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Research article

The influence of professional teacher development programmes on physical science teachers' content knowledge and practical skills in mechanics and electromagnetism

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Abstract: We focused on the effectiveness of Professional Teacher Development Programmes (PTDPs) on physical science teachers' Pedagogical Content Knowledge (PCK), integrated with practical skills in teaching mechanics and electromagnetism in one education district. This study was framed within the PCK and Andragogy as theoretical lenses. The interpretivist paradigm was employed. We focused on individual teachers' experiences, how these experiences were applied in their teaching practices, their engagement with the PTDPs, and how such programmes could be reshaped to enhance physical science teachers' professional growth. Purposeful sampling was used to engage eight physical sciences teachers from eight schools who attended these programmes. Data were collected through interviews and classroom observations. Thematic analysis was employed to analyse the data. The teachers reported perceived improvements in their PCK, while practical skills received less attention due to limited resources and limited time for practical activities. Teachers also reported the urgency of integrating content with practical activities and of aligning these programmes with their term-by-term annual teaching plans (ATPs). Based on the participants' accounts, this study suggests that PTDPs should be strategically designed to deepen physical science teachers' PCK and enhance their practical teaching skills in all challenging concepts in the subject.

Keywords: practical skills, pedagogical content knowledge, physical sciences, teacher professional development.

1. Introduction

Physical sciences is one of the most essential and significant fields of study at high schools in South Africa [1]. It is a fundamental science that underpins the development of all other sciences, including engineering and technology. Studying physical science develops transferable skills that are valuable in various fields, including medicine, engineering, technology, astronomy, financial analysis, and investment management. In addition, the subject plays a critical role in preparing learners for participation in a technologically advanced and knowledge-driven society [2]. However, the continued underperformance by grade 12 learners in physical sciences and the low proficiency levels of South African learners in physical sciences continue to dominate national education discourse [3,4]. At the heart of this challenge lies the quality of teaching, which is largely influenced by the teacher's content knowledge (CK) and practical teaching skills [5]. As such, professional teacher development programmes (PTDPs) have been globally recognised as key interventions to enhance teacher effectiveness and improve learner outcomes, particularly in underperforming and rural contexts [6,7].

Nonetheless, the South African Department of Basic Education (DBE) has invested in a number of PTDP initiatives, including subject-focused workshops, district support programmes, and externally funded interventions to build teacher capacity in physical sciences [8]. Although there is increasing acknowledgement of the importance of PTDPs in enhancing the teaching of science, evidence indicates that most of these initiatives tend to be generic rather than subject-specific, therefore limiting their effectiveness in influencing classroom practice. In the South African context, PTDPs frequently concentrate extensively on promoting awareness of curriculum reform or providing general pedagogical training, with limited emphasis on subject-specific Pedagogical Content Knowledge (PCK) [9,10]. This disparity is especially evident in the teaching of Mechanics and Electromagnetism, two fundamental yet conceptually challenging concepts within the physical sciences curriculum, where learners routinely demonstrate poor performance in the National Senior Certificate (NSC) examinations [11,12]. Although international studies demonstrate that the development of topic-specific PCK enhances conceptual clarity, instructional coherence, and learner understanding in physics education [13,14], such studies are limited within South Africa. Moreover, researchers have primarily investigated chemistry-centred interventions or general science teacher professional development, leaving a significant gap in empirical studies that address PTDPs tailored to Mechanics and Electromagnetism [15,16].

Therefore, it is essential to investigate how targeted professional development impacts teachers' content expertise and practical instructional skills in these concepts. Addressing this gap enhances the theoretical comprehension of topic-specific PCK development and practical insights for improving science teacher professional learning frameworks in South Africa.

Despite these efforts, a noticeable gap remains between teachers' participation in PTDPs and the improved teaching and learning of science concepts, such as Mechanics and Electromagnetism, in rural schools [17]. These concepts, which form foundational components of the Further Education and Training (FET) physical sciences curriculum, demand robust conceptual understanding and well-developed practical skills to enable teachers to design effective lessons, conduct experiments, and facilitate inquiry-based learning in resource-constrained environments [18]. Mechanics and Electromagnetism are conceptually dense and mathematically demanding areas of physical science. Teachers often struggle with these topics due to pre-existing gaps in their university preparation, limited opportunities for continuous learning, and insufficient exposure to practical applications [19–21]. Furthermore, the shift towards learner-centred pedagogies in the Curriculum Assessment Policy Statement (CAPS) curriculum requires teachers to integrate practical skills into their classroom instruction, a requirement that many teachers find challenging due to a lack of equipment and confidence in laboratory activities [22].

Research suggests that, while PTDPs have the potential to improve teaching practice, their impact depends significantly on how they are designed, delivered, and contextualised to meet the needs of teachers [23,24]. Moreover, sustained improvement in teachers' CK and pedagogical competence requires follow-up support, hands-on practice, and alignment with curriculum demands [25]. Desimone [26] identifies core features of effective professional development as a focus on content, active learning opportunities, coherence with school activities, sustained duration, and collective participation as key elements that significantly shape teacher effectiveness and, consequently, student learning outcomes. Hence, there is a need to assess the influence of PTDPs on the CK and practical skills of physical sciences teachers in Mechanics and Electromagnetism.

1.1. Research question

The following research questions guided the study:

1 How effective are professional teacher development programmes in improving the content knowledge of physical science teachers in Mechanics and Electromagnetism?
2 What influence do professional development programmes have on the practical teaching skills of physical science teachers in Mechanics and Electromagnetism?
3 What challenges do physical science teachers encounter when implementing the knowledge and skills acquired from professional development programmes in their classrooms?
4 What strategies can be implemented to enhance the design and delivery of professional teacher development programmes to better support physical science teachers?

2. Literature review

Internationally, PTDPs have adopted diverse approaches to improving science teachers' CK and practical skills, yielding mixed results. In the USA, researchers reported notable gains in teacher confidence and CK after attending PTDP [27]. However, the programme's brevity and absence of classroom follow-up limited evidence of sustained teaching transformation. In contrast, another study was conducted on a collaboration between universities and high school teachers in a PTDP format. The teachers praised its responsiveness and collegial learning environment, which shifted participants from peripheral to central positions within the learning community [28]. Despite these strengths, the study lacked robust measurement of learner outcomes or classroom performance. Moreover, in Greece, a long-term inquiry-based PTDP for science teachers was explored. The findings reported an improvement in teachers' pedagogical practices [29]. However, the study's generalisability was limited due to a small sample size (n = 4) and an absence of control groups.

