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Integrating Pneumatics and Hydraulics in STEM for 4IR-ready Technology Teacher Preparation

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ABSTRACT

The rapid advancements associated with the Fourth Industrial Revolution (4IR) have necessitated a paradigm shift in Science, Technology, Engineering, and Mathematics (STEM) education, particularly in the training and professional development of pre-service and in-service Technology teachers. As core elements of industrial automation, pneumatics and hydraulics are essential for preparing educators to engage learners in 4IR-aligned competencies. This study explores how pneumatics and hydraulics can be effectively integrated into teacher education programs to strengthen STEM capabilities and enhance classroom readiness. Grounded in the Technological Pedagogical Content Knowledge (TPACK) framework, Constructivist Learning Theory, and the Work-Integrated Learning (WIL) approach, the study investigates current pedagogical practices, institutional gaps, and opportunities for curriculum innovation in Technology Education. A qualitative research design, informed by an interpretivist paradigm, was adopted. Data were collected through semi-structured interviews, focus group discussions, and document analysis, drawing on insights from teacher educators, curriculum developers, and industry experts. The findings reveal significant challenges in equipping teachers with the necessary technical and pedagogical skills due to limited curriculum coverage, insufficient digital simulation resources, and weak collaboration between academic institutions and industry. However, the study also identifies best practices that include competency-based and inquiry-driven instructional strategies, enhanced access to industry-standard tools, and practical exposure through structured WIL placements. The study recommends urgent curriculum reforms and policy interventions that support the infusion of 4IR technologies in teacher training. Strengthening partnerships between industry and academia, investing in teacher professional development, and modernizing teaching resources are critical steps towards producing Technology teachers who are 4IR-ready and capable of shaping future-ready learners.
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KEYWORDS

STEM education, pneumatics, hydraulics, Fourth Industrial Revolution, teacher preparation.

INTRODUCTION

The Fourth Industrial Revolution (4IR) has ushered in a new era of technological advancements, characterized by the integration of automation, artificial intelligence, robotics, and innovative technologies into various sectors, including education (Shlenova et al., 2025) . As industries increasingly rely on advanced manufacturing systems incorporating pneumatics and hydraulics, the demand for a technologically competent workforce has grown significantly. Consequently, education systems, particularly teacher training programs, must adapt to ensure that pre-service and in-service educators have the necessary content knowledge and pedagogical strategies to teach these emerging technologies effectively (Miró-Pérez, 2020). Pneumatics and hydraulics are fundamental mechanical and industrial engineering principles that play a critical role in automation, manufacturing, and control systems (Leopold et al., 2025; Shastri, 2025). These technologies form the backbone of numerous industrial applications, including automotive systems, aerospace engineering, and advanced technology. The necessary content knowledge and pedagogical strategies to teach these emerging technologies in robotics effectively. Despite their importance, studies indicate that many technology educators lack adequate training and instructional resources to teach these concepts effectively at the secondary and tertiary levels (Blose, 2025; Muyambi & Ramorola, 2025). This skills gap poses a significant challenge to the development of a technologically literate generation capable of thriving in 4IR-driven economies (Maeko & Simon, 2024).

STEM education must undergo significant pedagogical and curricular transformations to meet the demands of modern industries (Govender et al., 2025; Pietrocola et al., 2025). Practical pedagogical approaches, including inquiry-based learning, problem-solving strategies, and work-integrated learning (WIL), are essential for equipping teachers with both theoretical and practical competencies in pneumatics and hydraulics (Mjenda & Kyaruzi, 2025; Seleke, 2021). Moreover, digital simulation tools and interactive learning environments have been identified as crucial in facilitating conceptual understanding and hands-on experience (Kefalis et al., 2025). However, integrating these approaches into teacher training programs remains limited due to curriculum constraints, resource limitations, and inadequate professional development opportunities for educators (Maringe & Prew, 2020). This study explores research-based effective content and pedagogical developments in STEM education, focusing on integrating pneumatics and hydraulics into teacher preparation programs. By examining existing literature, curriculum frameworks, and empirical research, the study aims to identify best practices for preparing educators to teach these critical concepts in alignment with 4IR demands. Furthermore, it provides recommendations for curriculum enhancement, policy interventions, and professional development initiatives that can bridge the gap between educational training and industrial needs. The following sections of this paper present the theoretical framework guiding this study, a review of relevant literature, the research methodology adopted, findings and discussions, and concluding recommendations. By addressing the challenges and opportunities associated with teaching pneumatics and hydraulics, this study contributes to the broader discourse on equipping educators with the skills and knowledge necessary to foster technological literacy in the 4IR era.

