International Journal of Learning, Teaching and Educational Research
Vol. 25, No. 8, pp. 1013-1044, August 2026
https://doi.org/10.26803/ijlter.25.8.40
Received May 30 2026; Revised Jul 22, 2026; Accepted Aug 10, 2026

Preparing Indonesian Vocational Education for Industry 5.0: A Systematic Review of Pedagogical Approaches, Competencies, and Emerging Challenges

Devin Heliana Pitaloka Sukis, Cica Yulia*, Yusep Sukrawan and Rudi Haryadi
Universitas Pendidikan Indonesia
Bandung, West Java, Indonesia

Abstract. The swift evolution of industrial technologies necessitates that vocational high schools enhance the preparedness of their graduates for Industry 4.0, while also gearing up for Industry 5.0. However, there is a little comprehensive evidence on how teaching methods, the application of the Merdeka Curriculum, and the development of Industry 4.0 competencies work together to facilitate this transition in Indonesia. This systematic literature review consolidates findings on teaching methodologies, the incorporation of Industry 4.0 skills, and the challenges facing implementing teaching methodologies in vocational high schools. In accordance with PRISMA guidelines, 30 peer-reviewed articles published from 2021 to 2026 were selected from Scopus and Google Scholar by applying specific inclusion criteria. Data was collected manually using a structured form and analyzed with thematic synthesis. The results indicate that project-based learning, Teaching Factory, and technology-enhanced learning are the predominant pedagogical strategies that aid in the execution of the Merdeka Curriculum. These strategies consistently enhance competencies relating to technical skills, digital literacy, critical thinking, problem-solving, creativity, and collaboration; communication remains the least-developed skill. The review also highlights significant challenges faced in applying these pedagogical approaches; these challenges relate to teacher proficiency, curriculum adaptability, industry partnerships, and disparities in digital infrastructure. Ultimately, to prepare vocational education for Industry 5.0, a comprehensive transformation is needed that incorporates innovative teaching practices, responsive curricula, institutional development, and sustainable collaborations with industry to bolster workforce readiness.

Citation:
Sukis, D, H, P., Yulia, C., Sukrawan, Y., & Haryadi, R. (2026). Preparing Indonesian Vocational Education for Industry 5.0: A Systematic Review of Pedagogical Approaches, Competencies, and Emerging Challenges. *International Journal of Learning, Teaching and Educational Research*, *25*(8), 1013–1044. https://doi.org/10.26803/ijlter.25.8.40

*Corresponding author: Cica Yulia; *cicayulia@upi.edu*

Keywords: Industry 4.0 competencies; Industry 5.0; Merdeka Curriculum; pedagogical innovation; vocational education

1. Introduction

The ability of education systems to continuously prepare a workforce whose competencies remain aligned with rapidly evolving industrial demands has become one of the defining challenges of contemporary workforce development. The Fourth Industrial Revolution has triggered an unprecedented restructuring of the global labor market, driven by the simultaneous convergence of AI, the Internet of Things, robotics, cloud computing, and cyber-physical systems (World Economic Forum, 2025). This transformation is not only changing the way production takes place but redefining the competencies required of the workforce of the future. Consequently, the competency profile required of the global workforce has shifted decisively toward high-level, adaptive, and interpersonal skills that are difficult to automate (Yusvana, 2025). This shift has placed technical and vocational education and training (TVET) systems under increasing pressure to move beyond the delivery of narrow technical skills, toward a holistic, competency-oriented model that is responsive to dynamic industry demands (Wickramasinghe & Wickramasinghe, 2024).

The acceleration of the development of AI and the Internet of Things is hastening the obsolescence of technical skills taught by TVET institutions, while the capacity of institutions to update their curricula lags far behind the pace of industrial change (Imama et al., 2025). The digital skills gap confronting TVET graduates is a major obstacle to workforce competitiveness, leading vocational education institutions to adopt adaptive, Industry 4.0 competency-based curricula as a matter of urgency (Yusvana, 2025). Various competency frameworks have been developed, and there is a consensus that core competencies for Industry 4.0 encompass four interrelated domains: digital literacy, critical thinking and problem-solving, adaptability and flexibility, and collaboration and communication (Elragal & Habibipour, 2025; Siti et al., 2023).