In Australia and the UK, studies were conducted on PTDP, which advocated for sustained, content-specific, and coherent PTDPs aligned with curriculum goals, arguing that such models are more effective than fragmented interventions [30,31]. While theoretically compelling, these frameworks are often not supported by detailed empirical studies that focus on rural science teaching in Mechanics or Electromagnetism. In this comparative review, we illustrate that international PTDPs highlight vital components, including content enhancement, pedagogical innovation, and collaboration; however, none offer a comprehensive model tailored to rural science teachers facing topic-specific challenges.

At the regional level, studies across sub-Saharan Africa, particularly in Ghana, Nigeria, Kenya, and Liberia, provide valuable insights into the influence of PTDPs on science teachers' PCK and practical skills. For example, a study was conducted to evaluate a cascade model of PTDPs in Ghana, where trained local teachers facilitated workshops for peers [32]. While this enhanced facilitator confidence and coherence, critiques included the risk of diluted expertise and a lack of contextual responsiveness. Collectively, these studies suggest that, while PTDPs can effectively enhance science teaching, structural and contextual limitations constrain their reach and depth. Importantly, across these contexts, PTDPs remain under-researched in physics concepts such as Mechanics and Electromagnetism.

In the South African context, CAPS mandates that teachers not only convey subject knowledge but also foster critical thinking, scientific reasoning, and inquiry-based learning. In this context, effective science teaching requires a deep understanding of content and the skills to translate that knowledge into accessible and engaging learning experiences [33,34]. This gap underscores the urgent need for focused, subject-specific PTDPs that go beyond generic in-service training and are tailored to enhance teachers' subject CK and practical instructional skills.

PTDPs are internationally recognised as vital to addressing these gaps. Short-term training interventions are insufficient; rather, continuous, subject-specific, and context-relevant professional development is essential for deepening teacher expertise and improving pedagogical practice [35]. In South Africa, the DBE acknowledges this by committing to strengthening continuous PTDP initiatives [36]. However, evidence suggests a mismatch between policy intentions and actual practice in rural and underserved areas, where implementation of structured and ongoing teacher development remains limited.

A study was conducted to explore how South African physical science teachers developed their PCK through participation in a university-led intervention programme [18]. The researchers found that teachers who engaged in sustained, content-specific PTDPs improved their ability to select appropriate teaching strategies, anticipate learner misconceptions, and connect theoretical knowledge with classroom practice. However, the study also highlighted that PCK development was highly uneven and largely dependent on teachers' prior CK and their ability to reflect on practice, suggesting that PTDPs must be adaptive and responsive to individual needs. A similar study entailed subject advisors' support as a form of embedded PTDP [37]. The study revealed that, where subject advisors actively facilitated content and pedagogical workshops, teachers reported increased confidence and competence. However, the researchers also identified systemic barriers such as overload, limited resources, and weak coordination between the DBE and schools. Another study entailed the impact of a computer-based PTDP intervention on physical sciences teachers' PCK in Projectile Motion and Electric Circuits [19]. The study revealed that integrating technology into

PTDP enhanced conceptual understanding and classroom delivery. This finding suggests that practical skill development must be integrated with theoretical instruction in PTDPs. These findings influenced us to focus on Mechanics and Electromagnetism, two underexplored areas of the physical sciences curriculum where teacher confidence and PCK are often weakest.

The convergence of international and African studies on PTDPs underscores a shared recognition of their crucial role in enhancing science teachers' PCK and practical teaching competencies. Despite this broad consensus on the values of PTDP, a notable gap remains in the literature regarding the subject-specific influence of PTDPs in the under-researched physical sciences units of Mechanics and Electromagnetism. Most researchers either aggregate findings across all science subjects or focus mostly on biology and chemistry, leaving a gap in understanding the unique challenges and requirements of teaching physical sciences. Moreover, few researchers critically explore how PTDPs affect CK and practical teaching skills in rural contexts. Hence, we examined the influence of PTDPs on the knowledge and classroom competencies of physical sciences teachers in Mechanics and Electromagnetism within a rural South African context.

3. Theoretical frameworks

3.1. Pedagogical Content Knowledge (PCK)

Shulman [5] characterises PCK as a distinctive blend of content and pedagogy that is exclusively the domain of teachers, representing their unique form of professional insight. Other scholars [38] elaborated on PCK as the conversion of knowledge for instructional purposes in relation to a student's understanding of a subject. Some [39] favoured the term "translate" over "transform", as their concept of PCK entails a teacher modifying content to align with their understanding of the learner, where the teacher translates the content into comprehensible units of understanding [39].

Following Shulman's [5] original assertion that PCK constitutes the "missing link" in understanding the distinctive nature of a teacher's knowledge compared to that of a content expert, Grossman [40] expanded upon Shulman's concepts and developed a novel model, as illustrated in Table 1 below.

Table 1. Grossman's Framework of Pedagogical Content Knowledge [40].

Pedagogical Content Knowledge		
Conceptions of purposes for teaching subject matter		
Knowledge of students' understanding	Curricular Knowledge	Knowledge of instructional strategies

The general pedagogical knowledge (PK) and contextual information together shape a teacher's views on the goals for teaching a topic [40]. This model served as a foundational reference for subsequent models [38]. The PCK model for science education positions science teaching orientation as a primary component that directly influences PCK and is influenced by several other elements [38]. The Magnusson model served as the foundational framework for PCK in this study for multiple reasons. First, this model recognises PCK as a specialised form of teacher knowledge that blends CK and PK, enabling teachers to transform scientific content into forms that are comprehensible and accessible to learners. In the context of this study, the model's detailed categorisation of PCK components provides a useful analytic lens. These components include orientations to teaching science, knowledge of learners' understanding, instructional strategies, curriculum knowledge, and assessment knowledge, all of which are vital in evaluating the impact of PTDPs on teachers' practice. Second, the Magnusson model supports a contextual and practice-oriented analysis of how teachers develop and apply PCK. Given that we explored teacher development within rural school settings, the model enabled a nuanced examination of how training interventions intersect with local realities, teacher beliefs, learner misconceptions, and curriculum constraints. Last, the model is well-suited for assessing how professional development interventions influence changes in teachers' pedagogical reasoning and instructional practice over time. It accommodates a dynamic view of teacher learning, where PCK is constructed through experiences, reflection, and collaboration. The PCK was operationalised into five analytic dimensions relevant to physical sciences teaching: (1) Subject Matter Knowledge (SMK), referring to teachers' disciplinary understanding of Mechanics and Electromagnetism; (2) Instructional Strategies, including topic-specific teaching approaches such as inquiry-based demonstrations or modelling abstract concepts; (3) Curriculum Knowledge, focusing on the alignment with national CAPS requirements and appropriate sequencing of concepts [18]; (4) Assessment Knowledge, highlighting teachers' use of diagnostic, formative, and summative assessment to gauge learner understanding; and (5) Knowledge of Learners and Learning, including awareness of common misconceptions and learning difficulties specific to Mechanics and Electromagnetism to guide the analytical framework for this study. By applying this model, we were able to identify areas of growth in teacher knowledge, providing a structured way to evaluate the efficacy of the programmes.