Problem statement and research objectives

Despite the increasing importance of pneumatics and hydraulics in automation and advanced manufacturing, their integration into teacher education programs remains inconsistent and underdeveloped (Khamkar & Patil; Shastri, 2025). While 4IR technologies have transformed industrial processes, many pre-service and in-service Technology educators continue to operate within outdated curricular frameworks that inadequately reflect current industry demands (Glasgow, 2025; Mahaswa & Gebbyano, 2025; Ryalat et al., 2024). This disconnect has resulted in a pronounced skills gap, where graduates from teacher training institutions often lack the practical competencies, digital literacy, and pedagogical agility required for effective instruction in fluid power systems (Teele, 2025; Maeko & Simon, 2024). Curriculum constraints, limited access to modern simulation tools, and insufficient

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exposure to real-world automation environments continue to hinder the preparation of 4IR-ready educators (Maringe & Prew, 2020; Masunda, 2024; Oloba, 2025). Although research supports the use of inquiry-based learning, digital simulation, and Work-Integrated Learning (WIL) to address these challenges (Seleke, 2021; Mjenda & Kyaruzi, 2025), their implementation remains sporadic and uneven, especially in under-resourced institutions. Despite increasing interest in 4IR-aligned education, there remains a significant gap in the integration of automation-related competencies—particularly pneumatics and hydraulics—into Technology teacher training programmes in South Africa (Shastri, 2025; Glasgow, 2025; Mpofu & Chasokela, 2025). While frameworks such as TPACK and Constructivist Learning Theory are promoted in STEM education (Huang et al., 2025; Zhou & Divekar, 2025), limited empirical research explores how these are operationalised to prepare educators for industrial technologies. Furthermore, policy frameworks like the National Development Plan 2030 and MRTEQ advocate for Work-Integrated Learning (WIL), yet few studies examine its implementation in teacher education for automation (Visser, 2024; Ramrathan et al., 2024). This persistent gap, therefore, calls for an empirical investigation into the specific pedagogical, infrastructural, and institutional barriers that constrain the integration of pneumatics and hydraulics into Technology teacher training.

This study, therefore, aims to:

- Examine the pedagogical and curricular challenges experienced by teacher educators in incorporating pneumatics and hydraulics into STEM education;
- Identify best practices, instructional tools, and policy interventions that can enhance the competency of Technology teachers in 4IR-related content;
- Recommend curriculum reforms and industry-linked strategies to improve teacher readiness and student learning outcomes in the context of industrial automation.

This study, located within the South African context, investigates the pedagogical, curricular, and institutional barriers that hinder the incorporation of pneumatics and hydraulics into pre-service and in-service Technology education. By drawing on perspectives from educators, curriculum developers, and industry experts, and using an integrated theoretical lens (TPACK, Constructivism, and WIL), this research contributes practical, theoretical, and policy insights for bridging the disconnect between training and 4IR workforce demands

Theoretical Framework

The preparation of technology teachers for the demands of the Fourth Industrial Revolution (4IR) necessitates a strong theoretical foundation that informs both content delivery and pedagogical approaches. This study is grounded in three key educational frameworks that are particularly relevant to the effective teaching of pneumatics and hydraulics: the Technological Pedagogical Content Knowledge (TPACK) framework, Constructivist Learning Theory, and the Work-Integrated Learning (WIL) approach. These theoretical perspectives collectively provide an integrative lens through which the development of teacher competencies can be analyzed concerning 4IR-aligned technology education. The Technological Pedagogical Content Knowledge (TPACK) framework emphasizes the intersection of three core components: content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK) (Aqib et al., 2025; Huang et al., 2025; Niess, 2016). In the context of pneumatics and hydraulics education, content knowledge pertains to the fundamental principles of fluid power systems, their applications in automation, and their role in modern industrial processes. Pedagogical knowledge focuses on instructional methodologies that facilitate effective learning, including inquiry-based learning, problem-solving strategies, and active experimentation. In this context, technological knowledge integrates digital tools, simulation software, and innovative technologies into teaching practices, ensuring students engage with contemporary industry-relevant resources. The TPACK model underscores the necessity of balancing these three knowledge domains to create a learning environment that is both technologically enriched and pedagogically effective (Huang et al., 2025). Given the increasing role of intelligent automation in 4IR, integrating pneumatics and hydraulics into teacher education curricula must be framed within the TPACK model to ensure conceptual depth, technological proficiency, and pedagogical adaptability.

