable patterns [37]. However, this methodological dominance raises important concerns regarding the adequacy with which complex teacher learning processes are captured. Quantitative designs frequently operationalize professional development outcomes through simplified variables, thereby overlooking the dynamic interplay among pedagogical knowledge, digital competencies, and context-specific conditions [38]. In addition, limited reporting on instrument validity and reliability in several studies further weakens confidence in the robustness of the findings and may lead to an overestimation of professional development effectiveness [39].

In contrast, qualitative approaches provide more nuanced and contextually grounded insights into teachers’ experiences, reflective practices, and classroom enactments of professional development. Nevertheless, these studies often face challenges related to transferability, sample representativeness, and researcher reflexivity, which constrain the broader applicability of their conclusions [40]. Although mixed-methods designs are theoretically positioned to integrate the strengths of both paradigms, many studies reviewed demonstrate only partial integration, with qualitative and quantitative components remaining analytically disconnected rather than mutually informing [41].

Taken together, these patterns suggest that current methodological approaches do not fully capture the complexity of professional development as a situated and multi-layered process [42]. This limitation has important implications for both the validity and interpretability of existing findings. Future research would

benefit from the adoption of longitudinal and experimental designs, the integration of multiple data sources, and more transparent reporting of instrument validation procedures. Such methodological advancements are necessary to better represent the interactions among policy environments, school structures, and teacher agency, and to generate more reliable and context-sensitive evidence on professional development effectiveness.

4.2. Cross-cultural comparison

Comparative analysis reveals systematic differences in dominant professional development orientations and underlying governance logics across China, developed Western countries, and emerging educational contexts. Rather than representing isolated national characteristics, these differences reflect how policy structures, institutional arrangements, and cultural expectations shape the configuration of professional development systems.

In China, professional development is primarily system-driven and policy-aligned, characterized by centralized governance, standardized training models, and structured implementation mechanisms such as tiered mentoring systems, school-based research groups, and the “1+2+X” teaching-research framework. This orientation is closely linked to a governance logic emphasizing large-scale coordination, equity promotion, and curriculum reform implementation. As a result, professional development programs tend to prioritize procedural consistency and system-wide coverage. However, this structure may also limit teacher autonomy and constrain opportunities for localized pedagogical innovation, with survey-based evidence indicating relatively strong procedural compliance but weaker adaptive expertise among teachers engaged in highly structured professional development systems [43].

By contrast, professional development systems in the United States and Europe are predominantly innovation-driven and teacher-centered, reflecting decentralized governance structures and a professional culture that emphasizes teacher autonomy and inquiry-based practice. These systems support collaborative curriculum design, interdisciplinary STEM integration, and sustained professional learning communities. In such contexts, sustainability-oriented professional development practices are also more prominent, as long-term professional growth is often embedded within school-based networks and reflective practice structures. However, this model presupposes relatively strong institutional capacity and may be less transferable to contexts with limited resources or centralized governance [44].

Emerging educational contexts, including Thailand and Nigeria, place greater emphasis on capacity-building-oriented professional development, focusing on foundational teacher competencies, basic instructional skills, and community-based support mechanisms. While such approaches address urgent capacity gaps, their effectiveness is often constrained by limited infrastructure, resource scarcity, and challenges in ensuring long-term program sustainability.

These cross-cultural differences suggest that professional development effectiveness is not determined by a single model, but is instead shaped by the interaction between governance structures, institutional capacity, and teacher agency. Importantly, the findings indicate that system-driven, innovation-driven, sustainability-oriented, and capacity-building approaches should not be viewed as mutually exclusive categories, but as interrelated orientations that emerge differently across contexts. This interpretation provides a conceptual basis for the integrated framework developed in Section 4.4, which further conceptualizes professional development as an interconnected system of interacting orientations rather than discrete national models.

4.3. Theoretical contributions

This review reinforces and extends existing theories of professional development, particularly the technological pedagogical content knowledge (TPACK) framework and the educational ecology perspective, by demonstrating that teacher learning is shaped through complex interactions among teachers, schools, communities, and policy systems [45]. The findings suggest that professional development should not be understood solely as an individual process of skill acquisition, but rather as a contextually situated and structurally mediated process influenced by institutional, pedagogical, and sociocultural conditions.

Cross-cultural evidence further highlights the importance of teacher agency, collaborative learning, and contextual responsiveness in supporting meaningful professional growth [46]. In the Chinese context, system-driven professional development reflects centralized curriculum reform structures, policy accountability mechanisms, and coordinated national initiatives aimed at reducing regional disparities and improving instructional consistency. By contrast, professional development approaches in Western contexts more frequently prioritize teacher autonomy, inquiry-oriented learning, and decentralized professional collaboration. These differences indicate that professional development effectiveness is deeply shaped by broader governance traditions and educational cultures, challenging the assumption that a single professional development model can be universally effective across contexts.