3.2. Andragogy: A theoretical framework of professional learning

Malcolm Knowles introduced the term *andragogy* in the late 1960s, but the term originated in Germany with Alexander Kapp in 1833, and the first American use of the term was in 1926 in Eduard Lindeman's *The Meaning of Adult Education* [41,42]. Adult Learning Theory requires professional development designers to consider the complete needs of the adult when designing learning experiences. This theory emphasises growth and development through activities that build upon the learner's prior experiences and provide the learner with an opportunity to make decisions about their own learning [42]. While teacher professional development usually occurs within the context of a school system, the adults engaging in professional learning are very different from the learners they teach [42]. While learning is the primary occupation of most learners, adult learning occurs within the context of the rest of an adult's life, which often includes a career and family obligations. In addition, adult learners bring many life experiences that define who they are and what they believe.

Teachers want to be treated as professionals who are developing or possess high levels of skills and knowledge [43]. Valuing the professionalism of the adults in a learning experience is critical to effectively reaching and impacting the adult learners. In addition, the adults come to the learning experience at different stages of the life cycle. Because adults think and learn differently from children, teachers' learning experiences should differ from those of their learners [44,45]. Pedagogy refers to "the art and science of teaching children" [45]. Within the pedagogical model, the teacher assumes responsibility for the learning in the classroom. Learning new content is an end rather than a means, and students are generally extrinsically motivated through the use of rewards or grades. Hence, the emphasis on the differences between the learning processes of children and adults highlights the need for distinct principles of learning for these groups of learners [46].

Andragogy, the theory of adult learning grounded in learner-centred experiences, adheres to assumptions about adults and asserts that the following characteristics of the learner must be considered in all learning situations: The learner's need to know; self-concept; prior experiences; readiness and motivation to learn; and orientation [45]. Andragogical principles have found their way into all levels of formal education [47] and have influenced the design of adult learning experiences as the dominant framework for adult learning.

4. Methodology

4.1. Research design

This study was within the interpretivist qualitative research approach, which was best suited to exploring how PTDPs influence physical science teachers' content knowledge and practical skills in Mechanics and Electromagnetism. We adopted a qualitative multiple-case study. Accordingly, a case study design was employed [48]. The rationale for selecting a multiple-case study design, involving eight schools, lies in the need to understand how school settings influence the impact of PTDP interventions. Examining multiple cases not only enhances comparative analysis but also strengthens the validity of the findings [48,49].

4.2. Population

For this study, the population comprised all physical sciences teachers in the O.R. Tambo Inland District who had participated in a PTDP focused on Mechanics and Electromagnetism. These teachers were employed in public secondary schools across the district and are registered under the Eastern Cape Department of Education. The rationale for choosing this population was threefold. First, Mechanics and Electromagnetism are core areas in the physical sciences curriculum that consistently yield low learner performance in the NSC examinations [36]. These topics require strong conceptual understanding and practical demonstration skills, which many teachers have historically struggled to teach effectively [50]. Second, targeting teachers who had participated in PTDPs provided an opportunity to evaluate how such initiatives influenced their PCK and practical skills, which are essential dimensions of teacher competence [5]. Third, this population was accessible and relevant, as the teachers are working within a manageable geographic area and had been exposed to a similar development programme. This ensured consistency in the type of training received and enabled us to make credible inferences about the relationship between professional development and classroom practice.

We employed a purposive sampling technique [51]. A total of eight secondary schools within the O.R. Tambo Inland District were purposively selected. The criteria for school selection included: (a) Schools must offer physical sciences at the FET phase; (b) the schools must have at least one physical science teacher who participated in the recent PTDPs focused on Mechanics and Electromagnetism; and (c) schools must represent a variety of contexts (e.g., urban vs rural, well-resourced vs under-resourced) to enable comparative insights into the influence of the PTDP. From each selected school, one physical science teacher who attended the PTDP was randomly sampled. This resulted in a total sample of eight teachers. These teachers formed a homogeneous group based on their shared experience of participating in the PTDP initiative.

4.3. Data collection instruments and their administration

The semi-structured interview schedule used in this study was organised into two major sections: Section A collected basic demographic and professional information from the participants to provide context for interpreting their responses; and Section B consisted of open-ended questions aimed at exploring teachers' experiences of the influence of PTDPs on their content knowledge and practical teaching skills in Mechanics and Electromagnetism. They included: (a) Changes in conceptual understanding of Mechanics and Electromagnetism; (b) shifts in teaching approaches and confidence after attending PTD programmes; (c) examples of practical applications or strategies adopted from the training; (d) challenges encountered when translating training into classroom practice; and (e) reflections on learner engagement and outcomes after implementing new practices. The flexibility of the semi-structured format enabled the researchers to probe further for clarification and elaboration, thereby capturing rich, descriptive data.

The observation schedule was designed to systematically capture the practical application of content knowledge and teaching skills in the physical sciences classroom, with a focus on Mechanics and Electromagnetism. The schedule was divided into two major sections. Section A contextualised the teaching practices being observed and enabled cross-case comparisons. Section B included a structured list of observation items aligned to key indicators of teacher CK and pedagogical skills. Items were grouped into sub-categories such as: Accuracy and depth of content delivery; use of teaching resources and practical demonstrations; learner engagement strategies; classroom management and pacing; CK development: How the PTDPs impacted their understanding of Mechanics and Electromagnetism; practical skill enhancement: Changes in how they perform experiments; and shifts in pedagogical approaches or teaching strategies following participation in PTDPs.

With the participants' informed consent, individual interviews were audio-recorded to ensure accurate documentation and were supplemented by field notes from two classroom observations that captured non-verbal cues, setting dynamics, and emergent insights not captured in the recordings.

4.4. Data treatment and analysis

Data analysis followed an iterative, systematic process grounded in qualitative thematic analysis, guided by the PCK framework [5,52]. The analytical procedure began with first-cycle descriptive data and coding, enabling participant language and context to emerge inductively from the transcripts [53]. Through this process, recurrent ideas relating to instructional challenges, conceptual understanding, and classroom enactment were identified from interview and observation data.