Accordingly, pedagogical approaches have become a critical mechanism for translating competency frameworks into authentic learning experiences that foster the adaptive competencies required by Industry 4.0 and Industry 5.0 (Chen & Chan, 2024; Pharamela & Singh-Pillay, 2025). Recent studies, furthermore, emphasize that learner-centered, work-integrated, and technology-enhanced pedagogical approaches are essential for developing adaptive, human-centered, and lifelong learning competencies. The transition from Industry 4.0 to Industry 5.0 is fundamentally shifting workforce requirements by widening the skills gap between TVET graduates and employer expectations (Hongli & Wai Yie, 2024).

The mismatch between TVET graduates and industry needs is not unique to Indonesia; more than 60% of developing countries in Southeast Asia and Africa face similar challenges (International Labour Organization, 2024). This situation is exacerbated by the emerging transition to Industry 5.0, which expands competency expectations placed on vocational graduates beyond technical competencies to encompass meta-cognitive, digital, and socio-emotional dimensions (Tjahjono et al., 2025). Consequently, vocational curriculum reforms worldwide increasingly emphasize the integration of competency frameworks with industry needs and broader workforce transformation (Chigbu & Makapela, 2025; Jumani-Alwani, 2025; Lin et al., 2024). Although effective TVET systems rely on robust ecosystem integration encompassing industry partnerships, curriculum alignment, and adaptive governance, achieving such integration remains a persistent challenge in many low- and middle-income countries (Wahyuni et al., 2026; World Bank et al., 2024). In Indonesia, this challenge is reflected in the fact that graduates of vocational high schools (SMK) consistently record the highest open unemployment rate at all education attainment levels: 8.63%, the highest of all levels of education (Badan Pusat Statistik, 2026). Industry stakeholders consistently assess SMK graduates as lacking competitiveness in adaptive competencies, digital skills, and autonomous problem-solving (Muliadi et al., 2025; Nurjanah et al., 2022).

The Merdeka Curriculum (Kurikulum Merdeka), introduced by the Ministry of Education, Culture, Research, and Technology, is the most ambitious curriculum reform in Indonesia to date, and supports innovative learning such as project-based learning (PjBL) and Teaching Factory (TeFa) (Handito et al., 2026; Indarta et al., 2022). However, in practice, the quality of application varies widely across institutions, and is influenced by teacher readiness, infrastructure, and the intensity of industry partnerships (Setiawan et al., 2024). Although research on the Merdeka Curriculum surged in 2022, significant gaps remain. Several studies focused on general elementary and secondary school levels and paid little attention to the practice of the Merdeka Curriculum in vocational subjects in SMK in relation to Industry 4.0 (Ditjen Pendidikan Vokasi PKPLK, 2024; Mujiburrahman et al., 2025; Yani et al., 2024). These studies are generally single-case studies, which limits their generalizability.

To our knowledge, implementation of the Merdeka Curriculum in SMK remains fragmented in three critical ways: (1) A dominance of single-case or small-scale empirical studies that limit generalizability across Indonesia's diverse archipelagic school contexts; (2) The absence of integrated mapping between pedagogical models, Merdeka Curriculum policy mechanisms, and Industry 4.0 competency outcomes in a single synthesis; and (3) A lack of any systematic review specifically examining SMK integration in relation to Industry 4.0 competency development and the emerging demands of Industry 5.0. To address these gaps, this study conducted a systematic literature review of peer-reviewed empirical research on pedagogical approaches in SMK under the Merdeka Curriculum, using the industry 4.0 competency framework as an analytical lens in relation to Industry 5.0 readiness.

Three complementary research questions guided the review:
1. What pedagogical approaches are applied in the implementation of the Merdeka Curriculum in vocational education?
2. What Industry 4.0 competencies are integrated in vocational learning practices?