Complementing the TPACK framework is the Constructivist Learning Theory, which emphasizes the active role of learners in constructing knowledge through experience, inquiry, and social interaction (Piaget, 1972; Vygotsky, 1978). The constructivist paradigm is particularly relevant in teaching pneumatics and hydraulics, as these topics require learners to engage in hands-on experimentation, critical thinking, and real-world problem-solving. Through inquiry-based learning, students can explore the functionality of fluid power systems by manipulating pneumatic and hydraulic components, testing variables, and troubleshooting performance challenges (Drakatos et al., 2024). The problem-based learning (PBL) approach, a constructivist instructional strategy, further reinforces this experiential learning process by presenting learners with industry-related challenges that require the application of fluid power principles to devise solutions (Conley, 2022; Pahwa; Simonsen et al., 2021). Additionally, constructivist learning fosters collaborative engagement, wherein learners work in teams to design, simulate, and optimize fluid power systems, reflecting the interdisciplinary nature of STEM education (Zhou & Divekar, 2025). In the context of teacher preparation, embedding constructivist methodologies in technology education ensures that educators are equipped to facilitate discovery-driven learning environments that encourage innovation and adaptability, key competencies for the 4IR era.

Furthermore, the Work-Integrated Learning (WIL) approach provides a critical link between theoretical instruction and real-world application in teacher training programs (Pietersen & Langeveldt, 2024).In South Africa, the Minimum Requirements for Teacher Qualifications (MRTEQ) policy outlines precise and detailed criteria for designing learning programs, along with directives on practical training and work-integrated learning (WIL) frameworks (Ramrathan et al., 2024). However, recent studies by Visser (2024) and Doh Nubia et al. (2024) highlight that current practice is placing pre-service teachers only in schools for experiential learning with little or no attempt to place them in Industry-Based Learning. According to Both (2023), WIL promotes authentic learning experiences by integrating industry-relevant exposure, digital simulation tools, and hands-on experimentation into educational practice. Given the applied nature of pneumatics and hydraulics, WIL serves as an essential pedagogical strategy that enables pre-service and in-service teachers to develop practical competencies through structured industry partnerships, internships, and simulated training environments. In particular, the use of digital laboratories, augmented reality (AR), and computer-aided engineering (CAE) software facilitates a practice-oriented understanding of fluid power systems without the limitations of physical resource constraints (Abele et al., 2024). Additionally, by aligning curriculum content with industry standards and certification frameworks, WIL ensures that technology educators are adequately prepared to teach job-ready skills that meet the evolving demands of 4IR-driven workplaces. These theoretical perspectives provide a robust foundation for understanding the pedagogical imperatives of technology education in the 4IR era. By adopting an integrative theoretical framework,

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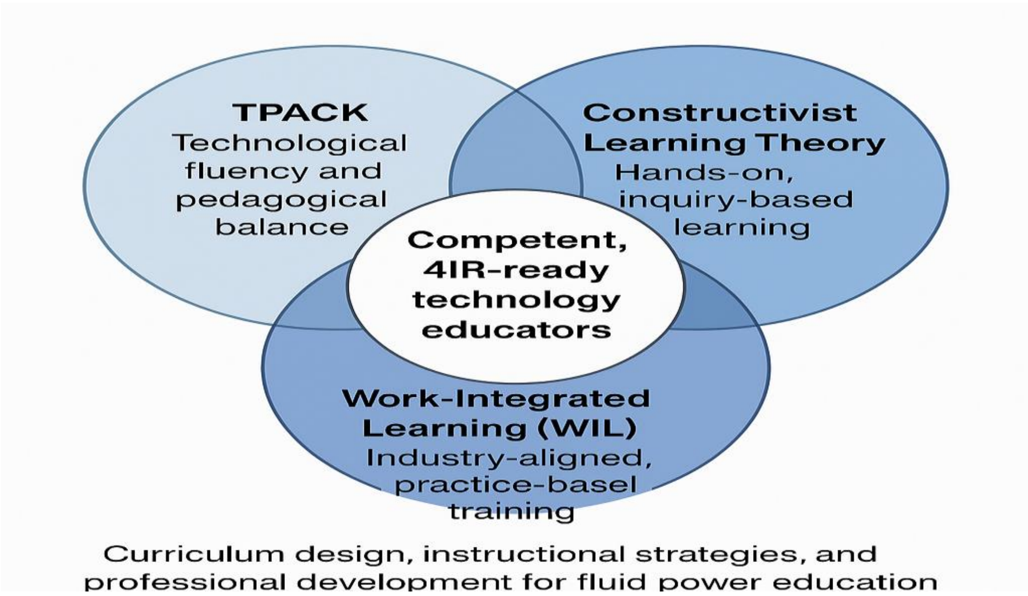
this study offers a conceptual lens for analyzing the challenges and opportunities in technology teacher education, offering insights into best practices for curriculum development, instructional strategies, and professional development initiatives. Through this framework, the research aims to contribute to the broader discourse on technology education reform, ensuring that pre-service and in-service teachers are adequately equipped to navigate the complexities of 4IR-aligned teaching and learning. To enhance conceptual clarity, the interrelationship between the three theoretical frameworks underpinning this study, TPACK, Constructivist Learning Theory, and Work-Integrated Learning, is illustrated in Figure 1 below.



