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Integrating Digital Technology in Teaching Factory–Based Vocational Learning: A Systematic Literature Review

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Abstract: Digital transformation requires vocational education to provide learning experiences that are increasingly relevant to the needs of modern industry. This study aims to examine the integration of digital technology in Teaching Factory–based vocational learning to strengthen the Vocational High School Center of Excellence Program. This research employed a Systematic Literature Review method guided by the PRISMA framework. Data were obtained from Scopus and Google Scholar through Publish or Perish, covering publications from 2017 to 2026. From 369 initially identified documents, 67 articles were selected as the final corpus after the identification, screening, eligibility, and inclusion stages. The findings show that publications related to Teaching Factory, digital technology, and the Vocational High School Center of Excellence increased markedly during 2023–2025, with Indonesia as the dominant research context. The identified digital technologies span six domains, ranging from classroom-level ICT and digital marketing tools to simulation-based and Industry 4.0-oriented technologies, and are pedagogically integrated through six recurring patterns centered on authentic production-based learning, project- and work-based learning, teacher capacity-building, and digital entrepreneurship. The reviewed literature reports several potential contributions of digital technology integration, including stronger school–industry alignment, student competency development, teacher pedagogical readiness, Teaching Factory management, school product commercialization, and the identity of Vocational High School Centers of Excellence as reference schools. However, this review also identifies several challenges, including uneven digital integration, limited infrastructure, teacher readiness, industry collaboration, quality control, and limited evaluation of learning impact. Building on these findings, this review proposes a preliminary Digital Teaching Factory model comprising seven interlocking components (curriculum, pedagogy, technology, teacher capacity, industry partnership, production and management, and quality assurance and evaluation), offered as a direction for future empirical validation rather than as a finalized framework.

Keywords: Teaching factory, Digital technology, Vocational education

Introduction

The development of digital technology has brought substantial changes to education, including vocational education, and Vocational High Schools (SMK) can no longer rely solely on conventional practical training to prepare a workforce that meets industry needs. Industrial shifts toward automation, digital marketing, simulation, and data-driven work systems demand that SMK graduates possess technical competencies, digital skills, and work readiness aligned with the needs of the business and industrial sectors (Yoto et al., 2019; Yondri et al., 2020; Mazlan et al., 2025a, 2025b, 2025c). Meeting this demand requires more than mastering theory and basic skills: vocational learning must give students authentic exposure to work processes, industry standards, real-world

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problem-solving, quality control, and technology relevant to their field (Roll & Ifenthaler, 2021; Vilppola et al., 2022; Ramanda et al., 2025).

One widely used approach for meeting this demand is the Teaching Factory, which transforms the school into a learning space that mimics an industrial environment so that students engage directly in production processes, services, problem-solving, and product development rather than learning concepts alone (Sugianto & Casmudi, 2022; Setiadi et al., 2025; Cholis et al., 2025; Elisabet et al., 2025). This role is increasingly at stake, however, as production-based learning that remains disconnected from digital technology risks falling behind an industry already reshaped by simulation, automation, and data-driven tools (Riemann et al., 2020; Nanda et al., 2025). Teaching Factories therefore need to evolve from physical production spaces into digital learning ecosystems that integrate work practices, technology, entrepreneurship, school management, and industry needs (Yondri et al., 2020; Muhardono & Meliza, 2023; Shofiana & Tohirin, 2025).

This context is increasingly relevant with the introduction of the Vocational High School Center of Excellence Program, which aims to strengthen the quality of vocational education through curriculum alignment, improved learning quality, stronger link-and-match initiatives, industry collaboration, teacher competency development, and enhanced graduate work readiness (Ahmanda et al., 2022; Sholihah, 2022; Tessa & Humaedi, 2023). The Teaching Factory is a relevant strategy for these objectives (Akyuwen et al., 2023; Elisabet et al., 2025), but strengthening Centers of Excellence through this approach is insufficient if it focuses solely on production: digital technology must also be incorporated into strategies for learning, management, marketing, evaluation, and industry collaboration (Septianingsih, 2023; Hastuti et al., 2025; Prihantoro et al., 2025).

Although Teaching Factories, digital technology, and Centers of Excellence in Vocational High Schools all hold important roles in vocational education, the three are often still discussed separately. Studies on Teaching Factories generally focus on the implementation of production-based learning, TeFa management, facility readiness, or industry relations (Baharsyah & Irfan, 2024; Muharam et al., 2024; Prihantoro et al., 2025). On the other hand, studies on digital technology in vocational education often discuss the use of learning media, ICT, simulations, or the digitization of learning without always linking them to Teaching Factories (Riemann et al., 2020; Vilppola et al., 2022; Nanda et al., 2025). Meanwhile, discussions regarding Vocational High Schools of Excellence (SMK Pusat Keunggulan) are largely focused on policy, industry-education alignment (link and match), curriculum, and industry partnerships (Asngad et al., 2023; Nuryanti et al., 2025; Sulistyawati & Mulyono, 2024). This situation reveals a specific fragmentation: many studies document the digital tools and technologies used in vocational settings, while comparatively few offer a synthesis of the instructional design or pedagogical strategies through which such tools can be meaningfully integrated into Teaching Factory-based learning. This situation highlights the need for a study that maps these three literatures onto one another and synthesizes their combined findings into an actionable model, an outcome this review works toward in the form of the integrative Digital Teaching Factory model presented in the Conclusion.

To interpret the patterns that emerge from this body of literature, this review draws on four complementary theoretical lenses: activity theory (Engeström, 2001), situated learning theory (Lave & Wenger, 1991), the TPACK framework (Mishra & Koehler, 2006), and the concept of boundary crossing (Akkerman & Bakker, 2011). These lenses are applied in the Discussion section to interpret the thematic patterns generated through the synthesis procedure described in the Method, providing a conceptual basis for understanding digital technology integration in the Teaching Factory as more than an inventory of individual tools and interventions.

A systematic review of the integration of digital technology in Teaching Factory-based vocational learning is crucial as it can provide a more comprehensive understanding of the direction of vocational education development. Through a Systematic Literature Review (SLR), previous studies can be mapped to determine how digital technology is utilized, how it is pedagogically integrated, its contributions to strengthening Center of Excellence vocational high schools (SMK), as well as the challenges and future development directions (Roll & Ifenthaler, 2021; Vilppola et al., 2022; Mazlan et al., 2025a, 2025b, 2025c). In this way, the SLR functions as more than a summary of prior research: it also identifies conceptual and practical gaps that can form the basis for developing a digital technology-based Teaching Factory model (Yondri et al., 2020; Nanda et al., 2025).

Given this urgency, this article is designed to examine the integration of digital technology into Teaching Factory-based vocational learning and its implications for strengthening the Vocational High School Center of Excellence Program. The primary focus of this article is to understand how digital technology can strengthen the Teaching Factory as a more authentic, adaptive, and industry-relevant vocational learning strategy. Through this study, it is hoped that a more comprehensive understanding of the relationship between the Teaching Factory, digital

transformation, and the strengthening of Vocational High School Centers of Excellence in addressing the demands of the future workforce will be achieved.

The research questions in this article are as follows:

RQ1. What are the publication trends and thematic focuses of studies on Teaching Factory–based vocational learning, digital technology integration, and Vocational High School Centers of Excellence from 2017 to 2026?

RQ2. What digital technology and digitalization domains are integrated into Teaching Factory–based vocational learning?

RQ3. How is digital technology pedagogically integrated into Teaching Factory, Learning Factory, production-based learning, work-based learning, or industry-based vocational learning?

RQ4. What contributions of digital technology integration in Teaching Factory-based vocational learning are reported in relation to strengthening the Vocational High School Center of Excellence Program?

RQ5. What challenges, gaps, and future directions have been identified in integrating digital technology into Teaching Factory-based vocational learning?

Method

Research Design

This study employs the Systematic Literature Review (SLR) method to identify, evaluate, and synthesize prior research related to the integration of digital technology in Teaching Factory-based vocational education. The SLR method was chosen because it is suitable for mapping literature trends, identifying thematic patterns, pinpointing research gaps, and formulating directions for future research based on published academic evidence. SLR is an approach used to systematically collect and interpret previous research so that the literature review process is not conducted randomly but through clear, transparent, and accountable stages (Kitchenham & Charters, 2007; Snyder, 2019). Methodologically, this study adheres to the PRISMA framework to ensure the article selection process is conducted systematically, transparently, and traceably. PRISMA is used to describe the stages of identification, screening, eligibility assessment, and the final selection of articles for analysis. The PRISMA framework helps researchers report the study selection process more clearly through flowcharts and structured reporting criteria (Moher et al., 2009; Page et al., 2021). This study does not aim to directly test the effectiveness of an intervention but rather to map and interpret trends in literature. Accordingly, the analysis was conducted using two approaches: descriptive mapping and thematic synthesis. Article screening, eligibility assessment, data extraction, and quality appraisal were conducted by a single reviewer (the first author); no second reviewer independently verified these stages, and no review protocol was registered in a public registry (e.g., PROSPERO) prior to conducting this review, and no second-reviewer check was subsequently performed on any stage. The single-reviewer process may therefore have increased the risk of selection and coding subjectivity, and both points are acknowledged as limitations of the review process.

Data Sources and Search Strategy

The research data sources were drawn from two databases: Scopus and Google Scholar. Scopus was used to obtain international articles related to Teaching Factory, Learning Factory, Work-Based Learning, TVET, Industry 4.0, and digital technology in vocational education. Google Scholar was used to expand the scope of the literature, particularly national articles discussing vocational high schools (SMK), Centers of Excellence for Vocational High Schools (SMK Pusat Keunggulan), Teaching Factory/TeFa, digital technology, ICT, and Industry 4.0. The search on Google Scholar was conducted using the Publish or Perish application. Both the Scopus and Google Scholar searches were executed on 27 April 2026. The use of more than one data source was employed to broaden the scope of articles and reduce the risk of limited search results from a single database. In a systematic literature review (SLR), search strategies must be designed systematically to ensure that the retrieved articles align with the research questions and that the search process can be traced back (Tranfield et al., 2003; Booth et al., 2016). The publication year range was limited to 2017–2026 to ensure that the analyzed articles remain relevant to the latest developments regarding the digitization of vocational education, Teaching Factory, Learning Factory 4.0, Industry 4.0, and Centers of Excellence for Vocational High Schools. The Scopus search was intentionally structured

around broader international terminology for Teaching Factory-related vocational learning and digital technology integration, because terminology corresponding to Indonesia's SMK Center of Excellence policy is not necessarily used in international vocational education literature; Google Scholar was additionally searched to capture Indonesia-specific studies using contextual terms such as SMK Pusat Keunggulan (SMK PK), TeFa, and related policy terminology. Because international and national studies use overlapping but non-equivalent terminology, related work-oriented learning concepts, including Teaching Factory, Learning Factory, Work-Based Learning, Production-Based Learning, and Industry-Based Learning, were included as retrieval terms and subsequently differentiated during screening and synthesis rather than treated as exact synonyms.

Keyword Selection

Keywords were developed based on the three main research focuses: Teaching Factory-based vocational learning, digital technology integration, and the Vocational High School Center of Excellence Program. When selecting keywords for a systematic literature review (SLR), it is essential to consider main terms, synonyms, and related terms to ensure search results are not overly narrow while remaining relevant to the study's focus (Kitchenham & Charters, 2007; Booth et al., 2016). On Scopus, the search was conducted using the following Boolean combination: (("teaching factory" OR "learning factory" OR "production-based learning" OR "work-based learning" OR "industry-based learning" OR "factory-based learning") AND ("vocational education" OR "vocational training" OR "vocational learning" OR "vocational school" OR "vocational high school" OR "technical and vocational education and training" OR TVET) AND ("digital technology" OR "digital transformation" OR "technology integration" OR "technology-enhanced learning" OR "educational technology" OR ICT OR "Industry 4.0" OR "smart factory" OR "digital manufacturing" OR "digital simulation" OR "virtual reality" OR "augmented reality"))

On Google Scholar via Publish or Perish, the search combined the following terms as alternatives within a single query field: "Teaching Factory" OR "TeFa" OR "Learning Factory" OR "SMK" OR "Vocational High School" OR "Digital Technology" OR "Technology Integration" OR "ICT" OR "Industry 4.0", restricted to the 2017–2026 publication-year range through Publish or Perish's built-in date filter.

