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STRATEGIES AND OUTCOMES OF SCIENCE TEACHER PROFESSIONAL DEVELOPMENT: A SYSTEMATIC REVIEW

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Abstract. This study explores the theoretical foundations of various models, approaches, and strategies for professional development in Science Education. The study identifies relevant models and strategies that contribute to professional growth through a systematic literature review. It highlights effective approaches that strengthen teachers' knowledge, perception, and classroom practice. By integrating these strategies, the study aims to support Science teachers in adapting to educational reforms, fostering a more engaging and effective learning environment for students. The strategies employed in Science Teacher Professional Development (S-TPD) can be grouped into five main clusters: (1) Immersion Science experiences, (2) Technology-integrated approaches in S-TPD, (3) Collaborative structures in S-TPD, (4) Design-Based Research in S-TPD, and (5) Aligning and implementing science curriculum in S-TPD. Ultimately, the findings provide insights into designing professional development programs that address both instructional competence and the evolving needs of teachers in curriculum reform.

Keywords: teacher professional development, science education, strategies, outcomes.

1. Introduction

In the new era of information technology, learners need to be equipped with essential competencies to cope with the challenges of the 21st century, including scientific literacy [1]. Accordingly, science teachers play a crucial role in enhancing students' competencies by providing knowledge and fostering critical thinking, collaboration, and problem-solving skills [2]. To improve the quality of science teaching, teacher professional development (TPD) is considered a core factor in fulfilling the goals of educational reform [3], [4]. High-quality professional development (PD) programs help teachers overcome teaching challenges and enhance their science teaching competence. Educators and researchers continually propose various PD models, ranging from short-term workshops, collaborative lesson design, to practice-based and inquiry-driven programs [5]-[7]. Researchers have also affirmed the effectiveness of professional development programs in enhancing teachers' knowledge, improving their pedagogical competence, raising teaching quality, and changing their beliefs and attitudes. The effectiveness of a professional development program should be measured by the knowledge teachers acquire and evaluated based on changes in their beliefs, instructional practices, and ultimately, student learning outcomes [8]-[9]. The diversity of strategies and outcomes across different contexts poses significant challenges for implementation, especially in transitional education systems. In fact, there remains a lack of systematic and comprehensive evidence regarding which PD strategies are most effective and what teachers gain through these processes, particularly in countries undergoing educational reform. Therefore, this study conducts a systematic literature review to address the following research questions:

+) *What strategies are adopted in S-TPD?*

+) *What have teachers achieved in S-TPD?*

2. Content

2.1. Theoretical Framework Background

TPD enhances teachers' subject-matter expertise and pedagogical competence [4]. In current educational reforms, TPD has moved beyond traditional short-term training courses to encompass more in-depth, interactive, and practice-oriented training activities [3]. Various theoretical models have been developed to guide the design and implementation of effective TPD programs. Desimone proposes a core conceptual framework consisting of five key features that determine the effectiveness of TPD: content focus, active learning, coherence with professional practice, sufficient duration, and collective participation [4]. Guskey emphasizes the importance of a sequential impact chain from professional development activities to changes in instructional practices, teachers' beliefs, and ultimately student learning outcomes [8]. Loucks-Horsley et al. list strategies for designing professional development for Science and Mathematics teachers [10]-[11]. Some such professional strategies are widely adopted in Science Teacher Professional Development (S-TPD). Moreover, several researchers have proposed comprehensive evaluation frameworks to measure the effectiveness of TPD programs. One notable model is Guskey's five-level framework, which includes: participants' reactions, teachers' learning, changes in classroom practice, student outcomes, and overall impact on the educational system [8].

Numerous studies have shown that TPD improves teachers' professional knowledge and instructional skills, fosters changes in their professional beliefs, supports the development of leadership capacity, and promotes autonomy in pedagogical innovation [5]-[6]. These positive effects are reflected in students through enhancing the learning environment, developing critical thinking, collaboration skills, and self-regulated learning. Therefore, the success of TPD should be evaluated within the reciprocal relationship between teacher professional growth and student academic outcomes.