In the second cycle of analysis, these preliminary codes were categorised into broader patterns using pattern coding, which supported the formation of provisional themes aligned with pedagogical, epistemic, and practice-based meanings [54]. To ensure theoretical coherence, these themes were deductively refined and mapped onto the established PCK dimensions, namely: (1) SMK, referring to teachers' disciplinary understanding of Mechanics and Electromagnetism; (2) Instructional Strategies, including topic-specific teaching approaches; (3) Curriculum Knowledge, focusing on alignment with national CAPS requirements and appropriate sequencing of concepts [18]; (4) Assessment Knowledge, highlighting teachers' use of different assessment strategies to gauge learner understanding; and (5) Knowledge of Learners and Learning, including awareness of common misconceptions and learning difficulties specific to Mechanics and Electromagnetism. These dimensions informed the development of the coding structure and the generation of themes. This dual inductive-deductive process ensured that emergent teacher perceptions and observable practices were meaningfully organised within the theoretical framing.

A coding matrix was developed to enhance transparency and traceability between the raw data, analytical decisions, and the final thematic structure, illustrating the alignment between exemplar excerpts, first-cycle codes, refined categories, and their corresponding PCK elements. This matrix is presented in Table 2, demonstrating how analytic decisions evolved from initial textual interpretation to theory-informed categorisation.

To enhance analytic rigour and trustworthiness, coding decisions were reviewed through peer debriefing and iterative comparison across data sources (interviews, classroom observations, and document analysis). Discrepancies in categorisation were resolved through consensus discussion, ensuring consistent application of the PCK framework across the dataset. This analytical strategy strengthened dependability, credibility, and theoretical alignment within the study.

4.5. Ethical considerations

The researchers sought permission from the University's Faculty Research Higher Degrees Ethics Committee to conduct the study. The permission was granted with a Protocol number (FEDFREC11) through a signed ethical clearance form. The researchers sought permission for the research from the Eastern Cape Department of Education, which was granted. The researchers took time to explain the consent form to the school principals and the participants. In this study, we used coding systems and pseudonyms to de-identify data and ensure participant anonymity during data analysis and reporting.

4.6. Trustworthiness of qualitative data

In this study, the classroom observation schedule was subjected to validation procedures. It was designed to capture content knowledge and pedagogical skills during lessons. The instrument was reviewed by subject experts to ensure content relevance and alignment with our objectives. The semi-structured interviews were validated through careful design and piloting. The interview guide was aligned with the research objectives and literature on PTDPs and Mechanics and Electromagnetism ensuring that questions were relevant and meaningful. A pilot interview was conducted to refine the clarity and sequencing of questions. In addition, the same interview guide was used for all participants, and an audit trail of the data collection and analysis process was maintained.

Credibility was enhanced through methodological triangulation. Furthermore, member checking was employed, where participants were given the opportunity to review and confirm the accuracy of interview transcripts. This process ensured that the findings reflect the participants' intended meanings and lived experiences. Credibility is strengthened when researchers engage with participants over time, foster trust, and use multiple data sources to confirm interpretations [55]. In this study, detailed contextual information was provided, including participant demographics, school infrastructure, class sizes, and teaching environments within the O.R. Tambo Inland District. Such comprehensive descriptions enable readers to assess the relevance and applicability of the findings to their own settings.

5. Results

5.1. Background profile

The sampled teachers were selected from eight schools, one teacher from each school. For ethical and confidentiality purposes, the schools were anonymised and coded as School A, B, C, D, E, F, G, and H. Correspondingly, participating teachers were assigned pseudonyms based on their school and participant number (PHSTA to PHSTH). This coding system ensured anonymity and logical sequencing, while enabling the researchers to trace responses and observed practices back to specific cases during the analysis and reporting stages. All participants were certified to teach physical sciences at the FET phase, having held a Bachelor of Education (B.Ed.) degree in Natural Sciences. The age range for the participants was 30 to 45 years. There were 5 males and 3 females. Some participants were from schools with well-resourced science laboratories, others were teachers in rural areas with under-resourced schools. This diversity of teaching environments enhanced the data by emphasising the ways in which PTDPs were implemented.

5.2. Generation of themes

The results of this study are presented through the framework of the five fundamental elements of PCK, as delineated in the PCK matrix. These components (Subject Matter Knowledge [SMK], Learner Knowledge [LK], Curricular Knowledge [CK], Instructional or Pedagogical Strategies [PS], and Assessment Knowledge [AK]) constitute a structured framework for presenting the data. Each component is methodically aligned with the overarching themes and sub-themes of the study, supported by evidence obtained from interviews, classroom observations, and pertinent documents, as presented below.

Table 2. Alignment of themes to PCK framework.

PCK component	Theme alignment	Evidence sources
Subject Matter Knowledge (SMK)	Influence of PTDPs on teachers' growth in content and confidence in Mechanics and Electromagnetism	Interviews, observations
Curricular Knowledge (CK)	Alignment between PTDP content and CAPS/ATPs and exam-driven focus	Interviews
Instructional/Pedagogical Strategies (PS)	Growth in teaching methods, modelling, problem-solving approaches, and demonstration-based teaching	Interviews, observations
Learner Knowledge (LK)	Understanding students' misconceptions, readiness, engagement, and contextual realities	Interviews
Assessment Knowledge (AK)	Limited modelling of assessment practices and exam-linked problem-solving approaches	Classroom observations and interviews

5.2.1. Subject Matter Knowledge (SMK)

Table 3. Theme 1: Content Knowledge growth through PTDP participation.

Sub-theme	**Description**	**Evidence code examples**
Growth in foundational Mechanics and Electromagnetism	Participants reported clearer conceptual understanding and reduced misconceptions	PHSTH2: "My understanding … improved as facilitators gave clarity."
Baseline differences in teacher competence	Teachers entered PTDPs with different levels of CK, affecting outcomes	PHSTA: "I would rate myself four out of 10 before PTDPs."
Remaining knowledge gaps	Teachers struggled with applied algebra, vectors, projectile motion, and Faraday's law	Observation notes: continued difficulty applying mathematical reasoning.

Sub-theme 1.1: Growth in foundational Mechanics and Electromagnetism knowledge

This sub-theme captured the participants' reflections on how PTDPs have contributed to the overall enhancement of their PCK in physical sciences. Interview data and classroom observations revealed that PTDPs played a pivotal role in strengthening teachers' content knowledge, problem-solving abilities, and conceptual clarity, essential components for effective science teaching. Teachers reported substantial improvements in understanding key concepts in Mechanics and Electromagnetism following PTDP participation. This growth was linked to structured guidance, clarity of explanations, and exposure to multiple instructional strategies. One teacher shared: "*My understanding of content has improved, as facilitators gave a clear picture and explanation of physics concepts*" (PHSTH2). Similarly, another participant highlighted collaborative and dialogic learning: "*PTDPs assisted me in improving my understanding of Mechanics and Electromagnetism because of information sharing*" (PHSTD2).