Because Publish or Perish retrieves records by querying Google Scholar's full-text index rather than a fielded metadata database, these terms could not be constrained to title, abstract, or keyword fields in the same way as the Scopus Boolean string above; this is a platform-level constraint rather than a difference in search intent, and it is acknowledged here as a limitation of the Google Scholar search channel relative to Scopus. No additional result-count cap was applied beyond this date filter: all 330 records returned by the query were carried forward to the identification stage, consistent with the identification-stage count reported below. These keywords were made flexible because national articles often use a mix of Indonesian and English terms, such as Teaching Factory, TeFa, SMK, SMK Center of Excellence, digital technology, ICT/TIK, and Industry 4.0.

Inclusion and Exclusion Criteria

Inclusion and exclusion criteria are used to ensure that the analyzed articles align with the research focus. In a systematic literature review (SLR), inclusion and exclusion criteria are essential for maintaining consistency in article selection and ensuring that included articles are truly relevant to the research questions (Kitchenham & Charters, 2007; Page et al., 2021).

Article Selection Process Using PRISMA

The article selection process was conducted through the stages of identification, screening, eligibility, and inclusion. These stages followed the PRISMA principles, which emphasize transparent reporting of the study selection process, ranging from the number of articles identified, articles excluded, reasons for exclusion, to the final articles analyzed (Moher et al., 2009; Page et al., 2021). During the identification stage, 369 documents were identified, comprising 39 documents from Scopus and 330 documents from Google Scholar via Publish or Perish. No registries were used in this study. Prior to screening, 1 duplicate article and 112 documents that did not meet the initial criteria were excluded. No articles were excluded via automated tools. Following this stage, 256 articles proceeded to the screening stage. During the screening phase, 163 articles were excluded because they did not align with the research focus, leaving 93 articles to proceed to the search and eligibility assessment phase.

Table 1. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Time frame	Articles published between 2017 and 2026	Articles outside the 2017–2026 range
Document type	Scientific articles (research-based or community-service articles) and conference proceedings on Teaching Factory or SMK PK implementation, with accessible full text.	Blogs, popular opinion pieces, news articles, unpublished theses or dissertations, preprints not yet peer-reviewed, non-academic documents, and unverifiable sources
Context focus	Articles discussing vocational high schools (SMK), vocational education, TVET, or vocational education	Articles that do not discuss the context of vocational education/SMK/TVET
Teaching Factory focus	Articles related to Teaching Factory, TeFa, Learning Factory, Production-Based Learning, Work-Based Learning, Industry-Based Learning, or Factory-Based Learning	Articles not related to Teaching Factory or industry/production/work-based learning
Focus on digital technology	Articles related to digital technology, ICT, Industry 4.0, digital transformation, digital marketing, simulators, VR/AR, LMS, smart factories, digital manufacturing, or learning technologies	Articles that only discuss vocational education in general without any connection to digital technology or learning transformation
Accessibility	Articles must be accessible at a minimum through metadata, abstracts, and/or full text for analysis	Articles lacking sufficient information for analysis

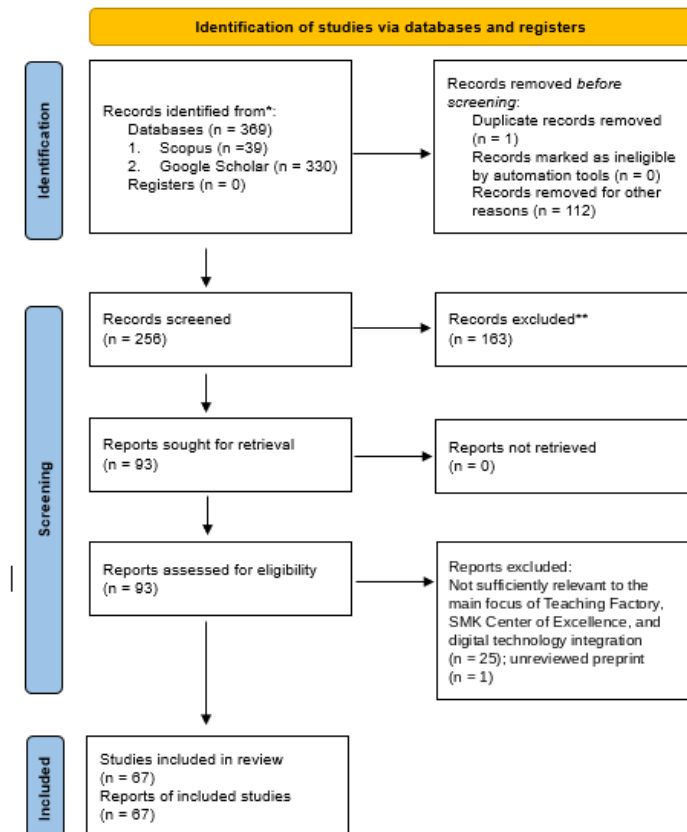


Figure 1. PRISMA diagram for literature selection

Exclusions at the initial-removal stage ($n = 112$) were applied primarily against the more readily verifiable criteria in Table 1: records outside the 2017–2026 time frame, document types outside the eligible set (blogs, opinion pieces, news articles, unpublished theses or dissertations, non-peer-reviewed preprints, and other non-academic or unverifiable sources), and records lacking sufficient metadata or abstract information for further assessment, since these criteria can typically be judged from bibliographic metadata alone, without reading the full abstract. Exclusions at the screening stage ($n = 163$) were applied primarily against the content-relevance criteria in Table 1: records that, on reading the title and abstract, did not sufficiently address the vocational education/SMK/TVET context, were not related to Teaching Factory or an equivalent production-, work-, or industry-based learning model, or discussed vocational education without a demonstrable connection to digital technology or learning-technology transformation. Because these exclusions were made by a single reviewer without a separate tally sheet coded to each individual criterion, disaggregated counts for each specific reason within these two broad groupings are not available and are reported here as a transparency limitation rather than estimated retrospectively; the criteria themselves, however, are identical to those already specified in Table 1, and the qualitative distinction between format/metadata-level exclusion at initial removal and content-relevance exclusion at screening reflects how the two PRISMA stages were operationally applied. All articles at this stage were accessible, so reports not retrieved = 0. In the eligibility stage, 26 articles were excluded: 25 because they were not sufficiently relevant to the main focus, namely Teaching Factory, Vocational High School Center of Excellence, and digital technology integration, and 1 because it was identified during full-text review as a preprint that had not undergone peer review, rather than a peer-reviewed journal article or conference/seminar proceedings paper. Thus, the final number of articles analyzed was 67.

Data Extraction

Once the final articles were selected, data extraction was conducted to gather key information from each article. Data extraction in a systematic literature review aims to ensure that information from the analyzed articles is recorded consistently and can be used to answer research questions (Kitchenham & Charters, 2007; Booth et al., 2016). The extracted data included author names, year of publication, article titles, country or research location, research methods, keywords, database sources, citations, types of digital technology, forms of pedagogical integration, contributions to the Center of Excellence for Vocational High Schools, as well as research challenges or gaps. This data was then grouped according to the five research questions. For RQ1, the data was analyzed based on year of publication, country, database, and keywords. For RQ2, the data focused on digital technology and digitalization domains. For RQ3, the data was analyzed based on pedagogical integration patterns. For RQ4, the data focused on contributions to strengthening the Center of Excellence Vocational High School. For RQ5, the data was analyzed based on challenges, gaps, and future research directions.

Article Quality Assessment

Article quality assessment was conducted to ensure that the articles included in the synthesis possess academic relevance and validity. In systematic reviews, quality assessment is necessary so that the synthesis is not based solely on the number of articles but also considers the appropriateness of the focus, clarity of methods, and the articles' contribution to the research questions (Tranfield et al., 2003; Snyder, 2019). This appraisal was carried out qualitatively by the first author against four indicators (topic relevance, methodological clarity, availability of findings, and contribution to the research questions) rather than through a standardized quantitative checklist (e.g., MMAT or CASP); this is acknowledged as a methodological limitation, and no per-article numeric scores were generated. For reference, these four indicators broadly parallel core domains used in standardized instruments such as the Mixed Methods Appraisal Tool (MMAT): clarity of the research question, appropriateness of the design to that question, adequacy of the reported data and findings, and coherence between aims and conclusions; however, this review applied them through the qualitative scoring rule described below rather than through the MMAT checklist itself, because the corpus mixes empirical, evaluative, community-service, and conceptual study types (see the classification below) that are not uniformly compatible with MMAT's category-specific criteria. Articles most relevant to the Teaching Factory, vocational education, digital technology, and the Center of Excellence Vocational High School (SMK) were used as the primary sources for the synthesis. Meanwhile, articles with more limited relevance were still utilized as contextual support if they helped explain the strengthening of the Center of Excellence Vocational High School (SMK) Program. This topical/methodological appraisal is conceptually distinct from the source-tier information (Scopus quartile and SINTA accreditation level) reported for transparency in the Appendix, which reflects the standing of the publishing outlet rather than the methodological quality of the individual study. To make this appraisal more transparent and operational, each article was scored qualitatively against the four indicators above using a three-point decision rule (fully met = 1,

partially met = 0.5, not met = 0) rather than a single holistic judgment; articles meeting most indicators fully were prioritized as primary evidence in the synthesis below, while articles meeting indicators only partially were retained mainly as contextual or illustrative support. In addition, to account for the corpus's methodological heterogeneity, the 67 included articles were further classified by study type based on their stated aims and methods: 36 empirical or implementation studies, 11 community-service or mentoring reports, 8 development/R&D studies, 6 programme evaluations, 5 conference or seminar proceedings papers, and 1 conceptual/policy analysis. This classification, together with the quality-appraisal scoring above, is used in the Discussion to qualify the evidentiary strength of specific claims, so that findings drawn from empirical studies and evaluations are distinguished from those drawn from more descriptive community-service or proceedings reports.

Data Analysis Techniques

Data analysis was conducted using two techniques: descriptive mapping and thematic synthesis. Descriptive mapping was used to address RQ1 by examining publication trends based on year, country, and keywords. The results of the mapping are presented in tables and diagrams to make publication patterns easier to interpret. Meanwhile, thematic synthesis was used to address RQ2 through RQ5. The synthesis involves reviewing the titles, abstracts, keywords, methods, results, and discussions of the articles, then grouping the findings based on main themes. Thematic synthesis enables researchers to systematically identify patterns, relationships, and meanings across a body of published literature (Thomas & Harden, 2008), drawing on principles of thematic analysis more broadly (Braun & Clarke, 2006). Coding followed a consistent sequence across all themes: each reported technology, practice, or outcome was first labeled by technology type, then by its primary instructional or institutional function, then by the specific pedagogical or managerial use described in the source article, and finally by the reported outcome or challenge associated with it; categories in Tables 2–4 were formed by grouping codes that shared the same function-level label. RQ2 groups digital technology and digitalization domains identified in the corpus, RQ3 groups patterns of pedagogical integration, RQ4 groups reported contributions relevant to strengthening Vocational High Schools of Excellence, and RQ5 groups challenges, evidence gaps, and directions for future development. Because several primary studies report both a classroom-level practice and its institutional payoff within the same account, RQ3 and RQ4 necessarily draw on a partially shared set of studies; to keep the two research questions analytically distinct, each shared study is cited for two different reported facts, a pedagogical mechanism under RQ3 and an institutional-level outcome under RQ4, and no single reported finding is used as evidence for both. In the Discussion, these thematic findings are further interpreted through four complementary interpretive theoretical lenses: activity theory (Engeström, 2001), situated learning theory (Lave & Wenger, 1991), the TPACK framework (Mishra & Koehler, 2006), and the concept of boundary crossing (Akkerman & Bakker, 2011). These lenses were used post hoc to aid interpretation and to help explain the patterns identified through thematic synthesis, rather than as frameworks that guided the original coding process.

Synthesis and Reporting of Findings

The synthesis results are organized according to the sequence of the research questions. RQ1 is reported through a mapping of publication trends and thematic focuses, while RQ2 through RQ5 are reported through a narrative synthesis supported by thematic tables. The reporting of SLR results must be structured systematically so that the relationship between research questions, the selection process, data extraction, analysis, and findings can be clearly traced (Page et al., 2021; Snyder, 2019). Therefore, the reporting maintains a direct connection between the data, categories, and research questions, ensuring that the entire discussion remains within the scope of the article: the integration of digital technology into Teaching Factory-based vocational learning to strengthen the Vocational High School Center of Excellence Program.