3. What implementation challenges exist, and what strategic directions have been developed for the transition toward Industry 5.0?

The urgency of this research is heightened further by the Merdeka Curriculum entering the consolidation phase of its national implementation, while the pressures of Industry 4.0 and the transformation toward Industry 5.0 continue to accelerate changes in workforce competency demands. In this case, a systematic review is appropriate, especially if the body of literature is mature enough for synthesis. This research contributes to theory by producing a conceptual map that integrates the constructs of vocational learning, Industry 4.0 competencies, and the dynamics of the Merdeka Curriculum policy.

Practically, the findings of this study are expected to provide an evidence-based foundation for policymakers, curriculum developers, and vocational education practitioners to design targeted interventions to improve the readiness of SMK to confront Industry 5.0 transformation through the Merdeka Curriculum. This research is positioned as a critical synthesis that bridges three previously fragmented domains: the Merdeka Curriculum policy, vocational learning pedagogy, the Industry 4.0 competency framework, and strategies to deal with the Industry 5.0 transformation in SMK. At the same time, it lays a conceptual foundation for further empirical research to deepen and expand the existing knowledge base.

2. Literature Review

2.1 Industry 4.0 to Industry 5.0 Transformation and Its Implications for Vocational Education

Industry 4.0 transformed industrial systems by integrating AI, cyber-physical systems, the Internet of Things, cloud computing, and big data analytics, thereby creating increasingly interconnected and automated production environments (Nayernia et al., 2022). These developments reshaped workforce requirements by increasing demand for digital, technological, and problem-solving competencies. By building on this foundation, Industry 5.0 extends the goals of Industry 4.0 by emphasizing human-centeredness, sustainability, and resilience alongside technological advancement (Sarıışık & Demir, 2025; Wickramasinghe & Wickramasinghe, 2024). Consequently, the workers of the future are expected not only to possess digital and technical expertise but also to demonstrate adaptability, critical thinking, creativity, collaboration, ethical awareness, and sustainability-oriented decision-making abilities (Abbu et al., 2025; Singaram et al., 2023).

These developments require vocational education to move beyond preparing technically competent graduates, toward fostering hybrid competencies that integrate technological, cognitive, and socio-emotional capabilities (Jaedun et al., 2024). Accordingly, curriculum reform must be accompanied by pedagogical transformation that enables authentic, learner-centered, and industry-oriented learning experiences, to provide the conceptual basis for examining the pedagogical approaches of the Merdeka Curriculum.

2.2 Constructivist Learning Theory and Competency-Based Education

This review is grounded in constructivist learning theory, which posits that competencies are actively constructed through authentic experience, social interaction, reflection, and problem-solving, rather than passively acquired through knowledge transmission. In contemporary TVET, this perspective underpins learner-centered pedagogies that situate students in authentic industrial contexts, where they are enabled to integrate technical knowledge and the higher order cognitive, collaborative, and adaptive capabilities demanded by digitally transformed workplaces (Chen & Chan, 2024; Vimbelo & Bayaga, 2024).

Competency-based education operationalizes these constructivist principles by aligning curriculum, pedagogy, learning outcomes, and assessment with demonstrable workplace competencies rather than time-based instructional inputs. Recent evidence indicates that competency-based TVET is most effective when competency standards are enacted in learning environments that combine continuous feedback, experiential learning, and industry engagement, thereby strengthening learners' employability and capacity for lifelong learning (Guzmán Hernández, 2024; Mafarja et al., 2025; Zhong & Juwaheer, 2024).

Pedagogical approaches should, therefore, be understood not merely as instructional techniques, but as the primary mechanism through which competency frameworks are translated into meaningful learning experiences and measurable outcomes. This theoretical integration provided the conceptual foundation for the present review, which examines how the pedagogical approaches of Indonesia's Merdeka Curriculum foster Industry 4.0 competencies while preparing vocational graduates for the human-centered, adaptive, and sustainable workforce envisioned under Industry 5.0.