These accounts suggest that PTDPs improved teachers' conceptual clarity and problem-solving abilities, which are essential aspects of SMK. The structured and scaffolded approach promoted deep engagement with subject content. Teachers reported increased confidence in explaining concepts, showing that content-focused professional development enhances knowledge and instructional confidence.

Sub-theme 1.2: Baseline differences in teacher competence

Several teachers acknowledged entering PTDPs with limited content knowledge. One teacher said: "*My level of content was very low before the PTDP, and I would rate myself four out of 10 before engagement with PTDPs*" (PHSTA). Another teacher added: "*My content knowledge was low, and I have not attended many of these programmes*" (PHSTB).

This reflects heterogeneity in SMK prior to training, highlighting the importance of diagnostic pre-assessment and differentiated support. PTDPs were particularly effective in raising baseline knowledge levels, but gaps remained for those with minimal prior exposure. This highlights the importance of providing tailored professional development to address the individual needs of teachers.

Sub-theme 1.3: Remaining knowledge gaps

Some participants acknowledged entering the programmes with significant gaps in their knowledge: "*My level of content was very low before the PTDP, and I would rate myself four out of 10 before engagement with PTDPs*" (PHSTA). PHSTB echoed this sentiment: "*My content knowledge was low, and I have not attended many of these programmes*." Despite growth, classroom observations revealed continued struggles in applying mathematical reasoning and abstract concepts. During the classroom observation, it was noted that some teachers struggle with applying algebraic methods in problem-solving Mechanics. "*Although I can explain concepts, applying algebraic methods and distinguishing between two dimensional motions is still challenging*" (Observation notes excerpts).

The participants' accounts indicate their perceptions that PTDPs strengthened conceptual understanding but did not fully resolve complex procedural knowledge gaps. Teachers were better at explanation and differentiation, but mathematical problem-solving remained a barrier. The findings highlight the need for ongoing content enrichment, particularly in abstract topics such as Electromagnetism.

Table 3 shows that PTDPs supported significant linear growth in teachers' subject matter knowledge, particularly through modelling, worked examples, and explanatory clarity. However, high variability in baseline competence resulted in uneven learning gains, especially among those teachers with weaker prior CK. These teachers improved but demonstrated gaps in higher-order reasoning (e.g., Vector Calculus, Linking Laws, and Quantitative Modelling). This suggests PTDPs work best when differentiated content support is embedded.

5.2.2. Curricular Knowledge (CK)

Table 4. Theme 2: CAPS alignment and examination-oriented teaching.

Sub-theme	Evidence summary	Sample evidence
CAPS alignment improved teachers' pacing and content delivery	Teachers felt PTDPs helped them "teach to the exam"	PHSTA1: "Programmes are in line with CAPS … solving exam questions."
Limited integration of practical/curriculum expectations	Practical work remained minimal, despite curriculum expectations	PHSTD2: "There is not much rollout of practical or real-life demonstrations."
Lack of demonstration modelling in PTDPs	Teachers desired demos, simulations, and modelling of experiments	PHSTB2: "There must be more time for demonstration lessons."

Sub-theme 2.1: CAPS alignment improved teachers' pacing and content delivery

Teachers expressed that PTDP content was well-aligned with CAPS and ATPs, supporting lesson pacing and exam readiness. One teacher shared her experience: "*The programmes align with CAPS in terms of solving examination questions and problem-solving*" (PHSTA1) and PHSTC1 added, "*Topics taught align with the syllabus topics*". This suggests that the foundational intent of PTDPs is relevant to daily instructional practices. This alignment has had a tangible impact on classroom delivery. Additionally, teachers reported improved approaches to content delivery and greater learner engagement during lessons. For example, one teacher from School D said: "*I noticed some improvement because, after the training, I gained more knowledge to address the same content*" (PHSTD2). Such remarks reveal a growing repertoire of pedagogical strategies acquired through PTDPs, which enable teachers to approach the same curriculum content from multiple angles, thereby supporting differentiated instruction and varied learner needs.

Sub-theme 2.2: Limited integration of practical and curriculum expectations

Most of the teachers indicated that, despite CAPS alignment, practical components were inadequately modelled. Despite physical sciences being inherently practical, the delivery of PTDPs remains heavily content-driven, with minimal emphasis on demonstrations, experiments, or real-life applications. This was echoed in both interviews and classroom observations, where traditional, lecture-style teaching dominated, particularly in rural schools. This was evident in a response given by one teacher: "*In training, there is not much of an examination guidelines rollout, nor are there resources to link content with real-life applications through demonstrations, experiments, or investigative skills*" (PHSTD2). In addition, another teacher reflected positively on the power of practical learning: "*Learner-centred approach is more effective, encouraging learners to be hands-on and participate in their learning, which improves their interests, skills, and competition*" (PHSTD2). This insight underscores the need for PTDPs to more deliberately model and scaffold practical, learner-centred methodologies that align with the demands of CAPS and 21st-century learning goals.

While PTDPs promoted theoretical alignment, teachers struggled to connect the curriculum with hands-on, learner-centred experiences, demonstrating a gap between intended curriculum and implemented curriculum.

Sub-theme 2.3: Lack of demonstration modelling in PTDPs

Teachers highlighted the absence of structured demonstrations. "*Learner-centred approach is more effective, encouraging learners to be hands-on and participate in their learning, which improves their interests, skills, and competencies*" (PHSTD2). Additionally, teachers recognised the value of practical, learner-centred approaches, but the limitations of PTDP design constrained the modelling of these strategies. The findings suggest that curricular knowledge alone is insufficient without pedagogical modelling and resource support to facilitate transfer to classroom practice. The PTDPs strengthened curriculum pacing and content sequencing; however, teachers' enacted practices leaned toward exam-driven theory transmission, rather than curriculum-intended practical inquiry. Participants' accounts indicate their perceptions that there is a disconnect between the intended, implemented, and experienced curriculum, which is influenced by resource scarcity, time constraints, and omissions in the PTDP design.

5.2.3. Pedagogical strategies (PSs)

Table 5. Theme 3: Growth in teaching strategies and practical demonstration skills.

Sub-theme	Findings	Evidence highlights
Use of PBL, demonstrations, and real-life analogies	PTDPs encouraged learner-centred strategies	PHSTC2: "Problem-based learning ... improved my teaching."
Use of low-cost improvisation, and resource confidence gaps affecting implementation	Some teachers used toy cars, pulleys, and recycled materials Teachers lacked tools, ICT access, and confidence in practical teaching	PHSTD2: "Using toy cars improved engagement. "PHSTB1: "I cannot practice because no equipment."