Results and Discussion

Results

Publication trends and thematic focuses of studies on Teaching Factory-based vocational learning, digital technology integration, and Vocational High School Center of Excellence from 2017 to 2026

Based on 67 final articles, publication trends regarding Teaching Factory-based vocational learning, digital technology integration, and the Vocational High School Center of Excellence show a clear increase in recent

years, particularly during the 2023–2025 period. Early studies in 2017 had already begun to incorporate technology into vocational learning, for example through an ICT-based creative economy learning model in vocational high schools (Swaramarinda & Nurmalasari, 2017). Subsequently, the issues of work-based learning and Teaching Factories in vocational education were further reinforced through studies on Work-Based Learning in the Industry 4.0 era and Teaching Factory IR 4.0 (Yoto et al., 2019; Yondri et al., 2020).

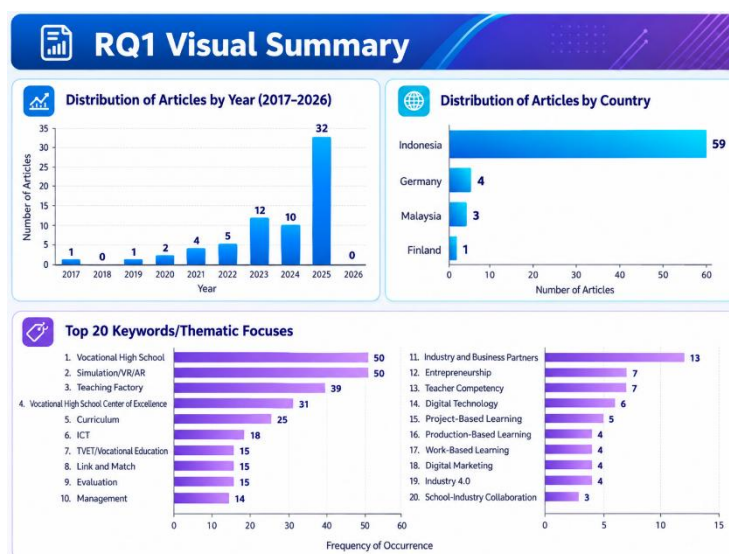


Figure 2. Distribution of articles by year, country, keywords/thematic focuses

Publication peaked in 2025, with 32 articles. This reflects the fact that issues such as Teaching Factory, Centers of Excellence for Vocational High Schools (SMK), link and match, and the integration of digital technology in vocational education are increasingly prominent in the latest literature. In 2025, the articles extend beyond discussing the Teaching Factory as a learning model, linking it as well to Teaching Factory management, program evaluation, guidebook development, teacher competencies, industry collaboration, digital products, digital marketing, and Industry 4.0 talent (Cholis et al., 2025; Elisabet et al., 2025; Hastuti et al., 2025; Mazlan et al., 2025a, 2025b, 2025c; Nanda et al., 2025; Prihantoro et al., 2025; Shofiana & Tohirin, 2025). During the 2023–2024 period, the focus of research began to shift markedly toward the context of Vocational High Schools (SMK) of Excellence, particularly through discussions on curriculum, the 8+i link-and-match initiative, strengthening DUDIKA, and the role of school principals in the development of Teaching Factories (Asngad et al., 2023; Akyuwen et al., 2023; Muharam et al., 2024; Samengasbumi et al., 2024; Sulistyawati & Mulyono, 2024). The annual trend accordingly points to the fact that this topic is evolving conceptually while also becoming increasingly linked to the practical implementation of the SMK PK program in Indonesia.

By country, the majority of articles originate from or discuss the Indonesian context, totaling 59 articles. This is understandable since the Vocational High School Center of Excellence corresponds to the SMK Pusat Keunggulan, which is the context of Indonesia's vocational education policy. Indonesian articles frequently discuss the implementation of SMK PK, Teaching Factory, TeFa, link and match, DUDIKA collaboration, curriculum, and the improvement of SMK graduate quality (Ahmanda et al., 2022; Sholihah, 2022; Asngad et al., 2023; Elisabet et al., 2025; Nuryanti et al., 2025). Meanwhile, articles from Germany, Malaysia, and Finland primarily reinforce the international perspective on TVET, Learning Factories, Work-Based Learning, Industry 4.0, ICT competence, and virtual reality in vocational training. For example, Roll and Ifenthaler (2021) discuss Learning Factories 4.0 in technical vocational schools, Riemann et al. (2020) discuss the opportunities and challenges of virtual reality in vocational training, Vilppola et al. (2022) discuss ICT competencies in work-based vocational teacher training, while Mazlan et al. (2025a, 2025b, 2025c) discuss the Industry 4.0 talent framework for TVET students through Work-Based Learning. Two further German contributions round out this international group: Meinokat and Wagner (2025) examine classroom disruptions and classroom management in learning factory settings at vocational schools, and Goller et al. (2021) discuss the digital knowledge and learning requirements of German dairy farmers as an adjacent vocational-training context.

Based on the keywords and thematic focus, it is evident that the most dominant studies relate to Vocational High Schools (SMK), Teaching Factories, Centers of Excellence for SMK, as well as supporting themes such as curriculum, ICT, link and match, evaluation, management, and DUDIKA/DUDI/IDUKA. This suggests that the analyzed literature discusses Teaching Factories as a learning model while also situating them within the broader

vocational education ecosystem, namely curriculum, school management, industry collaboration, and graduate quality improvement. Interestingly, the keywords Simulation/VR/AR appear very frequently in the reference files. This shows that digital technology aspects in the literature appear both through general terms like “digital technology” or “ICT/TIK” and through more applied forms of technology, such as simulation, virtual reality, augmented reality, mobile simulators, and digital learning systems. The article by Nanda et al. (2025), for example, directly developed a mobile QR-EFI simulator within the Problem-Based Teaching Factory model, while Riemann et al. (2020) discussed the opportunities and challenges of virtual reality in vocational training.

In general, the results of RQ1 indicate that the trend in publications on Teaching Factory–based vocational learning, digital technology integration, and Vocational High School Centers of Excellence has increased markedly during the 2023–2025 period. The year 2025 had the highest number of publications in the reviewed corpus, with 32 articles. This underscores the fact that the issues of Teaching Factories and Vocational High School Centers of Excellence are currently a major focus in vocational education research, particularly in the context of strengthening link and match initiatives, industry partnerships, curriculum development, and digital transformation. Geographically, Indonesia’s dominance suggests that this research is particularly strong at the national level, largely because Vocational High School Centers of Excellence are a distinctive Indonesian policy. However, Scopus articles from Germany, Malaysia, and Finland provide an important international foundation by expanding the discussion toward Learning Factory 4.0, TVET, Work-Based Learning, ICT competence, virtual reality, and Industry 4.0 talent (Roll & Ifenthaler, 2021; Vilppola et al., 2022; Mazlan et al., 2025a, 2025b, 2025c). Thematically, the analyzed articles can be grouped into several main focuses. First, studies on Teaching Factory/TeFa extensively discuss implementation, evaluation, management, model development, and their impact on graduate quality. Second, studies on Vocational High Schools of Excellence are largely associated with curriculum, link and match, DUDIKA collaboration, and strengthening the quality of vocational education. Third, studies on digital technology appear in the form of ICT, Industry 4.0, digital marketing, digital products, simulators, VR/AR, and Learning Factory 4.0.

Thus, the answer to RQ1 is that publications on this topic are growing stronger, but still reveal a notable gap: not all studies integrate Teaching Factory, digital technology, and Centers of Excellence in Vocational High Schools (SMK PK) into a single, cohesive framework. Some articles still focus on Teaching Factory without digitalization, some discuss Vocational High Schools of Excellence without delving deeply into Teaching Factory, and others address digital technology in vocational education without directly linking it to the Vocational High School of Excellence program. This persistent fragmentation across the three literatures is precisely the gap this systematic review addresses.

Digital Technology and Digitalization Domains Integrated into Teaching Factory–Based Vocational Learning

Based on an analysis of 67 articles, the integration of digital technology into Teaching Factory-based vocational learning does not appear in a uniform form. Some articles explicitly mention digital technologies such as ICT, digital marketing, digital products, mobile simulators, virtual reality, Learning Factory 4.0, Industry 4.0, learning management systems, and ISO-based digital systems. However, other articles discuss technology more indirectly, for example, through the strengthening of industry-based curricula, production-based learning, the development of Teaching Factories, or the enhancement of teacher and school capacity. Overall, the digital technology and digitalization domains found in the article corpus are classified into the typology presented in Table 2, which organizes the corpus into six categories rather than reporting each article’s technology use individually.

ICT and digital competencies constitute the most frequently cited domain in the corpus, appearing on both the student and teacher sides of vocational learning. On the student side, ICT is positioned as part of a creative economy learning model in vocational high schools (Swaramarinda & Nurmallasari, 2017); on the teacher side, ICT competencies are treated as a crucial component of work-based vocational teacher training (Vilppola et al., 2022). Together, these uses indicate that digital technology functions as a learning tool for students and, equally, as an integral part of vocational teachers’ professional competencies.

Digital marketing, digital business, and digital products form the second major category, closely aligned with the Teaching Factory context because TeFa products must ultimately be marketed and connected to customer needs rather than simply produced. Articles in this category range from teacher-facing digital marketing training for Vocational High Schools of Excellence (Septianingsih, 2023) and digital marketing literacy embedded in a boutique-fashion Teaching Factory (Muhardono & Meliza, 2023), to student-run digital businesses framed as part of the Pancasila student profile (Sholihatinnisa et al., 2021). In this category, digital technology functions as an integral part of production, entrepreneurship, and marketing activity rather than merely a learning medium.

Table 2. Typology of digital technologies and digitalization domains in teaching factory-based vocational learning

No.	Digital Technology / Digitalization Domain	Form of Integration in Articles	Source
1	ICT and digital competencies	Used to support learning, strengthen teacher competencies, develop learning models, and prepare teachers to face technological changes.	Swaramarinda and Nurmalasari (2017); Vilppola et al. (2022); Setiawan et al. (2025); Hastuti et al. (2025)
2	Digital marketing, digital business, and digital products	Used to support the marketing of Teaching Factory products, the development of student entrepreneurship, and the strengthening of school production activities to connect with the business world.	Septianingsih (2023); Muhardono and Meliza (2023); Sholihatinnisa et al. (2021); Shofiana and Tohirin (2025); Cahyadi and Respati (2025)
3	Digital simulations, virtual reality, and mobile simulators	Used to provide practical experiences that resemble the industrial world, strengthen technical skills, and provide a safer, more flexible, and contextual learning experience.	Riemann et al. (2020); Nanda et al. (2025); Setiadi et al. (2025)
4	Industry 4.0, IR4.0, Learning Factory 4.0, and smart factory orientation	Used as a framework to prepare TVET/vocational high school students for the demands of modern industry, automation, production digitization, and future work competencies.	Yoto et al. (2019); Yondri et al. (2020); Roll and Ifenthaler (2021); Wahjusaputri and Bunyamin (2022); Mazlan et al. (2025a, 2025b, 2025c)
5	Learning Management System, technology platforms, and school digital systems	Used to support learning management, service system development, documentation, and the management of Teaching Factory activities.	Yondri et al. (2020); Sumantri and Akmal (2023); Al Hasan and Hermawan (2025)
6	Technology for innovative works and product commercialization	Used to support innovation, technological works, patent potential, and the enhancement of the commercial value of products/services developed at vocational high schools.	Sunyoto et al. (2024); Cahyadi and Respati (2025); Shofiana and Tohirin (2025)

Note. Representative citations shown per category; the complete list of all 67 corpus articles is provided in the Appendix.

Digital simulations, virtual reality, and mobile simulators form the third category, valued primarily for providing practical experiences that closely mimic the workplace when physical facilities, training costs, or safety risks would otherwise constrain hands-on practice (Riemann et al., 2020). A more applied illustration is the mobile QR-EFI simulator developed within a Problem-Based Teaching Factory model to strengthen students' 4C skills (Nanda et al., 2025), which is particularly representative of the convergence this review seeks to map: Teaching Factory, digital technology, problem-based learning, and 21st-century skill development combined within a single intervention.

The fourth category encompasses Industry 4.0, Learning Factory 4.0, IR4.0, and smart factory orientation. This category shows that digitalization within the Teaching Factory extends beyond specific tools to involve a paradigm shift in competencies. Yoto et al. (2019) discuss Work-Based Learning in the Industry 4.0 era; Yondri et al. (2020) develop the syntax of the Teaching Factory IR 4.0; Roll and Ifenthaler (2021) discuss Learning Factories 4.0; Wahjusaputri and Bunyamin (2022) similarly document a competency-based Teaching Factory model for vocational secondary schools in Central Java, Indonesia; while Mazlan et al. (2025a, 2025b, 2025c) develop an Industry 4.0 talent framework for TVET students. From this, it can be understood that technology-based Teaching Factories must prepare students for current jobs as well as for increasingly automated, digitized, and data-driven industrial work patterns.