Seleke & Teis (2025). Figure 1: Integrated Theoretical Lens for 4IR-aligned Technology Teacher Preparation

LITERATURE

The transformation of STEM education in response to the Fourth Industrial Revolution (4IR) has been widely discussed in academic literature (Aboderin & Havenga, 2024; Kruger & Steyn, 2024; Van Truong & Dung, 2024). Research indicates that pneumatics and hydraulics are fundamental to automation, robotics, and smart manufacturing, yet their integration into teacher training programs remains inconsistent (Khamkar & Patil; Shastri, 2025). This section critically examines existing literature on three key areas: the impact of 4IR on education, the role of pneumatics and hydraulics in modern engineering and industry, and pedagogical approaches for teaching these technical concepts.

The 4th Industrial Revolution and Its Impact on Education

The Fourth Industrial Revolution (4IR) represents a technological paradigm shift characterized by the fusion of cyber-physical systems, artificial intelligence, the Internet of Things (IoT), and automation(Els et al., 2022; Teis et al., 2022). For Els et al. (2022), these advancements have redefined the competencies required for future workforces, necessitating a realignment of educational curricula, pedagogical strategies, and teacher training programs. Within this evolving landscape, technology teachers must be equipped with discipline-specific knowledge, digital literacy, and pedagogical adaptability to effectively prepare students for automation-driven industries (Bhattacharjya, 2025). Recent studies highlight that many technology education curricula remain rooted in traditional mechanical and electrical engineering principles, failing to integrate modern automation technologies such as pneumatics, hydraulics, and programmable logic controllers (PLCs) (Ryalat et al., 2024). This disconnect has led to a skills gap between educational outcomes and industry expectations, where graduates lack the practical competencies required for Industry 4.0 work environments (Low et al., 2021). Tuomi et al. (2023) and Mutembei (2024) highlight that UNESCO's 2022 report on STEM education further emphasizes that technical educators must transition from knowledge transmission models to competency-based, industry-driven learning approaches.

Furthermore, the integration of 4IR technologies in education has implications for teacher professional development and curriculum design. Research suggests that adequate teacher preparation requires a multidisciplinary approach, combining STEM integration, problem-based learning, and digital simulation tools to enhance technological fluency (AlAli, 2024; Aunzo Jr, 2025; Su, 2024). However, the limited availability of specialized training programs, infrastructure constraints, and resistance to pedagogical change remain significant challenges (Bremner et al., 2023; Mhlanga et al., 2022). These issues underscore the urgent need for curriculum reforms that align pre-service and in-service teacher training programs with 4IR-aligned industrial applications.

The Role of Pneumatics and Hydraulics in Modern Engineering and Industry

Pneumatics and hydraulics are essential components of industrial automation, manufacturing, and robotics, forming the foundation of modern mechatronic systems (Channi et al., 2024; Ryalat et al., 2024). Pneumatic systems, which use compressed air to generate mechanical motion, are widely employed in assembly lines, robotic arms, and packaging systems, while hydraulic systems, which utilise pressurised fluid, are crucial for heavy machinery, aerospace applications, and automated control systems (Pawar, 2020).