Sub-theme 3.1: Use of PBL, demonstrations, and real-life analogies

Teachers reported an improvement in the use of PBL, group discussions, and interactive instruction. One teacher narrated: "*Problem-based learning, projects, discussions, and instruction helped me understand the content better, which in turn improved my teaching practices and provided a deeper understanding of physical science concepts*" (PHSTC2). Teachers adopted more interactive and student-centred pedagogies, enhancing conceptual understanding. This aligns with Shulman's (1986) notion of PCK, where content knowledge is transformed through pedagogical representations that make it comprehensible to learners.

Sub-theme 3.2: Improvisation of resources and confidence gaps affecting implementation

The study revealed that most teachers used practical strategies and often relied on locally available resources. One teacher narrated: "… *using toy cars to demonstrate and illustrate the applications of momentum principles makes learners pay attention and be more engaged*" (PHSTD2). Teachers innovatively adapted PTDP strategies to constrained school environments, demonstrating resourceful pedagogical practice. This highlights the importance of contextualised PS, a critical aspect of effective PCK. Barriers, including limited laboratory equipment and ICT tools, impacted practice. One teacher mentioned that "*I am not confident enough in applying hands-on teaching strategies, as there are no resources to conduct experiments in my school*" (PHSTC2). Practical PK was not consistently enacted due to structural constraints. Even with strong PS from training, the contextual realities of schools moderated the impact of PTDPs. Teachers demonstrated strong willingness to apply newly learned strategies, shifting from teacher-centred rule teaching to concept-driven, inquiry-rich strategies during the lesson observation. However, implementation fidelity was dependent on the school context.

5.2.4. Learner Knowledge (LK)

Table 6. Theme 4: Understanding of learner misconceptions, motivation and context.

Emerging pattern	Evidence
Recognition of learner misconceptions (Newton's laws, EM fields, friction)	Teachers could predict typical learning difficulties
Impact of prior learning deficits	Learners struggle with transitions across abstract topics
Improved engagement during hands-on activities	Observations reveal that motivation increases with experiments

Sub-theme 4.1: Recognition of learner misconceptions

The findings revealed that teachers reported improved ability to anticipate learner difficulties after the PTDP. One teacher reported: "*Learners with limited prior content knowledge struggle significantly, which makes it challenging for them to cope with new and abstract concepts*" (PHSTB2). Moreover, some teachers reported that the training made efforts to accommodate teachers' varying prior knowledge through differentiated grouping. One teacher reflected: "*The facilitators grouped us according to our understanding, and that helped. I was placed with more experienced teachers who helped me grasp the abstract parts of Electromagnetism. That model should continue, but it would be even better if such grouping were done for learners too*" (PHSTB1). While this approach improved peer learning among teachers during training, the transfer of differentiated strategies to the learner level remains limited, as classroom settings often do not permit flexible grouping or diagnostic assessment prior to instruction. PTDPs enhanced teachers' awareness of learners' cognitive challenges, enabling them to plan and scaffold instruction more effectively. Understanding learner misconceptions is central to effective PCK.

Sub-theme 4.2: Impact of prior learning deficits

The findings indicated that most teachers noted that learners' foundational gaps limited engagement with abstract concepts. This was emphasised during the interviews with the teachers, where one teacher shared: "*In training, topics and concepts are introduced very well, but with little demonstration experiments to enhance teaching strategies and increase both teachers' and learners' enthusiasm*" (PHSTA1). Differential learner preparedness requires teachers to adjust instruction; PTDPs partially addressed this by exposing teachers to differentiation strategies, though application in under-resourced classrooms remained limited.

Sub-theme 4.3: Improved learner engagement during hands-on activities

Practical activities increased learner motivation and understanding. This finding highlighted that increased awareness of learners' engagement during classroom instruction led to higher learner motivation. One teacher noted: "*Learners positively appreciate hands-on classroom activities, get more excited and motivated*" (PHSTB2). Teachers' awareness of learner engagement and motivational drivers grew, highlighting the reciprocal relationship between PCK and student-centred learning. Hands-on activities facilitated better learning outcomes and reinforced teachers' pedagogical confidence. PTDPs enabled teachers to better recognise learners' learning trajectories and misconceptions. However, difficulties remain in converting this knowledge into adaptive teaching due to the limited availability of scaffolding tools and time.

5.2.5. Assessment Knowledge (AK)

Table 7. Theme 5: Assessment application is exam-centric and underdeveloped.

Observation	Evidence
PTDPs focused mainly on past papers, worked examples, and corrections	Teachers repeatedly referenced exam preparation as the main assessment skill
Limited modelling of inquiry-based assessment	Practical assessment and investigative skills are not prioritised

Table 7 shows that most teachers focused on past papers and procedural assessment, with limited modelling of inquiry-based assessment. One respondent emphasised the following: "*Facilitators gave guidance in problem-solving skills using previous examination questions*" (PHSTA2). The findings from the classroom observation show that teachers' assessment practices were largely summative and exam-oriented, reflecting systemic pressures. PTDPs emphasised procedural understanding over formative assessment strategies, limiting teachers' assessment literacy. PTDPs did not sufficiently scaffold authentic, inquiry-based assessment practices. This gap inhibits teachers from integrating assessment as a learning tool, particularly in practical topics such as Electromagnetism. One teacher shared: "*We were told about simulations and experiments, but no ICT tools or materials were provided. In our rural school, that's a big issue*" (PHSTD1). This implies that teachers' assessment practices remain procedural and summative, shaped by systemic exam pressure and PTDPs' focus and that assessment literacy for practical science remains underdeveloped.

Table 8. Summary of coded data mapped to PCK components.

Final theme framed within PCK components	Sub-theme	Research question	Raw data excerpt	Interpretive commentary
Subject Matter Knowledge (SMK)	Linear growth in content knowledge	RQ1	"My understanding of content has improved, as facilitators gave a clear picture and explanation of physics concepts" (PHSTH2)	PTDPs enhanced teachers' conceptual clarity, problem-solving abilities, and overall content knowledge. Growth was moderated by baseline knowledge levels and prior exposure to PTDPs
	Mechanics and Electromagnetism – specific growth	RQ1	"Facilitators gave guidance in problem-solving skills using previous examination questions" (PHSTA2)	Teachers demonstrated improved understanding of specific content areas, particularly fundamental Mechanics topics and Electromagnetism circuit analysis. However, conceptual gaps remained in momentum, energy transformations, and electric/magnetic field relationships
			"Problem-based learning, projects, discussions, and instruction helped me understand the content better, improving teaching practices" (PHSTC2)	
Curricular Knowledge (CK)	CAPS and ATP alignment	RQ1	"The programmes are in line with CAPS in terms of solving examination questions and problem-solving" (PHSTA1)	Teachers perceived PTDPs as aligned with curriculum requirements, which enhanced their confidence in delivering content and preparing for exams. Yet, content-to-practical integration remains limited, highlighting a need for stronger emphasis on practical applications
			"Topics taught are in line with the syllabus topics" (PHSTC1)	
Instructional / Pedagogical Strategies (PS)	Practical teaching skill development	RQ2	"PTDPs helped me connect and disconnect equipment and apparatus, and optimally utilise the available resources" (PHSTD1)	PTDPs strengthened teachers' practical skills and ability to implement hands-on lessons. Implementation is moderated by classroom realities such as resource constraints and time limits
			"Synthetic problem-solving methods and illustration and demonstration of experiments help [me] teach physical sciences" (PHSTC1)	
	Hands-on and learner-centred strategies	RQ2	"In Newton's laws, learners could draw free-body diagrams to calculate tension and acceleration" (PHSTA1)	Teachers employed active learning strategies aligned with PTDP training, fostering engagement and