Learning management systems, technology platforms, and school digital systems form the fifth category, oriented toward institutional and administrative functions rather than direct classroom instruction. This category includes a learning management system embedded in an IR 4.0 Teaching Factory model (Yondri et al., 2020), an ISO

25010-based rental system (Al Hasan & Hermawan, 2025), and technology platforms guiding schools toward Vocational High School with Specialized Programs status (Sumantri & Akmal, 2023), a mentoring approach echoed in a related SMK PK program focused on agribusiness competency development (Sumantri et al., 2024). This category shows that digital integration in the Teaching Factory extends beyond classroom learning media into service management, documentation, production management, and administrative processes.

A sixth domain is technology for innovative work and product commercialization, covering patentability and the commercial value of student-developed products or services (Sunyoto et al., 2024); it completes the typology in Table 2. This domain is comparatively thin in the corpus, supported primarily by a single dedicated study rather than a cluster of converging evidence, and is reported here for completeness; its evidentiary weight is markedly lower than that of the first five domains, and future research documenting commercialization and intellectual-property practices in Teaching Factory settings would strengthen this category considerably.

Digital technology in Teaching Factory-based vocational learning thus manifests across a wide range of forms, including ICT, digital marketing, digital business, digital products, simulators, virtual reality, Learning Factory 4.0, Industry 4.0, LMS, technology platforms, and school digital systems, although the pedagogically most powerful of these remain those directly linked to production activities, industrial practices, work simulations, and student competency development.

Pedagogical Integration of Digital Technology into Teaching Factory, Learning Factory, Production-Based Learning, Work-Based Learning, or Industry-Based Vocational Learning

Analysis results indicate that the integration of digital technology in Teaching Factory and industry-based vocational learning is carried out through several pedagogical patterns. RQ3 is concerned specifically with the classroom- and workshop-level mechanisms of this integration, that is, how digital technology is embedded into the teaching–learning process itself, which is analytically distinct from RQ4, presented afterward, which examines the institutional-level outcomes of this same integration for the SMK PK program. These patterns are important because digital technology functions here as an integral part of instructional design rather than as a tool alone. In the corpus of articles, digital technology is utilized to enhance authentic learning experiences, project-based learning, production-based learning, industry collaboration, teacher training, program evaluation, and school entrepreneurship. Of these, the first three approaches discussed below (authentic production-based learning, Project/Problem-Based Learning, and Work-Based Learning) constitute direct classroom- and workshop-level pedagogical integration, whereas the remaining three (teacher training and capacity building, evaluation/management/quality assurance, and entrepreneurship/commercialization) function as supporting implementation mechanisms that shape the conditions under which classroom-level integration occurs, rather than being pedagogical techniques in the narrow sense. Where a study is cited under both RQ3 and RQ4, each research question draws on a distinct fact reported in that study: RQ3, below, reports what the intervention does inside the classroom or workshop, while RQ4, presented afterward, reports what that same intervention is found to contribute at the institutional level; no single reported finding is used as evidence for both questions.

The first pedagogical pattern embeds authentic, production-based tasks directly into the workshop sequence, so that students move through the same production, service, and quality-control steps found in industry rather than a simplified classroom simulation. This is achieved by scheduling fieldwork practice alongside production-based coursework (Elisabet et al., 2025), sequencing workshop stages around a simulated industrial production cycle (Setiadi et al., 2025), embedding a mobile QR-EFI simulator directly into problem-based task design (Nanda et al., 2025), and adapting the same production-based structure to specific vocational tracks such as the laundry-industry subject (Nastiti, 2022) and general Teaching Factory practice (Purwaningtias & Chamami, 2025). Read together, these accounts describe a classroom-level mechanism: technology and authentic task design working together so that the resemblance to an industrial work system extends to the workshop itself, and not to its stated goals alone. What these same interventions are separately found to achieve at the school or program level is addressed under RQ4.

The second pattern structures learning around projects, problems, and product development rather than single-lesson tasks. This takes the form of a cross-subject Teaching Factory guidebook that threads production tasks through general and vocational courses alike (Cholis et al., 2025), a project-based management structure built on the New Teaching Factory model (Suranto et al., 2023), and problem-based tasks scaffolded through a mobile simulator (Nanda et al., 2025). Across these accounts, digital technology functions as the tool through which students design, test, refine, and present a product or solution, rather than as an add-on to an otherwise unchanged lesson plan.

Table 3. Pedagogical integration patterns of digital technology in Teaching Factory-based vocational learning

No.	Pedagogical Patterns	Integration	Form of Implementation	Source
1	Integration in authentic, production-based learning		Technology is used to support production processes, services, work simulations, and learning that resembles industrial practices.	Elisabet et al. (2025); Cholis et al. (2025); Setiadi et al. (2025); Nanda et al. (2025)
2	Integration in Project-Based Learning, Problem-Based Learning, and Production-Based Learning		Technology is integrated into projects, problem-solving, product development, and the design of cross-curricular learning experiences.	Cholis et al. (2025); Suranto et al. (2023); Nanda et al. (2025); Setiadi et al. (2025)
3	Integration in Work-Based Learning and School–Industry Collaboration		Technology is used to connect school learning with industry needs, work competencies, and the demands of Industry 4.0.	Ramanda et al. (2025); Yoto et al. (2019); Mazlan et al. (2025a, 2025b, 2025c); Vilppola et al. (2022)
4	Integration through training, mentoring, and teacher capacity building		Technology is introduced through digital marketing training, TeFa mentoring, focus group discussions (FGDs), workshops, and teacher competency enhancement.	Septianingsih (2023); Muhardono and Meliza (2023); Setiawan et al. (2025); Wahyudi et al. (2025); Ulfa and Yudianto (2025)
5	Integration in Teaching Factory evaluation, management, and quality assurance		Technology and evaluative approaches are used to map the implementation, facility readiness, process quality, and outputs of the Teaching Factory.	Prihantoro et al. (2025); Baharsyah and Irfan (2024); Husna et al. (2025); Hastuti et al. (2025)
6	Integration in entrepreneurship and commercialization of school products		Technology is used to expand marketing, develop digital businesses, test business models, and strengthen student entrepreneurship.	Sholihatinnisa et al. (2021); Septianingsih (2023); Muhardono and Meliza (2023); Cahyadi and Respati (2025); Shofiana and Tohirin (2025)

The third pattern situates learning inside Work-Based Learning arrangements and direct school–industry collaboration. Ramanda et al. (2025) structure a Building Information Modeling (BIM) Design program around contextual, industry-embedded tasks; Mazlan et al. (2025a, 2025b, 2025c) build Work-Based Learning placements around an Industry 4.0 talent framework for TVET students; Vilppola et al. (2022) embed ICT-focused tasks directly into work-based teacher-training placements themselves, rather than teaching ICT skills separately beforehand; and Srirahayu et al. (2025) document a comparable industry-collaboration mechanism for building Visual Communication Design capacity through a joint education-industry partnership. This pattern extends technology integration beyond the student, situating teachers and the industry partnership itself as part of the same work-based mechanism; the competency and satisfaction outcomes these placements are associated with are addressed as an RQ4 contribution rather than repeated here.

The fourth pattern channels technology integration through structured training, mentoring, and capacity-building activities aimed at teachers themselves, rather than assuming teachers already possess the needed skills. Concretely, this includes dedicated digital marketing training sessions (Septianingsih, 2023), digital marketing literacy workshops embedded in a boutique-fashion Teaching Factory (Muhardono & Meliza, 2023), a structured curriculum combining Teaching Factory instructional technique with scientific-research skill-building (Setiawan et al., 2025), and recurring mentoring and workshop cycles documented across several Centers of Excellence, including at SMK Negeri 8 Purworejo (Widiyatmoko et al., 2025; Wahyudi et al., 2025; Ulfa & Yudianto, 2025) and in a Smart Rapid Service management-administration workshop for motorcycle-business competency (Ariwibowo et al., 2025). The mechanism common to all of these is scheduled, direct instruction aimed at teachers rather than students; whether this training accumulates into institutional capacity over time is treated separately under RQ4.

The fifth pattern uses evaluation frameworks and monitoring routines to track the Teaching Factory's day-to-day operation. Prihantoro et al. (2025) apply the CIPP framework to examine context, input, process, and product; Baharsyah and Irfan (2024) assess implementation specifically within the Agribusiness, Food Crops, and Horticulture program; Husna et al. (2025) apply a Goal-Oriented evaluation model to the Refrigeration and Air Conditioning field; Hastuti et al. (2025) document the routine monitoring activity, scheduling, and facility-

readiness checks that keep a Teaching Factory running day to day; Ramzi and Sutadji (2025) apply the CIRO model to the link-and-match policy; and Satria and Ramadani (2025) evaluate a machining-technique program. The mechanism common to these accounts is a recurring evaluation cycle embedded into ongoing operations, tracking curriculum alignment, facility readiness, process quality, and learning outcomes at the level of daily practice; what this operational monitoring contributes to the school's broader managerial sustainability is addressed under RQ4.

The sixth pattern embeds entrepreneurial tasks directly into the production workshop, treating commercialization as a learning activity rather than an outcome measured afterward. This includes running a digital-business activity as coursework (Sholihatinnisa et al., 2021), incorporating digital-marketing tasks into teacher- and student-facing Teaching Factory activities (Septianingsih, 2023; Muhardono & Meliza, 2023), assigning Business Model Canvas exercises and market-testing tasks as part of a Participatory Action Research design (Cahyadi & Respati, 2025), building digital-product development into a pesantren-based curriculum (Shofiana & Tohirin, 2025), structuring a partnership-based agribusiness business-model exercise (Moata et al., 2023), and running a partnership-and-entrepreneurship program within the fashion expertise track (Wulandari & Sudira, 2025). Read as a set, these accounts describe entrepreneurship as something students practice inside the Teaching Factory; the revenue, market, and reputational payoff of these same activities is discussed separately as an RQ4 contribution.

Taken together, the six pedagogical patterns identified under RQ3 show that digital technology is integrated through authentic learning, projects, problem-solving, work-based placements, teacher training, operational evaluation, and classroom-level entrepreneurship. Each pattern operates at the level of what happens inside the teaching-learning process itself; the institutional-level outcomes these same patterns are reported to produce for the SMK PK program are taken up next, under RQ4.

Contributions of Digital Technology Integration in Teaching Factory-Based Vocational Learning for Strengthening the Vocational High School Center of Excellence Program

The reviewed literature reports that the integration of digital technology into Teaching Factory-based vocational education contributes to strengthening the Center of Excellence Vocational High School Program in several ways. Whereas RQ3 examined the pedagogical mechanisms of integration at the classroom and workshop level, RQ4 shifts the unit of analysis to the institutional level: it asks what these mechanisms contribute to the SMK PK program as a policy initiative, including their downstream effects on the school's external partnerships, aggregate human-capital outcomes, managerial capacity, revenue-generating capacity, and public identity, rather than describing the teaching methods themselves. This contribution spans curriculum enhancement, industry collaboration, teacher competencies, school management, entrepreneurship, and graduate readiness, in addition to student learning. As established in the Method, each contribution below draws on a fact distinct from its RQ3 counterpart even where the same study is cited in both places: RQ3 reports the classroom- or workshop-level mechanism, RQ4 reports the institutional-level outcome that mechanism is found to produce.

The first contribution operates at the institutional-policy level: the strengthening of link and match with the industrial world as a formal, school-wide partnership arrangement, distinct from the classroom-level Work-Based Learning practice discussed under RQ3. Many accounts position curriculum alignment, industrial training (PKL), and Teaching Factory activity as integral, policy-mandated components of Center of Excellence implementation itself (Elisabet et al., 2025), most often organized through the 8+i link-and-match concept at multiple SMK PK sites (Ahmanda et al., 2022; Sholihah, 2022; Astuti et al., 2025; Tessa & Humaedi, 2023; Fahmayani, 2021), with partnership-management responsibility specifically examined at the school-administration level (Ningtias et al., 2025; Tanjung et al., 2025). From this group of articles, digital technology can be understood as a means to strengthen this standing institutional connection between schools and industry, especially as curriculum, practical training, and Teaching Factory (TeFa) products must keep adapting to workforce change.