The findings further reveal important limitations in existing professional development theories and research. Much of the current literature tends to examine professional development approaches in isolation, often emphasizing institutional structures, teacher agency, or pedagogical innovation separately, without sufficiently addressing the dynamic interactions among these dimensions. As a result, existing frameworks risk underestimating how policy systems, school structures, and contextual conditions collectively shape teacher learning processes. This fragmentation suggests that current theoretical approaches remain insufficient for explaining professional development as a complex, multi-layered and contextually embedded process. Addressing this gap, this study contributes to the literature by proposing an integrated conceptual framework that conceptualizes professional development as an interconnected system in which structural, pedagogical, and contextual dimensions interact dynamically across different educational environments.

4.4. An integrated framework of professional development

Building on these findings, this study proposes an integrated framework of professional development for primary science teachers that conceptualizes professional development as an interconnected professional learning ecosystem rather than a collection of isolated training models. The four professional development orientations identified in this review—system-driven, innovation-driven, sustainability-oriented, and capacity-building—should therefore be understood as interdependent dimensions that interact dynamically across policy, institutional, and classroom levels. As illustrated in Figure 4, the proposed framework highlights the reciprocal relationships among structural support, teacher agency, sustainable learning mechanisms, and contextual adaptation within diverse educational environments.

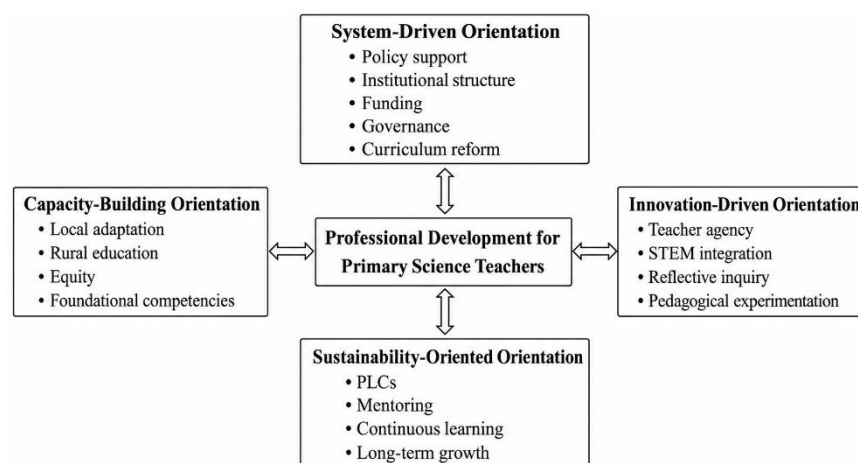


Figure 4. A multi-level ecosystem model of professional development for primary science teachers

Within this framework, system-driven professional development provides structural alignment through policy guidance, institutional coordination, funding support, and reform-oriented governance. These structures establish organizational stability and enable large-scale implementation of professional development initiatives. Innovation-driven professional development, in turn, strengthens teacher agency by encouraging pedagogical experimentation, interdisciplinary STEM integration, reflective inquiry, and collaborative instructional design. Sustainability-oriented professional development emphasizes long-term professional growth through continuous learning communities, mentoring systems, and reflective practice, thereby supporting enduring changes in instructional behavior. Capacity-building approaches further enhance contextual responsiveness by addressing local educational needs, resource disparities, and foundational competency development, particularly in rural or under-resourced settings.

Importantly, Figure 4 demonstrates that these orientations should not be interpreted as linear or isolated stages of professional development implementation. Rather, they operate as mutually reinforcing dimensions within a unified professional development ecosystem. Effective professional development depends not on the dominance of a single orientation, but on the alignment and interaction among structural support, teacher agency, sustainable learning mechanisms, and contextual adaptation. For example, system-driven structures may provide policy coherence and scalability, but without opportunities for teacher-led innovation, professional development risks becoming procedural rather than transformative. Similarly, innovation-driven approaches may foster

creativity and autonomy, yet require sustainable institutional support and contextual capacity to achieve long-term impact. The framework further reflects how professional development orientations are shaped by broader sociocultural and policy conditions across different educational systems. In centralized contexts such as China, system-driven structures play a critical role in ensuring implementation consistency and reducing regional disparities, whereas decentralized educational systems more frequently emphasize innovation-driven and teacher-centered approaches that support pedagogical flexibility and collaborative inquiry.

This integrated framework contributes to the literature by bridging structural, pedagogical, and contextual dimensions of teacher professional development. Unlike prior studies that examine professional development orientations separately, this review demonstrates how policy systems, collaborative learning, teacher agency, and contextual adaptation interact dynamically to shape professional learning outcomes across different educational systems. Taken together, the framework advances professional development theory by emphasizing that transformative and sustainable teacher development emerges through coordinated interactions within an interconnected professional learning ecosystem.