			"Using toy cars to demonstrate momentum principles … learners pay attention and be more engaged" (PHSTD2)	conceptual understanding. Success depends on resource availability and follow-up support
	Teachers-facilitators collaboration	RQ4	"The grouping helped a lot. We could share knowledge and practical skills, and even simulate how we would co-teach at school" (PHSTC2) "We were encouraged to form teaching teams at the school level" (PHSTB1)	Collaborative and scaffolded training improved peer learning and integration of PCK with practical skills. Teachers recommended structured post-training mentoring and team-teaching approaches for sustainability.
Learner Knowledge (LK)	Understanding learner misconceptions and engagement	RQ2 and RQ3	"Learners with limited prior content knowledge struggle a lot … This leads to a lack of confidence and interest, especially in topics like Electromagnetism" (PHSTB2) "Learners positively appreciate hands-on classroom activities, get more excited and motivated" (PHSTB2)	PTDPs encouraged teacher awareness of learners' prior knowledge and engagement. Active, practical strategies improved learner motivation and conceptual understanding. Classroom realities, however, constrain implementation
Assessment Knowledge (AK)	Examination and problem-solving alignment	RQ1 and RQ3	"The programmes are in line with CAPS in terms of solving examination questions and problem-solving" (PHSTA1)	Teachers used PTDP strategies to better prepare learners for assessments. Limitations included an overemphasis on exams over conceptual or practical learning
Challenges / Contextual Constraints	Resource limitations, class size, SMT support, ICT constraints	RQ3	"I have been shown how to conduct experiments, but could not practice at school due to a lack of equipment" (PHSTB1) "We write requests to management for materials … there's just no response" (PHSTD1)	Implementation of PCK and practical skills is heavily constrained in under-resourced schools. A lack of lab equipment, large classes, and limited administrative support impede the transfer of PTDP knowledge to classroom practice
	Learner prior knowledge, classroom environment	RQ3	"In training, topics and concepts are introduced very well, but with little demonstration experiments … We need more of these demonstrations to bring the theory to life" (PHSTA1)	Misalignment between training and classroom realities affects teacher efficacy. Teachers require strategies to address learner misconceptions and adapt methods to infrastructure limitations
	Teachers' recommendations for professional growth	RQ4	"Experienced teachers would always guide us by giving tips on how to simplify concepts or demonstrate them practically" (PHSTA2) "There must be more time allocated to demonstration lessons" (PHSTB2)	

6. Discussions

In this section, we present a critical discussion of the findings emerging from this study. The discussion is framed by the study's theoretical foundations, Shulman's theory of PCK, and Knowles' Adult Learning Theory (Andragogy), which collectively provide a lens for interpreting how professional development initiatives impact teachers' knowledge transformation and adult learning experiences. This alignment ensures that the insights drawn from the data not only reflect participants' lived experiences but also contribute meaningfully to broader academic and professional conversations in science education.

The first finding under SMK indicated that teachers experienced notable growth in content knowledge in Mechanics and Electromagnetism. Teachers reported enhanced clarity in conceptual explanations, improved problem-solving skills, and greater confidence in addressing these topics. The observed improvements in SMK suggest that PTDPs facilitated knowledge transformation, equipping teachers to translate abstract physics concepts into teachable forms. Nonetheless, partial mastery of mathematical applications highlights that content knowledge alone is insufficient without continued practice and reinforcement. Furthermore, the teachers' reflections reveal that PTDPs provided opportunities for practical engagement with real classroom challenges, aligning with adult learning principles [45]. Teachers valued activities that directly addressed classroom realities, confirming that relevance and immediacy of application are critical for adult learning. However, the findings also highlighted disparities in growth. Some entered with limited PCK and found the programmes transformative, while others continued to struggle with topics such as projectile motion or electromagnetic field interactions. These disparities highlight a limitation of PTDPs that employ a one-size-fits-all approach. This aligns with the study that emphasises that PCK develops over time and requires sustained mentorship, which was largely absent in the observed programmes [40]. This is a key concern, as effective PCK involves not only content mastery but also the ability to adapt instruction to student needs and curriculum demands [18].

The second finding reveals that PTDPs improved teachers' understanding of curriculum sequencing, pacing, and examination-oriented teaching, corroborating the literature [18]. They were able to align lessons to CAPS expectations, but integration of practical activities and demonstrations was limited. According to Shulman [5], while teachers demonstrated improved alignment with CAPS, the insufficient modelling of practical strategies indicates a gap between intended curriculum knowledge and enacted curriculum knowledge. This aligns with Shulman's assertion that CK must be complemented by pedagogical strategies to be fully effective. Teachers' concern about the lack of practical integration highlights the need for experiential, hands-on learning opportunities within PTDPs. The adult learning perspective [45] suggests that professional development should provide authentic classroom scenarios, enabling teachers to experiment and reflect on the enactment of their curriculum.

The third finding reveals that the teachers adapted strategies to suit their school contexts, but resource limitations constrained full implementation. Teachers' adoption of problem-based learning and hands-on activities demonstrates the conceptualisation of PCK in practice. The creative use of local resources reflects the dynamic interaction between pedagogical strategies and contextual constraints, a key aspect of PCK. Knowles' lens asserts that adults are motivated when learning addresses real-life problems. The practical application of strategies, such as using toy cars to demonstrate momentum, exemplifies problem-centred and contextually relevant learning. The findings suggest that PS gains are contingent on contextual feasibility. Thus, PTDPs should integrate coaching, mentoring, and access to resources to facilitate sustainable instructional innovation. Furthermore, supporting adult learners in overcoming contextual barriers is crucial for effective knowledge transfer [45].