The second contribution is the enhancement of students' technical and non-technical competencies as an aggregate outcome, rather than a single lesson's objective. This outcome is reported for a mobile QR-EFI simulator associated with stronger 4C-skill results (Nanda et al., 2025), a production-based model associated with soft-skill gains (Setiadi et al., 2025), a documented relationship between Teaching Factory participation, fieldwork practice, and work readiness (Endrastiti & Sholikhah, 2024), and graduates reported as more work-ready and entrepreneurial after Teaching Factory participation (Sugianto & Casmudi, 2022). Read together, these accounts treat competency development as a claimed downstream result of the classroom-level mechanisms described in RQ3, most consistently where technology is used in simulation, production, projects, or product marketing.

Table 4. Contributions of digital technology integration in teaching factory to the strengthening of center of excellence vocational high schools

No.	Contribution	Explanation	Source
1	Strengthening link and match with industry	Technology and Teaching Factories help schools align the curriculum, practices, and student competencies with the needs of the business and industrial sectors.	Elisabet et al. (2025); Ahmanda et al. (2022); Sholihah (2022); Astuti et al. (2025); Tessa and Humaedi (2023)
2	Enhancing students' technical competencies, soft skills, 4Cs, and work readiness	Digital technology supports authentic practice, work simulations, problem solving, collaboration, and the strengthening of work skills.	Nanda et al. (2025); Setiadi et al. (2025); Endrastiti and Sholikhah (2024); Sugianto and Casmudi (2022)
3	Strengthening teacher competencies and digital pedagogical readiness	Teachers receive training, mentoring, and experience in managing TeFa-based learning, digital marketing, ICT, and technology projects.	Septianingsih (2023); Setiawan et al. (2025); Vilppola et al. (2022); Swaramarinda and Nurmalasari (2017)
4	Supporting Teaching Factory management and sustainability	Technology and systematic evaluation help schools manage production, facilities, services, documentation, and the quality of learning.	Hastuti et al. (2025); Mujab et al. (2025); Ngusman et al. (2023); Prihantoro et al. (2025)
5	Promoting digital entrepreneurship and the commercialization of school products	Digital marketing, digital business, and digital products help students understand the production chain through to marketing.	Sholihatinnisa et al. (2021); Septianingsih (2023); Muhardono and Meliza (2023); Cahyadi and Respati (2025); Shofiana and Tohirin (2025)
6	Strengthening the identity of SMK PK as a reference school and center of excellence	Technology-based Teaching Factories make SMK PK better prepared to serve as a model for industry-based vocational education development.	Asngad et al. (2023); Akyuwen et al. (2023); Nuryanti et al. (2025); Sulistyawati and Mulyono (2024)

The third contribution operates at the level of accumulated institutional capacity: the school-wide stock of teachers' competencies and digital pedagogical readiness built up over time, not the individual training episodes RQ3 examines. Across the corpus, this accumulated readiness is reported as a downstream result of digital marketing training (Septianingsih, 2023), Teaching-Factory-and-research-oriented teacher preparation (Setiawan et al., 2025), work-based ICT-competency development (Vilppola et al., 2022), and ICT positioned within an entrepreneurship-learning model from the earliest years of the corpus (Swaramarinda & Nurmalasari, 2017). This contribution matters because teachers are the primary agents translating digital technology into meaningful learning, and it is their accumulated readiness, not any single training event, that determines whether the SMK PK program can sustain digital integration over time.

The fourth contribution sits at the institutional level: the school's overall managerial capacity and long-run sustainability, a different vantage point from RQ3's evaluation pattern, where monitoring was examined as a day-to-day operational practice rather than a school-wide outcome. This institutional capacity is reported specifically for Teaching Factory management at a Center of Excellence in Temanggung (Hastuti et al., 2025), management within the hospitality sector (Mujab et al., 2025), management improving Audio-Video Engineering quality (Ngusman et al., 2023), and a CIPP-based finding that sustained implementation must jointly consider context, input, process, and outcome (Prihantoro et al., 2025). This implies that digital technology can strengthen a Vocational High School's overall standing when it is used in production management, documentation, evaluation, and quality control collectively, and not in learning activities alone.

The fifth contribution moves the lens outward to the school's economic and reputational standing: how far digital entrepreneurship and product commercialization translate into revenue, market visibility, and community

reputation for the institution as a whole, where RQ3's parallel pattern examined entrepreneurship only as a classroom teaching activity. This institutional payoff is reported in connection with digital businesses supporting the Pancasila student profile (Sholihatinnisa et al., 2021), digital marketing positioned as a shared teacher-and-student competency supporting product marketing (Septianingsih, 2023; Muhardono & Meliza, 2023), Business Model Canvas and market-testing results feeding into commercialization decisions (Cahyadi & Respati, 2025), and digital-product development translating into pesantren-based entrepreneurial income (Shofiana & Tohirin, 2025). Taken together, these contributions point to an institutional payoff, market understanding and business viability, that extends beyond the pedagogical activity itself.

The sixth contribution focuses on strengthening the identity of Vocational High Schools (SMK) of Excellence as model schools. The SMK of Excellence program aims to make schools more outstanding, adaptive, and relevant to industry. Several studies locate this identity-building work in specific institutional levers: principal leadership in developing Teaching Factories at SMK of Excellence in Ambon City (Akyuwen et al., 2023), curriculum development innovation within the SMK of Excellence program (Asngad et al., 2023), collaboration management between the Center of Excellence Vocational High School and the business and industrial sectors (Nuryanti et al., 2025), and integrated quality management within the 8+i link-and-match program (Sulistyawati & Mulyono, 2024). Sarifudin and Suhri (2024) similarly describe Teaching Factory-based school revitalization as a reference model for private vocational schools in Pamekasan, Wardani and Raihani (2024) examine principal leadership at SMK PK Muhammadiyah 2 Pekanbaru, and Valentine (2025) discusses collaboration management at a Center of Excellence school in Jakarta. In this context, the integration of digital technology within the Teaching Factory is reported to support the strengthening of the Center of Excellence Vocational High School (SMK PK) as a model for vocational schools that are more responsive to industrial needs and technological advancements.

Altogether, RQ4 is answered by the finding that the integration of digital technology into Teaching Factory-based vocational learning is reported to be associated with link and match, student competencies, teacher competencies, Teaching Factory management, digital entrepreneurship, and the strengthening of the identity of the Center of Excellence Vocational High School. These contributions reinforce the argument that digital Teaching Factories may serve as an important strategy in the transformation of the Center of Excellence Vocational High School.

Challenges, Gaps, and Future Directions in Integrating Digital Technology into Teaching Factory-Based Vocational Learning

Analysis results indicate that the integration of digital technology into Teaching Factory-based vocational learning still faces several challenges. These challenges arise at the conceptual, pedagogical, institutional, technological, industry collaboration, and outcome evaluation levels. Additionally, there is a research gap because few articles have fully integrated Teaching Factory, digital technology, and Center of Excellence Vocational High Schools into a comprehensive model. For clarity, the seven patterns discussed below are organized into two families rather than treated as a single undifferentiated list: three concern evidence gaps, that is, aspects the reviewed literature itself has not adequately investigated (the first, fifth, and seventh patterns, concerning uneven digital-integration coverage across studies, limited outcome evaluation, and terminological fragmentation, respectively); the remaining four concern challenges reported within the field itself, that is, implementation barriers described by the primary studies (the second, third, fourth, and sixth patterns, concerning teacher readiness, infrastructure, industry collaboration, and product quality control). A separate closing paragraph then turns to directions for future research.

The first challenge is the uneven integration of digital technology in Teaching Factory studies. From the corpus of articles, many robust national studies discuss Teaching Factory, TeFa, Centers of Excellence for Vocational High Schools (SMK), link and match, and industry collaboration, but not all explicitly address the integration of digital technology. For example, Muharam et al. (2024), Baharsyah and Irfan (2024), Prihantoro et al. (2025), and Husna et al. (2025) discuss the evaluation and effectiveness of Teaching Factory, but their primary focus remains on program implementation, graduate quality, CIPP, or goal-oriented evaluation. Artha et al. (2024) likewise document the implementation of the Merdeka curriculum, Teaching Factory, and industrial internships at SMK Negeri 3 Solok without a specific digital-technology focus. Meanwhile, articles such as Septianingsih (2023), Muhardono and Meliza (2023), Nanda et al. (2025), Riemann et al. (2020), and Yondri et al. (2020) more explicitly discuss digital marketing, simulators, VR, LMS, and Industry 4.0. This gap points to the fact that digital integration in Teaching Factories has not yet become mainstream across all studies.

The second challenge is teacher readiness and digital competence. Several articles indicate that teachers are key actors in the implementation of Teaching Factory and digital technology. Septianingsih (2023) highlights the need

to enhance teachers' competence in digital marketing. Setiawan et al. (2025) discuss training to develop teachers' competence in Teaching Factory-based learning. Vilppola et al. (2022) emphasizes the importance of vocational teachers' ICT competencies in work-based training. Asngad et al. (2023) also note that teachers' adaptation to technology is one of the challenges in developing the curriculum for Vocational High Schools of Excellence. This means that digital technology integration may be constrained when teachers lack the pedagogical, technical, and managerial readiness to use it in authentic learning.

The third challenge is facilities, infrastructure, and practical equipment. Elisabet et al. (2025) indicate that the implementation of the Teaching Factory still requires updates to practical facilities to optimize learning outcomes. Prihantoro et al. (2025) found that regarding inputs, facilities and infrastructure remain inadequate due to budget constraints and a lack of equipment calibration. Widiastuti et al. (2023) similarly found that infrastructure facilities, alongside teacher quality and industry-partner involvement, significantly influence the achievement of Center of Excellence status among vocational high schools in Yogyakarta. This issue is critical because a digital-based Teaching Factory requires equipment that is both available and aligned with industry standards. If practical facilities are not up-to-date, the Teaching Factory risks becoming merely a standard school simulation rather than a true representation of the real-world workplace.

The fourth challenge is that industry collaboration is not always substantive. Asiah (2025) highlights that synergy between vocational high schools (SMK), the government, and industry is not yet optimal due to conflicting interests, weak coordination, limited capacity, and a lack of evaluation. Some collaborations also risk remaining mere formalities of a Memorandum of Understanding (MoU) without tangible follow-through. These findings align with articles on the 8+i link-and-match framework, such as those by Ahmanda et al. (2022), Sholihah (2022), Astuti et al. (2025), Putra (2023), and Tessa and Humaedi (2023), which position industry collaboration as the key to strengthening vocational high schools (SMK PK). In the context of digital integration, industry collaboration needs to go further, specifically toward curriculum co-design, real-world projects, industry mentors, product standards, and joint competency evaluations.

The fifth challenge is the limited evaluation of learning impacts. Many articles in the corpus employ qualitative, descriptive, evaluative, mentoring, community service, or case study approaches. While these approaches are essential for understanding the context, they are insufficient for robustly measuring the impact of digital technology integration on student learning outcomes. Some articles have moved toward impact testing, for example, Nanda et al. (2025) with R&D and effectiveness testing of the mobile QR-EFI simulator, Roll and Ifenthaler (2021) with a staged competency test, and Endrastiti and Sholikhah (2024) who tested the influence of Teaching Factory and PKL on work readiness. However, overall, longitudinal studies, mixed methods, and stronger outcome measurements are still needed.

The sixth challenge is product quality control in the Teaching Factory. Prihantoro et al. (2025) indicate that product aspects remain a weak point because product quality does not yet fully meet industry standards, the school's quality control system is not yet robust, and project-based assessment is not yet optimal. Cholis et al. (2025) also note that evaluation documentation needs to be strengthened in the development of the Teaching Factory guidebook. In the context of digital TeFa, quality control should be strengthened through digital documentation systems, industry-standard-based rubrics, production process tracking, and product validation by industry partners.

The seventh challenge is the fragmentation of terminology and conceptual models. In the corpus of articles, the terms used are highly diverse: Teaching Factory, TeFa, Learning Factory, Work-Based Learning, Production-Based Learning, Project-Based Learning, Industry-Based Learning, and Learning Factory 4.0. This diversity of terms reflects the richness of literature but also poses challenges in establishing a consistent conceptual framework. Riemann et al. (2020) and Roll and Ifenthaler (2021) predominantly use the term "learning factory" in an international context, whereas national articles frequently use "Teaching Factory" or "TeFa." Mazlan et al. (2025a, 2025b, 2025c) extensively discuss Work-Based Learning and Industry 4.0 talent within TVET. Therefore, future research needs to develop a framework capable of bridging these terms within the context of the Vocational High School Center of Excellence.

Research direction. Based on these challenges and evidence gaps, the direction for future development is to build a Digital Teaching Factory model for Vocational High School Centers of Excellence. This model must integrate several elements: industry-based curriculum, authentic learning, digital technology, simulation, digital marketing, production management systems, DUDIKA collaboration, teacher competencies, quality assurance, and student achievement evaluation. With such a model, the Teaching Factory moves beyond a production activity within the

school to become a digital learning ecosystem connecting students, teachers, schools, industry, technology, and the job market.