Industrial reports indicate that over 80% of manufacturing processes rely on either pneumatic or hydraulic technologies, demonstrating their widespread application across engineering disciplines (Karabegović et al., 2021). The automotive, aerospace, and energy sectors have seen significant automation advancements, where innovative pneumatic systems integrated with IoT sensors are now commonplace (Ghorpade & Sidharth, 2025). Given this industry shift, engineering and technology education must prioritize fluid power systems as a core component of technical training programs. Despite the increasing importance of pneumatics and hydraulics, research highlights several educational gaps in their teaching and application. A study by Glasgow (2025) found that most engineering and technology education programs still emphasize theoretical aspects of fluid mechanics while neglecting practical applications using industrial automation tools. This lack of hands-on experience has resulted in low competency levels among technology educators, further exacerbating the skills gap between academia and industry (Teele, 2025). To bridge this gap, researchers recommend the adoption of simulation-based learning platforms, real-world case studies, and industry collaboration initiatives (Madiyala & Prajapati, 2025). The development of industry-aligned curricula, incorporating programmable pneumatic and hydraulic control systems, sensor integration, and AI-driven automation, is essential to ensure that technology teachers are equipped with relevant skills (Caratozzolo et al., 2024).

Pedagogical Approaches for Teaching Pneumatics and Hydraulics

Effective teaching of pneumatics and hydraulics requires innovative pedagogical approaches that integrate active learning, digital technologies, and competency-based instruction (Sheng & Hu, 2014). Traditional lecture-based instruction has proven insufficient in equipping students with problem-solving abilities and real-world application skills, necessitating the adoption of constructivist and inquiry-driven teaching strategies (Verawati & Nisrina, 2025). Research in STEM education suggests that inquiry-based learning (IBL) enhances student engagement by encouraging them to explore, analyze, and experiment with fluid power systems (Avsec & Kocijancic, 2014; Self et al., 2013). Students can develop a deeper understanding of pneumatic and hydraulic principles through guided experimentation, reinforcing conceptual learning through practical application. Furthermore, problem-based learning (PBL) has been identified as a highly effective strategy for developing higher-order thinking skills in engineering and technology education (Husin et al., 2025). By presenting students with real-world automation challenges, PBL fosters critical thinking, creativity, and collaborative problem-solving (Shanthi et al., 2025).
Digital simulation tools such as FluidSIM, Automation Studio, and MATLAB-Simulink have gained traction in engineering education, allowing students to visualize, design, and test pneumatic and hydraulic systems in a virtual environment (BASTOS, 2021; del-Olmo et al., 2023). These tools address resource limitations by offering a cost-effective alternative to physical laboratory experiments, providing students with interactive learning experiences that simulate real-world industrial automation processes (Subramanian et al., 2025). Research indicates that the use of virtual reality (VR) and augmented reality (AR) technologies further enhances spatial reasoning, technical comprehension, and problem-solving abilities in students, making them highly effective in competency-based training programs (Dianatfar et al., 2025). Additionally, Work-Integrated Learning (WIL) has been identified as a crucial pedagogical approach for aligning technical education with industry needs (Billing, 2025). Industry-academic collaborations, where pre-service teachers engage in industry-based apprenticeships and internships, allow educators to develop hands-on competencies in pneumatics and hydraulics (Singh, 2024). Research suggests that WIL models enhance not only technical proficiency but also instil critical workplace skills, including problem-solving, adaptability, and teamwork (Ongartsuebsakul et al., 2024; Prohimi et al., 2024).

Research Methodology

This study employed a qualitative approach within a design-based research framework, underpinned by an interpretivist paradigm, which facilitated a context-sensitive exploration of pedagogical and curricular developments required for integrating pneumatics and hydraulics into STEM education. This paradigm aligns with the views of scholars such as Creswell (2012) and William (2024), who advocate for interpretivism in studies aimed at understanding participants' perspectives within specific educational contexts. The interpretivist lens was appropriate for understanding how various stakeholders conceptualised and responded to the challenges and opportunities of automation-related instruction, particularly in relation to 4IR imperatives. Data were gathered from a diverse group of stakeholders, including pre-service and in-service Technology teachers, curriculum developers, and industry professionals involved in fluid power systems and automation. These participants were selected using a purposive sampling strategy, ensuring they possessed relevant expertise and experience in teaching, curriculum development, or industrial automation (Lim, 2024). The final sample consisted of 25 purposively selected participants, including pre-service and in-service Technology teachers, curriculum developers, and industry professionals from teacher training institutions, education departments, and private-sector organisations engaged in pneumatics and hydraulics education. Of these, 15 participants took part in one-on-one