2.3 Industry 4.0 Competency Framework as an Analytical Lens

This review adopts the industry 4.0 competency framework as its analytical lens because it provides a comprehensive structure for evaluating competency development in vocational education. Literature consistently identifies four core competency domains: digital literacy, critical thinking and problem-solving, adaptability and flexibility, and collaboration and communication (Elragal & Habibipour, 2025; Siti et al., 2023).

Digital literacy refers to the ability to effectively utilize and integrate emerging digital technologies, while critical thinking and problem-solving emphasize analytical reasoning and data-driven decision-making in complex work environments (Barboutidis & Stiakakis, 2023; Kholifah et al., 2025). Adaptability refers to the capacity to respond to changing technologies and work contexts through continuous learning and innovation (Subrahmanyam & Slaiby, 2025), whereas collaboration and communication involve working effectively with multidisciplinary teams and across diverse digital environments (González-Pérez & Ramírez-Montoya, 2022). These four domains serve as the analytical categories for synthesizing pedagogical practices identified in the reviewed studies.

2.4 Merdeka Curriculum in SMK

The Merdeka Curriculum is a national curriculum reform policy that was developed in response to the learning crisis, and which is based on the principle of independent learning. This curriculum gives educational units, teachers, and students greater autonomy to determine the learning process and context according to their needs (Hamdi et al., 2022).

At the SMK level, the Merdeka Curriculum presents significant structural changes, including the elimination of rigid competency-based subjects, the practice of more flexible learning outcomes, the integration of the Pancasila Student Profile Strengthening Project (P5), and the strengthening of link-and-match programs with the business and industrial world (DUDI) through the 8+i concept (Ahmanda et al., 2022). Vocational subjects in SMK are designed according to learning outcomes, which are developed in collaboration with industry to make them conceptually more responsive to actual competency needs. The Merdeka Curriculum was designed to respond to the demands of the 21st century and the industry 4.0 era by strengthening critical, creative, collaborative, and communicative (4C) thinking skills, which are integrated in every subject (Indarta et al., 2022).

Several pedagogical approaches, including learning models, play a crucial role in realizing the Merdeka Curriculum in vocational subjects. The implementation of these Merdeka Curriculum objectives relies heavily on learner-centered pedagogical approaches. PjBL promotes authentic problem-solving through industry-relevant projects, whereas TeFa provides experiential learning by simulating industrial production processes (Handito et al., 2026; Rehman et al., 2024). Both approaches align with constructivist principles and support competency development through authentic learning experiences.

Nevertheless, their effectiveness remains influenced by contextual factors, including teacher readiness, institutional leadership, infrastructure, and the quality of industry partnerships (Azahar et al., 2025; Setiawan et al., 2024). These implementation challenges underscore the need for a systematic synthesis of evidence on pedagogical approaches, competency integration, and vocational curriculum transformation under the Merdeka Curriculum.

3. Methodology

3.1 Research Design

This study employed a systematic literature review methodology, which served as an analytical lens to systematically identify, select, evaluate, and synthesize reviewed empirical research on the implementation of pedagogical approaches under the Merdeka Curriculum in SMK and their alignment with Industry 4.0 competencies toward Industry 5.0 readiness. This review relied exclusively on published literature; therefore, it did not involve direct participation of human subjects, the collection of primary data, or any intervention requiring informed consent. Consequently, ethical approval was not required for this study. The systematic literature review approach was chosen for its ability to synthesize evidence from various studies in a transparent, replicable, and bias-minimizing manner, and lead to accountable conclusions for policy and practice (Ghamrawi et al., 2025). The review protocol was structured around four sequential phases, following the PRISMA 2020 guidelines. The conceptual boundaries of this review were defined by the population–concept–context framework. The population comprised students, vocational subject teachers, and curriculum managers in SMK. This framework encompasses the pedagogical approaches implemented under the Merdeka Curriculum, along with Industry 4.0 competencies. The context is limited to the implementation of the curriculum in Indonesia in the 2021–2026 period, which coincides with the official launch and national scale-up of the reform.