Discussion

Publication trends and thematic focuses of studies on Teaching Factory–based vocational learning, digital technology integration, and Vocational High School Center of Excellence from 2017 to 2026

The sharp rise in publications after 2022 is better explained by policy timing than by a sudden rise in scholarly interest in Teaching Factory or digital technology as topics, since both had already appeared earlier in the review period (Swaramarinda & Nurmalarasari, 2017; Yoto et al., 2019). A more likely explanation is policy diffusion. The SMK Pusat Keunggulan program was launched by Indonesia's Ministry of Education, Culture, Research, and Technology in 2021, and research on a new national policy typically appears one to three years after schools begin implementing it, once there is something concrete for researchers to document and evaluate. This review did not test publication lag or policy timing directly, so this explanation should be read as a plausible interpretation rather than a proven cause.

This pattern also shows up in the composition of the corpus. Indonesian-authored articles dominate, while the smaller international group (Riemann et al., 2020; Vilppola et al., 2022; Mazlan et al., 2025a, 2025b, 2025c) tends to focus on transferable competency frameworks such as Industry 4.0 talent models and Learning Factory 4.0 pedagogy. Few articles draw on both the Indonesian policy literature and the international competency-framework literature at the same time. This points to two research communities working close to the same topic without yet reading each other closely, a gap this review tries to help close.

A similar pattern appears internationally. A review of technology adaptability in vocational education and training reports that research in this area often focuses narrowly on technical skills, with less attention to how well schools and workplaces connect, and that funding differences between public and private VET providers shape what gets studied (Imama et al., 2025). Together with the present findings, this suggests that publication activity in this field tracks funding and policy cycles at least as closely as it tracks technological change itself. In practice, Indonesian SMK PK research would benefit from engaging more directly with this international competency-framework literature instead of developing separately from it.

This shift also shows up as a change in what the research is about, not only in how much of it there is. The earliest articles frame technology and vocational learning in fairly general terms, for instance an ICT-based creative economy learning model for vocational high schools published in 2017 (Swaramarinda & Nurmalarasari, 2017). By 2023 and 2024, articles narrow onto the SMK Pusat Keunggulan policy itself: curriculum development within the program, the 8+i link-and-match initiative, DUDIKA partnership strengthening, and principal leadership in building Teaching Factories (Asngad et al., 2023; Akyuwen et al., 2023; Muharam et al., 2024; Samengasbumi et al., 2024; Sulistyawati & Mulyono, 2024). The growth in publications, in other words, tracks a narrowing of focus toward one specific policy instrument, not simply a general rise in interest in vocational technology.

This has a direct implication for when useful evaluation evidence can be expected. If research on a new policy typically appears one to three years after implementation begins, and the SMK Pusat Keunggulan program expanded in cohorts from 2021 onward, then evidence on how later cohorts of schools use digital technology is only beginning to appear now and will keep accumulating over the next few years. Researchers and funders planning evaluation studies should build this lag into their timelines rather than expect mature, generalizable evidence from schools that have only recently joined the program.

Digital Technology and Digitalization Domains Integrated into Teaching Factory–Based Vocational Learning

The six technology domains identified under RQ2 do not point to one dominant tool, and this is worth explaining rather than treating as a gap. Activity theory (Engestrom, 2001) describes a learning activity as a system made up of several connected parts: the people involved, the tools they use, the goal they are working toward, the wider community, the rules that guide practice, and how tasks are divided among participants. The Teaching Factory literature fits this structure well. ICT and simulators support the relationship between students, teachers, and their tools inside the classroom. Digital marketing platforms support the relationship between students and their customers. Learning management systems and ISO-based digital systems (Al Hasan & Hermawan, 2025) support

the rules and division of labor within the school as an organization. Each technology serves a different part of the same system rather than competing for the same role.

This also explains a pattern that could otherwise look inconsistent. National studies concentrate on classroom- and management-level tools such as ICT, digital marketing, and LMS platforms, while the smaller international group of studies (Riemann et al., 2020; Roll & Ifenthaler, 2021) focuses more on simulation and competency-framework technologies. Rather than describing two unrelated phenomena, this reflects two groups of researchers looking at different parts of the same activity system.

This pattern is broadly consistent with a recent review of digital-skills integration in TVET under Industry 4.0, which also finds that effective integration works through several parallel strategies, including curriculum redesign, new learning technologies, and new pedagogical models, rather than one dominant type of intervention (Kurnia et al., 2026). What stands out in the present corpus is the prominence of digital marketing, digital business, and product commercialization as a technology domain in its own right (Septianingsih, 2023; Muhardono & Meliza, 2023; Sholihatinnisa et al., 2021), a domain that receives far less attention in the broader Industry 4.0 training literature, where virtual reality, simulation, and augmented reality dominate (Anholon et al., 2022). This difference likely reflects the Teaching Factory model itself: because TeFa learning is built around producing and selling real goods or services, not only practicing industrial tasks, digital technology naturally extends into commercialization in a way that general Industry 4.0 training does not need to.

The fifth domain, learning management systems and school digital platforms, also shows a shift over time rather than forming one static category. Earlier accounts describe a learning management system built into a Teaching Factory model without reference to any external standard (Yondri et al., 2020). A more recent account documents a rental management system built specifically to the ISO 25010 software-quality standard (Al Hasan & Hermawan, 2025), and the most recent accounts describe digital platforms used to guide and track a school's progress toward Center of Excellence status itself (Sumantri & Akmal, 2023; Sumantri et al., 2024). Read in sequence, these accounts suggest that administrative and institutional technology in the Teaching Factory is maturing from ad hoc digital tools toward systems referenced against external quality standards and tied directly to accreditation and policy status, a maturation consistent with the publication-timing pattern discussed under RQ1.

In practice, this points to a specific planning step for schools and program managers. Before adding new technology, a school should map which node of the activity system its current tools already serve, classroom instruction, customer-facing marketing, or institutional administration, and treat gaps in coverage as deliberate investment priorities rather than leave them to chance. The sixth domain, technology supporting innovative work and product commercialization, is the clearest such gap in the present corpus: it is documented in only one study (Sunyoto et al., 2024), against five to six sources for every other domain, which makes it a reasonable next target for schools and researchers alike rather than a category to treat as already adequately covered.

Pedagogical Integration of Digital Technology into Teaching Factory, Learning Factory, Production-Based Learning, Work-Based Learning, or Industry-Based Vocational Learning

The strong presence of authentic, production-based approaches among RQ3's six pedagogical patterns fits situated learning theory (Lave & Wenger, 1991), which holds that learning works best through real participation in a community of practice rather than through instruction detached from practice. Seen this way, the Teaching Factory functions as a community of practice in which students move from simple, peripheral tasks toward fuller involvement in production, marketing, and quality control. Digital technology supports this process where real industrial conditions cannot be reproduced at school, for example through mobile simulators that stand in for equipment students would otherwise not be able to access (Nanda et al., 2025).

This also helps explain why teacher training, the fourth pedagogical pattern, matters as much as it does. The TPACK framework (Mishra & Koehler, 2006) holds that effective technology integration needs teachers to combine content knowledge, pedagogical knowledge, and technological knowledge together, not develop them separately. The corpus suggests that many schools have so far strengthened only one or two of these, usually technological infrastructure or subject expertise, without the pedagogical knowledge needed to connect them. This gap also shows up in the type of evidence available: all five sources supporting this pattern (Septianingsih, 2023; Muhardono & Meliza, 2023; Setiawan et al., 2025; Wahyudi et al., 2025; Ulfa & Yudianto, 2025) are community-service or mentoring reports rather than empirical evaluations. Teacher training activity is well documented, but its effect on classroom-level technology use has not yet been measured by any study in this corpus. A similar

pattern appears in the wider vocational teacher-education literature, where digital competence alone is treated as necessary but not sufficient for effective work-based teaching unless it is paired with pedagogical redesign (Vilppola et al., 2022).

The same structural gap appears outside the Indonesian context. A recent review of technology adaptability across VET settings identifies instructor digital competence as a limiting factor, since vocational teachers need more than general digital literacy: they need competencies specific to connecting school and workplace, subject matter, and adaptive pedagogy (Imama et al., 2025). This closely matches the pedagogical-knowledge gap identified through TPACK above, even though the two reviews draw on largely different sets of studies. That two independent reviews reach a similar conclusion supports treating this as a real feature of vocational-technology integration rather than a result specific to this review's sample.

The six pedagogical patterns identified under RQ3 also differ in how far they place students inside a real, rather than school-simulated, work setting, a distinction situated learning theory treats as meaningful. The first pattern keeps production tasks inside the school workshop, sequencing fieldwork practice alongside coursework (Elisabet et al., 2025) or structuring workshop stages around a simulated industrial production cycle (Setiadi et al., 2025). The third pattern moves further, placing students or teachers inside actual Work-Based Learning arrangements with industry, for example a Building Information Modeling design program built around industry-embedded tasks (Ramanda et al., 2025) or ICT tasks embedded directly into work-based teacher-training placements themselves (Vilppola et al., 2022). Situated learning theory would predict that the industry-embedded form supports fuller participation than the workshop-based form, but no study in this corpus directly compares the two, which leaves this as a plausible extension of the theory rather than a tested finding.

In practice, this points to a specific and fairly low-cost step for teacher development: pairing teachers who are technically strong with teachers who are pedagogically strong, so that classroom-level knowledge of how to combine content, pedagogy, and technology develops through mentoring, rather than through further stand-alone digital-marketing or ICT workshops (Septianingsih, 2023; Muhardono & Meliza, 2023) of the kind this corpus already shows accumulating as documented training activity without a corresponding measure of classroom impact.

Contributions of Digital Technology Integration in Teaching Factory-Based Vocational Learning for Strengthening the Vocational High School Center of Excellence Program

The six contributions identified under RQ4 can be read together through the idea of boundary crossing (Akkerman & Bakker, 2011), which describes the work required when people or institutions move between different practice communities, in this case the school and the industry. Seen this way, digital technology in the Teaching Factory works less as a general productivity tool and more as an object that carries meaning on both sides of the school-industry relationship, even when each side uses and interprets it somewhat differently. Digital products made for real customers (Sholihatinnisa et al., 2021; Muhardono & Meliza, 2023), industry-referenced quality standards built into digital documentation (Prihantoro et al., 2025), and shared curriculum materials linked to DUDIKA partnerships (Elisabet et al., 2025; Ahmanda et al., 2022) all work this way.

This also explains a pattern in the evidence that would otherwise look uneven. As shown in the Results, the link-and-match and student-competency contributions rely mostly on empirical implementation studies and evaluations, while the entrepreneurship and SMK PK-identity contributions rely more on community-service and mentoring reports. Sharing a digital tool between school and industry does not by itself guarantee real collaboration; it depends on ongoing negotiation about how that tool is used and valued, a process most articles in this corpus describe only briefly rather than in operational detail. The contributions with the strongest evidence, link-and-match and competency gains, are also the ones where school-industry collaboration is most formally established, through MoUs and curriculum-alignment committees. The contributions with weaker evidence, entrepreneurship and identity-building, are the ones where this collaboration is still informal, which also makes it harder for descriptive studies to capture in detail.

This pattern is not unique to this corpus. A systematic review of Industry 4.0 training reports similarly limited attention to business-model impacts and managerial outcomes compared with technical-skill outcomes (Anholon et al., 2022). This suggests that vocational-technology research in general finds it easier to measure a change in a student's skill set than a change in an institution's standing or a partnership's durability.

This asymmetry is visible directly in how the two ends of RQ4's evidence run are documented. The link-and-match contribution is reported through the 8+i framework replicated across multiple SMK PK sites, with partnership management studied at the level of school administration (Ahmanda et al., 2022; Sholihah, 2022; Astuti et al., 2025; Tessa & Humaedi, 2023; Fahmayani, 2021; Ningtias et al., 2025; Tanjung et al., 2025). The identity-strengthening contribution, by contrast, is reported mainly through single-school leadership accounts: principal leadership in Ambon (Akyuwen et al., 2023), one school in Pekanbaru (Wardani & Raihani, 2024), one school in Jakarta (Valentine, 2025), and one school in Pamekasan (Sarifudin & Suhri, 2024). A contribution documented across many sites through a shared partnership framework is, on the evidence available here, simply better supported than one documented through separate single-site narratives, independent of which contribution schools or policymakers consider more important.