semi-structured face-to-face interviews, while the remaining 10 were organised into two focus group discussions (FGDs), each comprising five participants with shared disciplinary or institutional affiliations. This distribution enabled the study to obtain both individual depth and collaborative insight, enriching the thematic analysis through methodical triangulation. The sampling criteria included prior involvement in STEM curriculum design or implementation, at least three years of professional experience, and practical familiarity with automation technologies. Three qualitative data collection methods were used to enable triangulation and deepen the interpretive analysis: semi-structured interviews, focus group discussions (FGDs), and document analysis (Shoozan & Mohamad, 2024; Mwilongo, 2025). Semi-structured interviews served as the primary tool for eliciting in-depth views from individual participants, exploring their perceptions of curriculum relevance, instructional strategies, and resource limitations. Focus group discussions were subsequently conducted with sub-groups of participants to probe emergent themes and encourage collaborative dialogue. This sequencing allowed initial insights from interviews to inform the framing of FGDs.

In addition, a document analysis was conducted to assess the extent to which curricular and policy frameworks addressed the needs of 4IR-aligned education. Documents analysed included:

- The Curriculum and Assessment Policy Statement (CAPS) for Technology (Grades 7–9),
- TVET College curriculum guides,
- The National Development Plan 2030,
- The Fourth Industrial Revolution Discussion Document (DTPS, 2020),
- UNESCO’s ICT Competency Framework for Teachers (2018).

This approach enabled the researcher to assess the alignment (or lack thereof) between policy intentions and classroom realities.

Data were analysed using thematic analysis (Maguire, 2017), allowing for the identification, coding, and categorisation of recurrent patterns across the data sets. NVivo software was used to manage, visualise, and structure emerging themes systematically. Codes were developed inductively from the data, with analytic memos guiding the refinement of core categories. To ensure trustworthiness, a more suitable criterion than validity and reliability in qualitative inquiry, this study drew on Lincoln and Guba’s (1985) four criteria:

- Credibility was ensured through prolonged engagement with participants and triangulation of data sources.
- Transferability was supported by thick descriptions of the research context and participant profiles.
- Dependability was achieved by maintaining an audit trail of coding processes and analytic decisions.
- Confirmability was enhanced through researcher reflexivity and the use of verbatim transcripts to support interpretations.

Ethical clearance was obtained from the relevant university ethics committee [FEDSECC033-11-23], and all participants provided informed consent. Confidentiality and anonymity were maintained through coding of personal data and secure digital storage of all materials, in accordance with ethical standards for human subject research (Miller & Boulton, 2007).

FINDINGS

This section presents the analysed data obtained through semi-structured interviews, focus group discussions, and document analysis. Three main themes emerged from the data: (1) Current Gaps in Technology Teacher Preparation for 4IR, (2) Effective Pedagogical Strategies for Teaching Pneumatics and Hydraulics, and (3) Implications for Curriculum Development and Policy Reform.

Theme 1: Current Gaps in Technology Teacher Preparation for 4IR

Participants expressed deep concerns about the disconnect between current teacher training programmes and the practical demands of the Fourth Industrial Revolution. Pre-service teachers reported that their training lacked opportunities for hands-on engagement with fluid power systems, which left them feeling underprepared. One participant noted that although theoretical content was covered, there was little exposure to actual equipment or simulation tools.

> ***"We are taught the theory of how pneumatic systems work, but we've never seen or worked on an actual setup. It feels abstract."***

In-service teachers similarly reported that existing curricula did not include sufficient content on pneumatics or hydraulics. These topics were often embedded within mechanical systems but not explored in depth, leading to significant knowledge gaps. Participants indicated that inadequate training and a lack of resources made it difficult to introduce modern automation content into their classrooms.

> ***"The current curriculum is silent on pneumatics and hydraulics. Even if we wanted to teach it, we lack both the training and the resources."***

Industry stakeholders shared concerns that graduates entering the workforce lacked both theoretical understanding and practical experience. They observed that recent hires required substantial retraining before they could engage meaningfully with automated systems.