2.2. Methodology

This current study used the systematic literature review methodology to search, review, and analyze the existing literature using four complementary stages: (1) search, (2) selection, (3) coding, and (4) synthesis for conducting systematic reviews.

2.2.1. Search procedures

To begin with, we searched for empirical studies in research databases SCOPUS and ERIC with the keywords ("PD" OR "professional development" OR "teacher education" OR "teacher learning" AND "science education"). The search was carried out in May 2025.

2.2.2. Study selection

After searching, we found 1597 articles from SCOPUS and ERIC databases. The 1597 studies were analyzed based on the inclusion criteria (Table 1). This current study was guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [12]-[13]. Table 1 illustrates the relationship between the screening and eligibility phases regarding the inclusion principle. We excluded studies that didn't focus on professional development for practicing science teachers. We also filtered out research that didn't empirically investigate the effects of a PD program on teachers or students. Finally, we removed any studies that were not written in English. Based on the inclusion and exclusion principles (including the possibility of finding full text), 19 articles with a star (*) in the reference are included in this current study for reviewing the literature.

Table 1. The criteria for the inclusion studies

Inclusion principle	Description	The phase in PRISMA
Nature of an article [13]	The excluded papers are "expert interviews, editor's notes, or summaries of a person's work or theory."	Screening
Content foci	Articles have Titles and/or Abstracts related directly to TPD in Science education. TPD is mentioned as the main content in articles.	Screening
Sample properties	Articles in this category mainly focus on in-service science teachers.	Screening
Relevance	Articles show direct connections or alignments to the current study's focus (TPD strategeies and outcomes)	Eligibility

2.2.3. Synthesis procedure

We employed coding and synthesis [14]-[15] to address the two research questions. We read and agreed on the summary table of all 20 articles regarding: (1) first author and the year of publication; (2) participants; (3) methodological design; (4) measured variables; and (5) findings. Two authors independently coded five randomly selected articles, with an inter-rater agreement of 82%.

2.3. Research Results

2.3.1. TPD strategies in science education

Regarding the trends of strategies in Science education emerging in the reviewed papers, in total, five key strategies employed in S-TPD were identified: *Immersion Science experiences, Technology-integrated in S-TPD, Collaborative structures in S-TPD, Design-Based Research in S-TPD, and Aligning and Implementing Science curriculum in S-TPD.*

2.3.1.1. Immersion Science experiences

Immersion science experiences refer to engaging teachers in the role of scientists, allowing teachers to gain key disciplinary concepts such as scientific inquiry, science literacy, modeling, and scientific argumentation. The studies have demonstrated that strategies in S-TPD are increasingly designed to engage teachers in direct experiences of the scientific inquiry process [16]-[18]. These strategies typically involve teachers assuming the role of learners, including conducting experiments, formulating questions, and collecting and analyzing data, thereby fostering their competence in inquiry-based science teaching. Akuma and Callaghan integrated the Inquiry-Based Practical Work model so teachers could implement inquiry-based teaching effectively [16]. The results indicate that the teaching practices did not fully reflect inquiry-based teaching, and that some teaching practices, when implemented, were observed at a relatively low level. The study highlighted that implementing inquiry-based teaching presents substantial challenges. Lotter et al. [17] developed a two-week summer program focused on inquiry pedagogy and science content. The program enhanced their instructional effectiveness and self-efficacy in inquiry teaching by disscussion between teachers and scientists for guiding teachers through inquiry. The impacts of such initiatives extend beyond the immediate scope of professional development, fostering sustained professional growth over time through visitting science and technology sites [18]. Immersing science experience for teachers in dual roles as learners and scientists emerges as an effective professional development strategy.

2.3.1.2. Technology-integrated strategies in S-TPD

Technology-integrated strategies have been proven to be effective for S-TPD. The necessity of a structured training process that closely integrates technology with content and pedagogy, as in the domains of the TPACK (Technological Pedagogical Content Knowledge) model is highlighted. Hsu et al. [19] explored a PD program in which a biology teacher was introduced to augmented reality as a technological tool and a science-specific instructional planning tool supported by examples, reflection, and opportunities for practicing. Jimoyiannis [20] introduced the TPASK (Technological Pedagogical Science Knowledge) model to prepare teachers for effective technology-integrated teaching. Moosa & Ramnarain [21] implemented a technology-integrated PD model focused on applying technology in physics. These studies proposed an effective approach to implementing ICT integration PD program. Through this approach, teachers were able to enhance their confidence and competence, leading to changes in their attitudes and the development of technology-integrated teaching practices.