This suggests a concrete step for accreditation bodies and school evaluators: before treating identity-strengthening as an established outcome on par with link-and-match, ask for the same kind of multi-site, partnership-level documentation already available for link-and-match. For researchers, the identity-strengthening claim is well suited to a direct test, for example a multi-site case comparison using the same instruments already applied to link-and-match, rather than continued reliance on single-school leadership accounts.

Challenges, Gaps, and Future Directions in Integrating Digital Technology into Teaching Factory–Based Vocational Learning

The seven challenges identified under RQ5 are easier to understand as signs of two underlying problems than as seven separate issues needing seven separate fixes. Uneven digital-integration coverage (the first challenge) is visible in studies that discuss Teaching Factory implementation and evaluation in detail without a specific digital-technology focus (Muharam et al., 2024; Baharsyah & Irfan, 2024; Artha et al., 2024), alongside inconsistent terminology (the seventh challenge, Riemann et al., 2020; Roll & Ifenthaler, 2021; Mazlan et al., 2025a, 2025b, 2025c); together these point to the field still lacking a shared framework for describing digital Teaching Factory integration across studies. Limited teacher readiness (the second challenge, Asngad et al., 2023) and shallow industry collaboration (the fourth challenge, Asiah, 2025) both point to collaboration that stops at exchanging documents or signing agreements without moving into real joint work, which matches Akkerman and Bakker's (2011) own observation that boundary crossing is often attempted but rarely sustained without someone actively brokering it on both sides. Inadequate facilities (the third challenge, Prihantoro et al., 2025; Widiastuti et al., 2023) and weak product-quality control (the sixth challenge, Prihantoro et al., 2025; Cholis et al., 2025) suggest that, in many schools, the technology and content sides of TPACK are still developed separately from the pedagogical side needed to connect them to student learning.

Grouped this way, the seven challenges reduce to two underlying gaps rather than seven unrelated barriers. The first is a framework gap: challenges one and seven both reflect the absence of a shared way of describing what counts as digital Teaching Factory integration. The second is a depth-of-practice gap: challenges two, three, four, and six show that technology and partnerships exist on paper but are not yet built into daily practice. The fifth challenge, limited outcome evaluation, follows from both gaps rather than forming a third category on its own. Without a shared framework, it is unclear what should be measured, and without depth of practice, there is often not yet enough sustained activity to measure.

The same barrier pattern appears outside the Indonesian SMK PK context. A recent review of VET technology adaptability identifies almost the same group of barriers, institutional readiness, instructor competence, curriculum integration, and industry-education partnership, as the factors that together determine whether digital use actually becomes effective (Imama et al., 2025). A recent review of digital skills in TVET identifies four comparable success factors: teacher digital competence, learner readiness, institutional infrastructure, and policy support (Kurnia et al., 2026). These reviews draw on largely different sets of studies yet arrive at similar barrier categories, which supports treating these barriers as a real, general feature of vocational-technology integration rather than something specific to the SMK PK program or to this corpus. Read together with the pattern above, this suggests that the future direction identified in the Results should not be treated as a list of components to implement side by side, but as an attempt to close the framework gap and the depth-of-practice gap at the same time. A model is only useful once schools share a common vocabulary for it and put it into sustained practice, and defining the model's components alone does not guarantee either.

Looking at the corpus as a whole, rather than research question by research question, also reveals tensions worth stating directly. First, technology availability does not match pedagogical integration: RQ2 shows wide technology diversity, but RQ3's evidence shows integration is strongest for authentic task design and weakest for

teacher TPACK. Schools appear more able to acquire a tool than to build it into their teaching. Second, industry collaboration is reported as a real strength under RQ4, through link-and-match and formal partnerships, and at the same time as a persistent weakness under RQ5, where Asiah (2025) reports conflicting interests, weak coordination, and collaboration that stops at MoUs. Read together, this does not mean the corpus contradicts itself; it means formal partnership is fairly common, while the deeper, curriculum-co-design form of collaboration called for under RQ5 remains comparatively rare. Third, the evidence pattern under RQ4 means that the contribution stated most confidently, the role of Teaching Factory in strengthening SMK PK identity, is also among the least rigorously evidenced. None of these tensions are resolved by the literature reviewed here. They are reported as evidence-based qualifications rather than as flaws in individual studies, since no single study could be expected to address a pattern that is only visible at the level of the whole corpus.

No systematic review located during this study looks specifically at digital technology integration in Teaching Factory-based learning in relation to the SMK Pusat Keunggulan program. The closest comparable reviews are broader in scope. A review of technology adaptability in vocational education and training (Imama et al., 2025) and a review of digital-skills integration in TVET under Industry 4.0 (Kurnia et al., 2026) both look at technology adoption and barriers across VET settings generally, without a specific focus on Teaching Factory or Indonesia. A review of Industry 4.0 training (Anholon et al., 2022) looks at training for students and industrial employees more broadly, without a school-based production-learning focus. Against this background, the contribution of the present review is not a new list of technologies, since the domains identified here overlap substantially with what these broader reviews already report. The contribution is bringing together three areas that are each studied on their own but rarely combined: Teaching Factory pedagogy, digital technology integration, and a specific national policy, SMK PK, read through one consistent set of interpretive lenses, activity theory, situated learning, TPACK, and boundary crossing, instead of reported as a separate technology list. This combination shows a pattern that a single-topic review would not: the barriers to digital Teaching Factory integration come down to a shared-framework gap and a depth-of-practice gap rather than a checklist of separate problems, and the institutional contributions most often claimed for Teaching Factory digitalization are, on closer inspection, also the ones with the least rigorous evidence behind them.

Beyond the RQ-specific priorities noted above, the corpus points to one shared next step for research design. Across all five research questions, the studies most often cited as strong evidence use implementation, evaluation, or mixed-method designs, for example Prihantoro et al. (2025), Nanda et al. (2025), and Endrastiti and Sholikhah (2024), while the studies supporting the weaker contributions rely on single-site description or mentoring reports. The next priority for the field is therefore not more description of which technologies schools use, but evaluation designs, whether mixed-methods, quasi-experimental, or Design-Based Research, applied consistently across all six technology domains and pedagogical patterns rather than only the ones already well studied, so that closing the framework gap or the depth-of-practice gap can actually be measured rather than assumed.

This review has several limitations to consider when interpreting the discussion above. First, the corpus is dominated by Indonesian, mostly descriptive and qualitative studies, which limits how far the interpretive patterns discussed here, particularly the theoretical readings drawn from activity theory, situated learning, TPACK, and boundary crossing, can be generalized beyond the Indonesian SMK PK context without further testing. Second, the search was limited to two databases, Scopus and Google Scholar through Publish or Perish, rather than databases more specific to educational technology or engineering education such as ERIC or IEEE Xplore. Articles indexed only in other databases, published only in institutional repositories, or written in languages other than English and Indonesian may not have been captured, which could understate the true international scope of this literature. Third, as a narrative and thematic synthesis rather than a meta-analysis, this review reports patterns in the findings but does not statistically test the strength of relationships, for example between specific technology types and specific competency outcomes; such quantitative synthesis was not possible given how much the designs, outcome measures, and reporting practices vary across the 67 included articles. Fourth, the corpus leans toward nationally accredited (SINTA) and community-service sources rather than internationally peer-reviewed journals: only 13 of the 67 included articles (19 percent) are Scopus-indexed, and five are conference or seminar proceedings rather than peer-reviewed journal articles. This should be kept in mind when weighing how far the synthesized findings generalize internationally. Fifth, article screening, eligibility assessment, and quality appraisal were carried out by a single reviewer without independent second-reviewer verification or a registered review protocol, as noted in the Method, which may have increased the risk of selection and coding bias; this risk applies to the interpretive readings offered in this Discussion as much as to the original coding. These limitations do not undermine the review's main contribution, which is to map and interpret an emerging and still-fragmented body of literature, but they do mean the theoretical interpretations offered here should be treated as a starting point for future empirical testing rather than as an established explanation.

Conclusion

Based on the results of a systematic literature review of 67 final articles, it can be concluded that research on the integration of digital technology into Teaching Factory-based vocational education to strengthen the Vocational High School Center of Excellence Program shows a growing trend, particularly during the 2023–2025 period. This topic is frequently discussed in the Indonesian context due to its close association with the Vocational High School Center of Excellence Program, although several international articles also contribute to the perspective through studies on Learning Factory 4.0, Work-Based Learning, ICT competence, virtual reality, TVET, and Industry 4.0. The digital technology and digitalization domains integrated into Teaching Factory-based vocational education are quite diverse, encompassing ICT, digital marketing, digital products, digital simulations, virtual reality, augmented reality, mobile simulators, learning management systems, digital platforms, and Industry 4.0 orientation. These technologies serve as learning tools while also supporting production processes, marketing, documentation, evaluation, management, entrepreneurship, and industry collaboration. Pedagogically, digital technology is integrated through authentic production-based learning, project- and problem-based learning, work-based learning, teacher training, Teaching Factory evaluation, and digital entrepreneurship. This integration is reported to be associated with stronger link and match, student competency development, teachers' pedagogical readiness, Teaching Factory management, the commercialization of school products, and the identity of the Center of Excellence Vocational High School as a reference school that is adaptive to industry needs.

However, this study also identified several challenges, namely the uneven integration of digital technology, infrastructure limitations, teacher readiness, industry collaboration that is not always substantive, weak quality control, and limited evaluation of learning outcomes. It is consequently necessary to develop a Digital Teaching Factory model for Vocational High School Centers of Excellence that can systematically integrate industry-based curriculum, digital technology, authentic learning, production management, DUDIKA collaboration, quality assurance, and evaluation of student achievements.

Toward an integrated framework. Synthesizing the findings above, the review's results can be organized into a preliminary conceptual framework for a Digital Teaching Factory comprising seven interlocking components, rather than treating digital technology as a single add-on: (1) curriculum: industry-based content and standards aligned through link-and-match partnerships (RQ4); (2) pedagogy: authentic production-based learning, project- and problem-based learning, and Work-Based Learning as the classroom- and workshop-level mechanisms through which technology is used (RQ3); (3) technology: the digital technology and digitalization domains identified in RQ2 (ICT, digital marketing and business, simulation/VR/AR, Industry 4.0/Learning Factory 4.0 orientation, and learning-management/digital-platform systems), mapped onto the pedagogical and institutional functions they serve; (4) teacher capacity: sustained, TPACK-aligned training and mentoring rather than one-off workshops (RQ3, RQ5); (5) industry: school–industry boundary-crossing arrangements that extend beyond MoUs to joint curriculum design, mentoring, and product validation (RQ4, RQ5); (6) production and management: systematic Teaching Factory management, documentation, and quality-control systems (RQ3, RQ4); and (7) quality assurance and evaluation: outcome evaluation extending beyond descriptive or case-study designs toward measures capable of testing the framework's own components (RQ5). This framework is offered as a preliminary synthesis derived from the reviewed literature rather than as an empirically validated model; testing its components and their interrelationships is identified above as a priority for future research.

Recommendations

Vocational High School Centers of Excellence need to develop Teaching Factories as integrated digital learning ecosystems aligned with the curriculum, industry standards, marketing, evaluation, and school management, rather than as practice or production units alone. Schools must also develop a technology needs map tailored to vocational competencies, such as simulators, learning platforms, production documentation systems, digital marketing tools, and project-based evaluation systems.

Productive teachers and Teaching Factory managers need to receive ongoing training in digital pedagogy, production-based learning, project-based learning, the use of simulators, digital marketing, authentic assessment, and production management. This training is essential so that teachers can use technology and connect it to real-world learning experiences relevant to the industry.

Policy makers and DUDIKA partners need to strengthen support for the digitalization of Teaching Factories through the provision of facilities, implementation guidance, teacher training, infrastructure upgrades, and more substantive industry collaboration. Collaboration with industry should not stop at a Memorandum of

Understanding (MoU) but should extend to curriculum development, project design, validation of student competencies, determination of product standards, and evaluation of learning outcomes.

Future researchers are advised to conduct more in-depth studies on the Digital Teaching Factory model within the context of Vocational High Schools of Excellence. Future research may employ mixed-methods approaches, quasi-experiments, longitudinal studies, Design-Based Research, or Research and Development to assess the impact of digital technology integration on student competencies, work readiness, teacher competencies, product quality, and the effectiveness of Teaching Factory management.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPESS Journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Appendix. Journal Quality Indicators of the Included Articles

To provide additional transparency regarding the quality of the sources included in this review, Table A1 reports the Scopus quartile (SJR, Scimago Journal Rank) for the 13 Scopus-indexed articles and the SINTA (Science and Technology Index, Indonesian Ministry of Higher Education, Science, and Technology) accreditation level for the 54 Google Scholar-indexed articles in the corpus. This information was not used as an inclusion or exclusion criterion during article selection, consistent with the search strategy described in the Methods section, which prioritized topical relevance to Teaching Factory, digital technology, and Vocational High School Center of Excellence over source ranking, but is reported here so readers can independently assess the quality distribution of the corpus.