> ***"We spend the first six months teaching them what their degrees should have covered how to use simulation software, troubleshoot hydraulic faults, and interpret pneumatic schematics."***

Resource limitations, especially in rural institutions, were also highlighted, with many institutions unable to afford even basic simulation software or laboratory setups.

> ***"Budget constraints mean our students read about systems they may never operate. It's frustrating."***

Theme 2: Effective Pedagogical Strategies for Teaching Pneumatics and Hydraulics

Participants strongly advocated for inquiry-based, problem-solving approaches to teaching these technical subjects. Many described how hands-on experimentation and project-based learning improved their understanding. One pre-service teacher described a transformative experience using a basic pneumatic kit, which made abstract concepts more tangible.

> ***"I only began to understand pneumatics after we experimented with small kits during a workshop. Before that, it was just diagrams in a textbook."***

The use of simulation tools was cited as a highly effective strategy, enabling teaching and learning of hydraulic and pneumatic functions even in contexts where physical labs were unavailable. Several participants emphasized the need for project-based assignments that mirror real-world automation problems to enhance learners' problem-solving abilities and foster critical thinking.

> ***"Simulation tools allow us to teach functions, faults, and flow control without needing expensive physical labs."***

Work-integrated learning experiences were also highly valued. Participants described how site visits to industrial plants, internships, and mentoring from technicians helped bridge the gap between theory and practice.

> ***"We design real-life automation problems for our students to solve. That's when they truly start thinking like engineers."***

Such experiences were seen as vital for enabling teachers to teach 4IR-aligned content with confidence and relevance.

> ***"Until our students enter an actual plant and see these systems running, they won't fully grasp what they're learning."***

Theme 3: Implications for Curriculum Development and Policy Reform

Findings revealed a consistent call for structural reform in teacher education curricula. Participants lamented the lack of dedicated modules on pneumatics and hydraulics and called for greater integration of automation systems into existing programmes.

> ***"There is no dedicated module on pneumatics and hydraulics in our teacher education programme. If it is mentioned, it's embedded under mechanical systems and often overlooked."***

Many suggested that the content was either entirely absent or only briefly mentioned in general technology modules. The absence of a national benchmark for automation competencies in teacher education was also highlighted as a serious concern.

> ***There's no national benchmark for teacher skills in pneumatics or automation, it depends on the institution, and many don't prioritise it."***

Participants also pointed to a lack of standardisation across institutions, which led to inconsistency in graduate preparedness.

> ***"Even if we wanted to modernise our course, we simply don't have the tools."***

Further, under-resourced institutions reported difficulties implementing modernised programmes due to inadequate infrastructure and limited budgets. Participants advocated for a collaborative approach to curriculum development involving educators, government officials, and industry experts.

> ***"Without experiencing a factory environment, it's impossible to teach automation with confidence."***

There was strong support for expanding the concept of work-integrated learning beyond school placements to include structured industrial exposure as a standard part of teacher training.

DISCUSSION OF FINDINGS

This section interprets the key findings in light of the study's four objectives and relevant literature. The discussion integrates theoretical and empirical insights, offering a comprehensive explanation of how pneumatics and hydraulics can be effectively embedded in Technology teacher education within the context of the Fourth Industrial Revolution (4IR).

Objective 1: To identify current content and pedagogical gaps in the teaching of pneumatics and hydraulics

The findings reveal that teacher preparation programmes across institutions inadequately address fluid power systems, particularly pneumatics and hydraulics. This aligns with the assertions of Maeko and Simon (2024), who noted that Technology Education curricula remain heavily focused on outdated mechanical content. Mpofu and Chasokela (2025) similarly argue that fragmented curriculum designs have contributed to pre-service teachers lacking exposure to real or simulated industrial automation systems. The insufficient use of digital tools like FluidSIM or MATLAB-Simulink was further reinforced by Mhlanga et al. (2022), who found that under-resourced institutions struggle to integrate simulation technologies into their training environments. These observations underscore the systemic disconnect between educational offerings and the competencies demanded in modern 4IR industries.