2.3.1.3. Collaborative structures in S-TPD

Some studies confirmed the effectiveness of collaborative structures in supporting meaningful and sustainable PD for science teachers. Collaboration with researchers, as demonstrated in the studies of Siry et al. [22] and Cutucache et al. [23], has promoted the co-development of teaching implementation while enhancing teachers' science knowledge, confidence, and perception. In addition, collaboration among teachers within virtual communities of practice has facilitated experience sharing, thereby reducing teachers' classroom isolation and promoting their engagement in PD and collaborative critical reflection [24]. However, professional learning networks are most effective when the implemantation of specific content lesson and PD activities is synchronized [25]. Finally, interdisciplinary collaboration and co-design of curricula, as explored by Chan & Erduran [26] and Bossér [27], have helped teachers deepen their understanding of scientific argumentation and evidence-based reasoning. Collaboration in S-TPD programs is diverse and extends beyond cooperation among teachers. Implementing a collaborative model to support teachers' professional development has shown initial effectiveness, especially in certain stages of the PD process, such as co-designing lessons.

2.3.1.4. Design-Based Research in S-TPD

Typically, teachers are provided with knowledge and skills, or they passively follow the content of programs. However, several studies have proposed a more effective strategy: *Design-Based Research (DBR).* For instance, Peters-Burton et al. [28] conducted a three-year collaborative professional development initiative to integrate computational thinking and self-regulated learning for implementing data practise in science instruction. In Gandolfi's [29] study, a researcher–teacher collaboration was established to co-design teaching plans incorporating Nature of Science concepts. Teachers worked with researchers as co-creators through repeated design, testing, and refinement, engaging in scientific practices and building more effective professional development.

2.3.1.5. Aligning and implementing science curriculum in S-TPD

One important focus of S-TPD is supporting teachers in aligning instruction with curriculum goals and implementing reforms effectively. Christodoulou and Osborne [30] highlighted teachers' challenges when implementing argument-based teaching and suggested that S-TPD should support teachers in "talking science based on argument." Alignment of curriculum is essential for supporting teachers' effective implementation [31]. From a broader perspective, aligning with the curriculum alone is insufficient [32]. PD models should also aim at helping teachers master complex pedagogical skills such as scaffolding. The blended professional development program was implemented, and data sources - including videos of three small groups per class period and students' written responses to prompts from computer-based argumentation scaffolds - were collected to demonstrate that the teacher provided one-to-one scaffolding comparable to inquiry-oriented teaching practices [33]. Furthermore, providing teachers with tools to access and understand curriculum content and assessment methods can be beneficial, such as the "Brandon's Matrix" introduced by Cullinane et al. [34], a pedagogical framework tool to align lesson planning and assessment with objectives related to the nature of science and scientific thinking. PD programs should be designed to align with curriculum content and assessment tools. Sometimes, it is unnecessary to organize S-TPD programs; instead, accompanying teachers during implementation and supporting them in aligning and applying curriculum reforms or innovative teaching approaches can also be an effective strategy to enhance professional development.

2.3.2. Teachers' professional outcomes in terms of Knowledge, Perception, and Classroom Practice

2.3.2.1. Teachers' professional outcomes in terms of Knowledge

Teachers' knowledge, perception, and classroom practice were measured as professional learning outcomes of S-TPD as professional growth. S-TPD programs have been shown to improve both science teachers' content knowledge and pedagogical knowledge. For content knowledge, some studies show that PD helps teachers better understand key scientific concepts and practices. Gandolfi [19] found that creating curriculum materials helped teachers instruct the Nature of Science more meaningfully. Similarly, Henze et al. [31], Cutucache et al. [23], and Bossér [27] reported that teachers improved their knowledge of scientific modeling, inquiry, and literacy. Cullinane et al. [34] also found that using evaluation tools helped teachers better understand scientific methods. Besides, PD also helps teachers improve pedagogical knowledge. Jimoyiannis [20] emphasized the TPASK framework, which encompasses both science content knowledge and pedagogical knowledge, highlighting the necessity of these components in teachers' professional development. For professional development, teachers need both content knowledge and pedagogical knowledge. The reviewed papers once again affirmed the importance of these two types of knowledge and highlighted them as key outcomes of professional development programs.