The fourth finding shows that teachers reported increased awareness of learner misconceptions, motivational factors, and lack of prior knowledge. They acknowledged the importance of differentiating instruction to accommodate learner needs yet noted challenges in fully addressing gaps in rural schools with limited resources. According to Shulman [5], LK is a central dimension of PCK, emphasising the teacher's understanding of learners' cognitive structures and prior knowledge. While PTDPs promoted awareness of learner knowledge, limitations in resources and time affected the translation of insight into differentiated instruction. The findings echo the critique of South African PTDP models as being policy-driven and compliance-oriented, offering limited support for contextual adaptation [17]. The literature is emphatic about the need to align PTDP content with the realities of school infrastructure [7,26]. This finding also corroborates the findings in the Ghanaian context, where science teachers often abandon newly learned instructional methods due to a lack of basic teaching resources [56]. Our findings mirror this, especially in schools where overcrowding, time limitations, and a lack of resource support create structural hurdles to pedagogical innovation.

Last, the study reveals that teachers reported assessment practices that were predominantly exam-focused. Assessment knowledge, as part of PCK, involves understanding how to measure student learning and inform instruction [5]. The predominance of summative, exam-centred assessment reflects partial development of PCK, where teachers can gauge learner performance but lack strategies for formative feedback and ongoing learning assessment. Supporting adult learners in designing and implementing diverse assessment tools can enhance PCK comprehensively [45]. Teachers' reflections speak directly to the need for a PCK-informed, andragogical, responsive, and collaboratively sustained model of teacher development that integrates theory with practical classroom realities. As highlighted from the literature, the intrinsic desire for growth necessitates sustained and reflective professional learning [57]. These collaborative approaches align well with the PTDP framework, and the findings corroborate the view that, when teachers are engaged in functional PTDPs, they enhance their teaching practices [58]. This is consistent with the interpersonal and social dimensions of PCK development, as described by scholars [59]. PCK is not simply developed in isolation but through shared dialogue, modelling, and iterative feedback. As suggested, PTDP in South African contexts need not only informal structures but also embedded mentorship and access to ongoing resources to become truly transformative [58].

Taken together, the findings suggest that PTDPs are perceived by participating teachers to have a differentiated and context-dependent influence on content knowledge and practical teaching skills in Mechanics and Electromagnetism. Teachers' accounts indicate perceived improvements in curriculum sequencing, pacing, and examination-oriented instruction, alongside increased awareness of learner misconceptions, motivational factors, and prior knowledge gaps, thereby reflecting growth in aspects of PCK. However, the data also reflect persistent challenges of exam-focused assessment practices, the limited use of inquiry-based assessments, and constraints imposed by inadequate resources that restrict the full implementation of newly acquired strategies in the classroom. Collectively, these insights extend PTDP research in South Africa by foregrounding underexplored content areas and highlighting the need for differentiated, context-responsive programme designs that more explicitly integrate content depth, practical experimentation, and sustained instructional support.

7. Conclusions and recommendations

In this study, we aimed to investigate the influence of PTDPs on the content knowledge and practical teaching skills of physical science teachers within selected schools in the O.R. Tambo Inland District. Grounded in the theoretical frameworks of PCK and andragogy, we sought to understand whether PTDPs were effective and how they impacted classroom practice in Mechanics and Electromagnetism.

In relation to RQ1, the findings, as reported by the participants, indicate that teachers perceived improvements in their content knowledge; however, growth was uneven, with some teachers reporting persistent difficulties in specific topics. Addressing RQ2, participants reported perceived PTDPs influenced their practical teaching skills by enhancing awareness of learner misconceptions and prior knowledge, although assessment practices remained largely exam-focused. Regarding RQ3, teachers reported perceived challenges in translating acquired knowledge and skills into classroom practice, which hindered full implementation despite the use of adaptive strategies. Finally, in response to RQ4, the findings, as reported by the participants, indicate that PTDPs could be strengthened through greater emphasis on inquiry-based pedagogies, differentiated support for teachers with varying levels of PCK, and sustained follow-up mechanisms that account for diverse school contexts.

In conclusion, while PTDPs have laid a foundation for content reinforcement, their influence on practical teaching remains constrained. To ensure that physical science teachers are equipped not only with knowledge but with the ability to teach effectively and confidently, there is a pressing need for a shift towards PCK-informed, context-sensitive, and andragogically sound professional learning models. Only then can PTDPs serve as true catalysts for improved teaching practices and learner achievement in physical sciences. These lines of inquiry have the potential to make a substantial contribution to the development of more effective teacher education programmes that promote inventive mathematical thinking and a deeper understanding of conceptual paradigms.

The theoretical implications of this study are that integrating Shulman’s PCK and Knowles' andragogy provides a dual interpretive lens, offering evidence that PTDPs strengthened SMK, CK, PS, and LK, reflecting meaningful development of PCK. However, gaps remain in AK and procedural application, highlighting partial transformation. Therefore, motivation, relevance, and experiential learning were key drivers of engagement and knowledge uptake. Hence, the findings suggest that content knowledge, pedagogy, learner awareness, and assessment are interdependent, and that effective professional development must address all dimensions holistically, considering adult learning principles.

From the findings, the following recommendations are made to enhance the effectiveness of PTDPs for the effective teaching of physical sciences in schools:

The Eastern Cape Department of Education should enhance the organisation of PTDPs for physical sciences teachers. The frequency of these PTDPs should be augmented and executed with minimal interference to teaching and learning. The PTDPs must be goal-oriented and tailored in their approach. Schools are advised to promote science teachers' participation in PTDPs to facilitate the exchange of best practices with peers from other institutions. Schools must encourage teachers to submit reports detailing the occurrences within the PTDPs, the best practices acquired, and the application of that information for the school's benefit. It is also recommended that policymakers establish a policy mandating science teacher to assume responsibility for their professional development. The policy must also stipulate that educators enrolling in PTDP commit to attending these programmes and ensure that the PCK of most physical sciences teachers is consistently evaluated and enhanced.

In future studies, researchers could explore the incorporation of simulations in physical science education to enhance the PCK of physical science teachers during PTDPs. In addition, we sampled eight teachers from eight schools. In future studies, researchers could utilise a larger sample of teachers from urban and rural school environments.

Author contributions

Zimasile Bongani Mndela**:** Conceptualisation, investigation, methodology, formal analysis; Sakyiwaa Boateng: Supervision, writing original draft, writing review and editing, and formal analysis.

Use of Generative-AI tools declaration

The authors declare they have used Artificial Intelligence (AI) tools (Grammarly and Quillbolt) to refine language and improve the grammar of the document.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethics declaration

The studies involving humans were approved by the Ethics Committee of the Research Unit of Walter Sisulu University (FEDFREC-2457). The study was conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants.

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