4.5. Practical implications

The findings offer actionable guidance for professional development program design, particularly in resource-limited settings such as rural China or developing countries. System-driven professional development can efficiently address structural inequities and workforce shortages. However, embedding teacher autonomy, scaffolded digital competency development, and blended learning approaches is essential for sustained impact [47].

Hybrid models combining structured, policy-aligned training with innovation-driven practices promote both scalability and adaptability, allowing for broad coverage while encouraging localized pedagogical experimentation [48]. Practical strategies may include multi-tiered mentoring, peer coaching, and structured reflection cycles, alongside community-based inquiry and collaborative networks. These strategies help teachers develop adaptive expertise while respecting local constraints and resource limitations.

4.6. COVID-19 Impact

The 2020-2024 period reflects significant transformations in professional development modalities due to the COVID-19 pandemic. Rapid adoption of online and blended professional development programs accelerated integration of digital literacy and ICT competencies into teacher practice [49]. Simultaneously, the pandemic exposed inequities in technology access, particularly in rural or under-resourced regions, highlighting the necessity for resilient and flexible professional development frameworks [50].

Beyond immediate adaptation, COVID-19 has reshaped professional development design paradigms. Digital platforms have been shown to enhance teacher agency, enable self-directed learning, and facilitate collaboration across geographically dispersed schools. These experiences suggest that emergency-driven professional development innovations can produce lasting benefits if incorporated into long-term program design, supporting both scalability and context responsiveness.

4.7. Limitations and future directions

Despite the comprehensive coverage of English- and Chinese-language literature, this review has several limitations. First, reliance on self-reported data introduces subjectivity and potential overestimation of professional development effectiveness. Second, sample bias—predominantly urban, school-based, or policy-aligned participants—limits generalizability, particularly to rural or resource-constrained contexts [51]. Third, methodological constraints, including quantitative dominance and partial mixed-method integration, restrict understanding of context-specific teacher learning and nuanced professional development effects.

Future research should adopt longitudinal, cross-cultural, and experimental designs, employing multi-source data collection to enhance reliability and contextual understanding. Equity-focused studies, integration of digital competencies, and hybrid professional development approaches that combine structural support with teacher agency should be prioritized [52]. Such efforts will strengthen both theoretical frameworks and practical guidance for scalable, context-sensitive professional development for primary science teachers worldwide.

5. CONCLUSION

This systematic review synthesized evidence from 30 studies on primary science teacher professional development across international and Chinese contexts. The analysis identified four interrelated professional development orientations—system-driven, innovation-driven, sustainability-oriented, and capacity-building—which reflect different responses to policy demands, institutional arrangements, and resource conditions. Across contexts, professional development implementation is shaped by persistent structural and pedagogical challenges, including unequal access to digital resources, limited interdisciplinary integration, and variability

in implementation fidelity. The COVID-19 pandemic further accelerated the adoption of online and blended professional development models, simultaneously expanding opportunities for digital competency development while exposing existing inequities in access and participation.

This review contributes to the literature by moving beyond fragmented descriptions of professional development practices to propose an integrated analytical perspective in which professional development is understood as a multidimensional and interdependent system rather than a set of isolated approaches. The findings extend existing theoretical perspectives, particularly TPACK and educational ecology frameworks, by demonstrating how teacher agency, institutional structures, and contextual environments interact dynamically to shape professional learning outcomes. Importantly, the four identified professional development orientations should not be interpreted as country-specific categories, but as interconnected dimensions within a unified professional development ecosystem that operates across varying governance and cultural contexts.

From a policy perspective, the findings suggest the need for professional development systems that balance structural coordination with teacher autonomy, ensuring both scalability and contextual adaptability. For teacher education and professional development design, effective programs should integrate structured training with collaborative learning opportunities, mentoring systems, and reflective practice to strengthen both pedagogical competence and digital literacy in science teaching. Finally, future research should prioritize longitudinal and cross-cultural studies, as well as rigorous evaluation of blended and technology-enhanced professional development models, to better understand how digital transformation reshapes teacher learning processes and to develop more resilient and context-responsive professional development frameworks.

ACKNOWLEDGMENTS

This study was supported by research grant or contract.

FUNDING INFORMATION

The authors declare that no funding was received for this study.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization

M : **M**ethodology

So : **S**oftware

Va : **V**alidation

Fo : **F**ormal analysis

I : **I**nvestigation

R : **R**esources

D : **D**ata Curation

O : **O** Writing - **O**riginal Draft

E : **E** Writing - Review & **E**editing

Vi : **V**isualization

Su : **S**upervision

P : **P**roject administration

Fu : **F**unding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

INFORMED CONSENT

Informed consent is not applicable to this study as it does not involve human participants.

ETHICAL APPROVAL

Ethical approval is not required for this study as it is based on a review of existing literature.

DATA AVAILABILITY

Data availability is not applicable to this study as no new data were created or analyzed.

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