2.3.2.2. Teachers' professional outcomes in terms of Perceptions

PD programs enhance teachers' perceptions and shape their self-efficacy, empowerment, and attitudes within the context of Science educational reform. Moosa and Ramnarain [21] demonstrated that empowerment evaluation-based PD can strengthen teachers' confidence and behavioral intentions to integrate information and communication technology into science instruction. Siry et al. [22] emphasized the effectiveness of PD in enhancing teacher agency and leadership capacity. From a professional engagement perspective, El-Hani and Greca [24] highlighted that participation in virtual communities of practice fosters deeper connections between professional development and a sense of belonging to a learning community. Peters-Burton et al. [28] pointed out that involvement in designing instructional tools within a DBR framework enhances content knowledge and empowers teachers to assume ownership and central roles in pedagogical innovation. The perceptions that teachers can change through professional development programs are diverse and are considered a crucial outcome. This is because perceptions are closely linked to teachers' instructional behaviors.

2.3.2.3. Teachers' Professional Outcomes in terms of Classroom Practice

Ultimately, the effectiveness of professional development (PD) programs for teachers should be assessed through changes in teaching practices and the impact on student learning outcomes. The articles reviewed in this analysis provide substantial empirical evidence demonstrating a direct link between teachers' professional development and student improvement. Regarding academic achievement, Tsaliki et al. [18] asserted that students can enhance their understanding of scientific concepts in inquiry-based learning. Southerland et al. [35] suggested that Research Experiences for Teachers (RET) participation contributes to changes in science teachers' beliefs and practices, and the proposed model highlights ways to enhance the professional development impact of RET on teachers' engagement in disciplinary practices. Effective S-TPD programs are not merely about teachers ' professional development but also serve as a powerful mechanism to positively and directly influence students' competencies.

3. Conclusions

Through an in-depth analysis of the reviewed studies, we identified five main strategies commonly used in S-TPD: *(1) immersion science experiences, (2) technology-integrated approaches, (3) collaborative structures, (4) design-based research, and (5) curriculum alignment and implementation* (Figure 1). These strategies are generally applied flexibly, allowing adaptation to different goals, contexts, and participant needs. Established theoretical frameworks often support these strategies, which guide program design and evaluation. Frequently referenced frameworks include the TPACK framework, the Technology Acceptance Model, the Inquiry-Based Practical Work model, and models for evaluating S-TPD effectiveness. S-TPD outcomes are typically assessed across three main dimensions: *teachers' knowledge, perception, and classroom practice* (Figure 1). Notably, some studies also include student learning outcomes as an important measure of the final impact of professional development programs. Combining clearly defined strategies, guiding frameworks, and targeted evaluation provides a structured approach to S-TPD. This approach aims to improve teachers' professional competence and, in turn, enhance students' science learning.

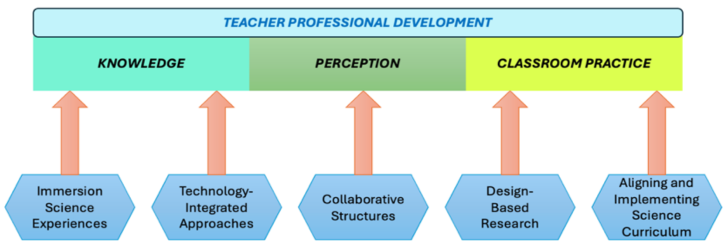

Figure 1. Professional Development in Science Education

Limitations: While a transparent and systematic approach was applied in selecting and including reviewed articles, the study has limitations. Specifically, restricting the search to two electronic databases, Scopus and ERIC, may have omitted valuable and high-quality literature not covered by these platforms. Nevertheless, a rigorous review procedure was implemented, supported by a well-grounded theoretical framework to guide the article analysis.

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