Table A1. Scopus quartile and SINTA accreditation level of the 67 included articles

No.	Author(s), Year	Journal / Source	Country	Database	Quality Indicator	Verification Note
1	Elisabet et al. (2025)	JIIP-Jurnal Ilmiah Ilmu Pendidikan	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
2	Asiah (2025)	TANZHIMUNA Jurnal Manajemen Pendidikan Islam	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
3	Ramanda et al. (2025)	Jurnal Applied Science in Civil Engineering	Indonesia	Google Scholar	Not found in SINTA	Not found in SINTA (Kemdiktisain tek); indexed in Garuda
4	Asngad et al. (2023)	Edukasi: Journal of Educational Research	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
5	Cholis et al. (2025)	Prisma Sains (IKIP Mataram)	Indonesia	Google Scholar	SINTA 2	Verified in SINTA (Kemdiktisain tek)
6	Septianingsih (2023)	Dinamisia: Jurnal Pengabdian Kepada Masyarakat	Indonesia	Google Scholar	SINTA 3	Verified in SINTA (Kemdiktisain tek)
7	Muharam et al. (2024)	Edusaintek: Jurnal Pendidikan, Sains dan Teknologi	Indonesia	Google Scholar	SINTA 5	Verified in SINTA (Kemdiktisain tek)
8	Baharsyah & Irfan (2024)	UNM Journal of Technology and Vocational	Indonesia	Google Scholar	SINTA 5	Verified in SINTA (Kemdiktisain tek)
9	Prihantoro et al. (2025)	Jurnal Pendidikan Teknik Mesin Undiksha	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
10	Ramzi & Sutadji (2025)	VANOS Journal of Mechanical Engineering Education	Indonesia	Google Scholar	SINTA 3	Verified in SINTA (Kemdiktisain tek)
11	Satria & Ramadani (2025)	Jurnal Pendidikan Teknik Mesin	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)

12	Astuti et al. (2025)	POACE: Program Administrasi Pendidikan	Jurnal Studi Indonesia	Google Scholar	SINTA 5	Verified in SINTA (Kemdiktisain tek)
13	Artha et al. (2024)	JTPVI: Teknologi Pendidikan Indonesia	Jurnal dan Vokasi Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
14	Wulandari Sudira (2025)	Ideguru: Karya Ilmiah Guru	Jurnal Indonesia	Google Scholar	SINTA 3	Verified in SINTA (Kemdiktisain tek)
15	Tanjung et al. (2025)	Reswara: Pengabdian Masyarakat	Jurnal Kepada Masyarakat Indonesia	Google Scholar	SINTA 5	Verified in SINTA (Kemdiktisain tek)
16	Ahmanda et al. (2022)	Jurnal Pendidikan Teknik Bangunan	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
17	Sholihah (2022)	Jurnal Pendidikan Profesional	Indonesia	Google Scholar	Not found in SINTA	Not found in SINTA (Kemdiktisain tek)
18	Shofiana Tohirin (2025)	Journal of Pedagogy and Education Science	Indonesia	Google Scholar	SINTA 2	Verified in SINTA (Kemdiktisain tek)
19	Putra (2023)	Journal of Education Informatic Technology and Science	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
20	Nuryanti et al. (2025)	Pendas: Jurnal Ilmiah Pendidikan Dasar	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
21	Valentine (2025)	Prosiding Nasional Publikasi Seminar dan Ilmiah FIP UMJ	Indonesia	Google Scholar	Not a journal (proceedings)	Not applicable (conference proceedings); SINTA accreditation does not apply
22	Sulistyawati & Mulyono (2024)	Media Manajemen Pendidikan	Indonesia	Google Scholar	SINTA 3	Verified in SINTA (Kemdiktisain tek)
23	Ningtias et al. (2025)	JIIP – Jurnal Ilmiah Ilmu Pendidikan	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
24	Ngusman et al. (2023)	Jurnal Manajemen Pendidikan (JMP)	Indonesia	Google Scholar	SINTA 5	Verified in SINTA (Kemdiktisain tek)
25	Purwaningtias & Chamami (2025)	Jurnal Pendidikan Tambusai	Indonesia	Google Scholar	SINTA 5	Verified in SINTA (Kemdiktisain tek)

26	Fahmayani (2021)	Prosiding Pendidikan Teknik Boga Busana	Indonesia	Google Scholar	Not journal (proceedings)	a	Not applicable (conference proceedings); SINTA accreditation does not apply
27	Ariwibowo et al. (2025)	TEMATIK	Indonesia	Google Scholar	SINTA 5		Verified in SINTA (Kemdiktisain tek)
28	Sumantri & Akmal (2023)	Madaniya	Indonesia	Google Scholar	SINTA 5		Verified in SINTA (Kemdiktisain tek)
29	Wahyudi et al. (2025)	Jurnal Pengabdian Masyarakat Manage	Indonesia	Google Scholar	SINTA 4		Verified in SINTA (Kemdiktisain tek)
30	Sumantri, Idawati, & Amrullah (2024)	Madaniya	Indonesia	Google Scholar	SINTA 5		Verified in SINTA (Kemdiktisain tek)
31	Widiyatmoko et al. (2025)	Jurnal Gerakan Mengabdi untuk Negeri	Indonesia	Google Scholar	Not found in SINTA		Not found in SINTA (Kemdiktisain tek)
32	Nastiti (2022)	Dewantara Seminar Nasional Pendidikan	Indonesia	Google Scholar	Not journal (seminar proceedings)	a	Not applicable (conference proceedings); SINTA accreditation does not apply
33	Endrastiti Sholikhah (2024)	& Fashion and Fashion Education Journal	Indonesia	Google Scholar	SINTA 5		Verified in SINTA (Kemdiktisain tek)
34	Ulfa & Yudianto (2025)	Jurnal Pengabdian Masyarakat Kesehatan	Indonesia	Google Scholar	SINTA 5		Verified in SINTA (Kemdiktisain tek)
35	Muhardono & Meliza (2023)	Buletin Masyarakat Abdi	Indonesia	Google Scholar	SINTA 6		Verified in SINTA (Kemdiktisain tek)
36	Srirahayu et al. (2025)	Duta Abdimas: Jurnal Pengabdian Masyarakat	Indonesia	Google Scholar	Not found in SINTA		Not found in SINTA (Kemdiktisain tek); indexed in Garuda
37	Akyuwen et al. (2023)	EDUKASIA Jurnal Pendidikan dan Pembelajaran	Indonesia	Google Scholar	SINTA 2		Verified in SINTA (Kemdiktisain tek)
38	Wardani & Raihani (2024)	Asatiza: Jurnal Pendidikan	Indonesia	Google Scholar	Not found in SINTA		Not found in SINTA (Kemdiktisain tek)
39	Setiadi et al. (2025)	Indonesian Journal of Educational	Indonesia	Google Scholar	SINTA 2		Verified in SINTA

			Development (IJED)				(Kemdiktisain tek)
40	Al Hasan Hermawan (2025)	&	Jurnal Teknologi Informasi dan Multimedia	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
41	Sholihatinnisa et al. (2021)	et	Jurnal Ilmiah Kampus Mengajar	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
42	Sarifudin Suhri (2024)	&	Studia Religia: Jurnal Pemikiran dan Pendidikan Islam	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
43	Cahyadi Respati (2025)	&	DedikasiMU: Journal of Community Service	Indonesia	Google Scholar	SINTA 5	Verified in SINTA (Kemdiktisain tek)
44	Samengasbumi et al. (2024)		Jurnal Pembelajaran Pemberdayaan Masyarakat (JP2M)	Indonesia	Google Scholar	SINTA 3	Verified in SINTA (Kemdiktisain tek)
45	Moata et al. (2023)	et al.	Prosiding Seminar Nasional Politani Kupang Ke-6	Indonesia	Google Scholar	Not a journal (proceedin gs)	Not applicable (conference proceedings); SINTA accreditation does not apply
46	Setiawan et al. (2025)	et al.	Jurnal Abmas	Indonesia	Google Scholar	SINTA 5	Verified in SINTA (Kemdiktisain tek)
47	Sunyoto et al. (2024)	et al.	Proc. 5th Vocational Education International Conference (VEIC- 5 2023), Atlantis Press	Indonesia	Google Scholar	Not a journal; not Scopus- indexed	Not applicable (conference proceedings); SINTA accreditation does not apply
48	Sugianto Casmudi (2022)	&	Jurnal Pendidikan Ekonomi (JURKAMI)	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
49	Hastuti et al. (2025)	et al.	Jurnal Dimensi Pendidikan dan Pembelajaran	Indonesia	Google Scholar	SINTA 4	Verified in SINTA (Kemdiktisain tek)
50	Mujab et al. (2025)	et al.	Journal of Science and Education (JSE)	Indonesia	Google Scholar	SINTA 3	Verified in SINTA (Kemdiktisain tek)
51	Husna et al. (2025)	et al.	Journal of Educational Sciences	Indonesia	Google Scholar	SINTA 3	Verified in SINTA (Kemdiktisain tek)
52	Widiastuti et al. (2023)	et al.	International Journal of Research in Education Humanities and Commerce	Indonesia	Google Scholar	Not an Indonesian journal	Not applicable (international journal); SINTA

							accreditation does not apply
53	Tessa Humaedi (2023)	&	Jurnal Penelitian Kebijakan Pendidikan	Indonesia	Google Scholar	SINTA 2	Verified in SINTA (Kemdiktisain tek)
54	Suranto (2023)	et al.	Jurnal Inovasi Hasil Pengabdian Masyarakat (JIPEMAS)	Indonesia	Google Scholar	SINTA 3	Verified in SINTA (Kemdiktisain tek)
55	Goller (2021)	et al.	International Journal for Research in Vocational Education and Training	Germany	Scopus	Q2	Verified in SCImago Journal Rank (SJR); Education category, 2021 data
56	Mazlan (2025c)	et al.	Higher Education, Skills and Work-based Learning	Malaysia	Scopus	Q2	Verified in SCImago Journal Rank (SJR); Education category, 2025 data
57	Mazlan (2025a)	et al.	Higher Education, Skills and Work-based Learning	Malaysia	Scopus	Q2	Verified in SCImago Journal Rank (SJR); Education category, 2025 data
58	Mazlan (2025b)	et al.	Journal of Technical Education and Training	Malaysia	Scopus	Q3	Verified in SCImago Journal Rank (SJR); Education category, 2025 data
59	Meinokat Wagner (2025)	&	International Journal for Research in Vocational Education and Training	Germany	Scopus	Q2	Verified in SCImago Journal Rank (SJR); Education category, 2025 data
60	Nanda (2025)	et al.	International Journal of Interactive Mobile Technologies	Indonesia	Scopus	Q2	Verified in SCImago Journal Rank (SJR); quartile varies by subject category (2025 data)
61	Riemann (2020)	et al.	ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb	Germany	Scopus	Q3	Verified in SCImago Journal Rank (SJR); 2020 data
62	Roll & Ifenthaler (2021)		Empirical Research in Vocational	Germany	Scopus	Q3	Verified in SCImago

		Education and Training					Journal Rank (SJR); Education category, 2021 data
63	Swaramarinda & Nurmallasari (2017)	Advanced Science Letters	Indonesia	Scopus	Q4		Verified in SCImago Journal Rank (SJR); journal discontinued from Scopus after 2017
64	Vilppola et al. (2022)	International Journal Research Vocational Education Training	for in Finland	Scopus	Q2		Verified in SCImago Journal Rank (SJR); Education category, 2022 data
65	Wahjusaputri & Bunyamin (2022)	International Journal Evaluation Research Education	of and in Indonesia	Scopus	Q3		Verified in SCImago Journal Rank (SJR); Education category, 2022 data
66	Yondri et al. (2020)	International Journal Advanced Engineering Information Technology	on Science, and Indonesia	Scopus	Q3		Verified in SCImago Journal Rank (SJR); 2020 data
67	Yoto et al. (2019)	International Journal Innovation, Creativity Change	of and Indonesia	Scopus	Q3		Verified in SCImago Journal Rank (SJR); quartile varies by subject category; journal discontinued from Scopus after 2020