Objective 2: To explore effective pedagogical strategies for teaching pneumatics and hydraulics in STEM education

Findings demonstrate that active, inquiry-based learning approaches are essential for promoting deep conceptual understanding of pneumatics and hydraulics. The emphasis on simulation-based instruction and project-based learning supports Piaget's (1972) and Vygotsky's (1978) constructivist learning theories, where experiential knowledge-building is prioritised. Seleke (2021) highlighted that learners perform better when exposed to real-world tools and problems through work-integrated and simulation-driven pedagogy. Tools such as Automation Studio, MATLAB-Simulink, and FluidSIM were found to facilitate interactive teaching, particularly where physical labs are limited. This aligns with the UNESCO (2018) ICT Competency Framework's recommendation for embedding digital pedagogy and simulation-based instruction into teacher training.

Objective 3: To assess the potential of Work-Integrated Learning (WIL) and simulation tools in preparing 4IR-ready Technology teachers

Participants emphasised the importance of integrating WIL models into pre-service and in-service training. Real-world exposure through internships, site visits, and simulation tasks was shown to build both confidence and competence in teaching complex technologies. This observation supports Syafruddin et al. (2025) and Epaphras (2025), who advocate for industry immersion in teacher education to ensure alignment with industrial practices. Visser (2024) noted that many South African teacher education programmes fall short of this ideal, particularly in

STEM and TVET fields, due to policy and funding limitations. The limited institutionalisation of WIL in the Minimum Requirements for Teacher Education Qualifications (MRTEQ) (Ramrathan et al., 2024) further constrains implementation. Nonetheless, the participants' feedback indicates that WIL, when fully embraced, contributes significantly to building 4IR teaching capacity.

Objective 4: To recommend curriculum and policy interventions for aligning Technology Education with 4IR demands

The findings affirm that Technology teacher education requires urgent reform. Respondents pointed to the absence of standardised competencies for teaching automation systems. Khoza and Mpungose (2025) have similarly called for a national curriculum audit to reflect 4IR-aligned standards in technical education. The lack of simulation laboratories and automation modules in university curricula underscores recommendations made by Teis and Els (2021; 2022) and Els et al. (2022), who advocate for expanding infrastructure and teacher professional development. Furthermore, the National Development Plan 2030's (South Africa, 2012) call for equitable access to technical education remains largely unrealised. Bremner et al. (2023) underscore the structural limitations that continue to disadvantage rural and peri-urban institutions. This study confirms the urgent need to overhaul Technology Education to include automation, simulation tools, and structured WIL. Doing so requires curriculum flexibility, enhanced industry-academia partnerships, and robust funding models that can support technology integration across the teacher education pipeline.

CONCLUSION, IMPLICATIONS AND SUGGESTIONS

This study set out to explore the integration of pneumatics and hydraulics into Technology teacher education as a critical response to the demands of the Fourth Industrial Revolution (4IR). Despite their foundational role in modern automation and manufacturing systems, these technologies remain underrepresented in teacher training programmes across South Africa. The findings revealed three major challenges: outdated curricula that marginalise automation content; inadequate access to simulation tools and physical training resources; and the absence of structured Work-Integrated Learning (WIL) experiences in industrial settings. Participants highlighted a disconnect between theoretical instruction and practical application, as well as between educational outcomes and industry expectations. These findings are significant in the broader field of STEM and Technology Education as they underscore the urgent need to realign teacher preparation with the realities of 4IR-driven industrial environments. The study contributes to the theoretical literature by demonstrating how the TPACK framework, Constructivist Learning Theory, and WIL can be jointly applied to guide curriculum innovation and professional development in Technology Education. It also adds empirical value by triangulating data from educators, curriculum experts, and industry stakeholders to offer a grounded understanding of the skills gap in fluid power education.

Based on the evidence, the study recommends the following:

- Curriculum reform to explicitly include pneumatics, hydraulics, and automation as core modules.
- Investment in simulation tools and digital laboratories, particularly in under-resourced institutions.
- Development of national competency standards for Technology educators in 4IR-related content; and
- Formal industry-academic partnerships to facilitate structured WIL placements for teacher trainees.

While the study offers valuable insights, its limitations include a relatively small purposive sample size and its geographic focus on selected institutions and stakeholders. Future research should expand the participant pool to include a broader range of provinces and institutional types and assess the longitudinal impact of simulation-based training and industry exposure on teacher effectiveness. In closing, preparing Technology teachers for 4IR requires more than policy rhetoric; it demands pedagogical innovation, curriculum transformation, and strategic collaboration. If South Africa is to build a future-ready education system, then equipping teachers with automation-related competencies must be treated not as an option, but as a national imperative.

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