To ensure an accurate representation of the findings of the included studies, two authors independently screened the retrieved records and extracted data using a standardized extraction matrix. The extracted information was independently verified against the original full-text articles to minimize transcription errors and misinterpretation. Any discrepancies in data interpretation were resolved through discussion among the authors until consensus was reached. All eligibility decisions, extraction records, and synthesis procedures were documented to provide a transparent audit trail. Data synthesis was based exclusively on findings explicitly reported in the source documents, and thematic interpretations were cross-checked across studies to ensure that the synthesized evidence faithfully reflected the original research rather than the reviewers' subjective interpretations.

3.2 Procedure

3.2.1 Study Identification

The identification phase aimed to retrieve all potentially relevant publications from Scopus and Google Scholar. Scopus served as the primary database to capture high-quality studies, while Google Scholar complemented the search by retrieving Indonesian-language and nationally indexed publications not covered by Scopus. Because the review was limited to the implementation of the Merdeka Curriculum in Indonesia, the combined use of these databases was considered sufficient to ensure comprehensive coverage of the available evidence. A total of 299 articles were retrieved from both databases. The search strategy employed Boolean operators to combine three thematic clusters: Merdeka Curriculum pedagogical approaches, vocational education, and Industry 4.0 competencies. The complete search string applied to each database is presented in Table 1.

Table 1: Search string

Database	Search string
Scopus	(TITLE-ABS-KEY (“Merdeka Belajar” OR “Merdeka Curriculum” OR “independent learning curriculum” OR “Kurikulum Merdeka” OR “learning model” OR “instructional model” OR “project-based learning” OR “teaching factory” OR “learning program”) AND TITLE-ABS-KEY (“digital literacy” OR “digital competence” OR “critical thinking” OR “problem solving” OR “adaptability” OR “21st century competenc*”) AND TITLE-ABS-KEY (“vocational school” OR “vocational education” OR “SMK” OR “TVET”)) AND PUBYEAR > 2020 AND PUBYEAR < 2027)
Google Scholar	(“Kurikulum Merdeka” OR “Merdeka Belajar”) (“SMK” OR “vocational”) (“Industry 4.0” OR “Industri 4.0”) (“model pembelajaran” OR “project-based learning” OR “teaching factory” OR “problem-based learning”) (“kompetensi industri 4.0” OR “kesiapan” OR “readiness” OR “hambatan” OR “kompetensi digital”) [Special range 2021-2026]

3.2.2 Screening

After the identification stage, all identified articles underwent a two-stage screening process. In the first stage, 23 duplicate articles were identified and removed after cross-checking the title, author(s), and year of publication. In the second stage, the titles and abstracts of the remaining 276 articles were screened. Articles whose titles and abstracts were clearly irrelevant to the research focus were excluded at this stage.

3.2.3 Eligibility

After title and abstract screening, a total of 173 articles progressed to the full-text eligibility assessment. To minimize selection bias, inclusion and exclusion criteria (Table 2) were developed a priori, based on the review objectives and the population–concept–context framework, and were applied consistently throughout the screening process. Two authors independently assessed the eligibility of each full-text article against these predefined criteria; discrepancies were resolved through discussion until consensus was reached. This process resulted in the exclusion of 143 studies.

Table 2: Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Empirical, peer-reviewed studies published between 2021 and 2026, written in English or Indonesian, with full-text availability	Studies published outside the period 2021–2026, gray literature, non-English/Indonesian publications, or those with full texts unavailable
Studies conducted in the SMK context and involving relevant educational stakeholders	Studies conducted outside the SMK context, including those focusing on primary, secondary, higher education, or vocational education systems in other countries
Studies examining pedagogical approaches under the Merdeka Curriculum for the development of Industry 4.0 competencies in vocational education	Studies that do not address both the Merdeka Curriculum pedagogical approaches and Industry 4.0 competencies, or that focus solely on curriculum implementation, digital transformation, or technical/industrial issues, without integrating the two concepts

3.2.4 Data Abstraction and Analysis

A total of 30 articles were identified from the Scopus and Google Scholar databases for data extraction, as illustrated through the PRISMA flow diagram in Figure 1.

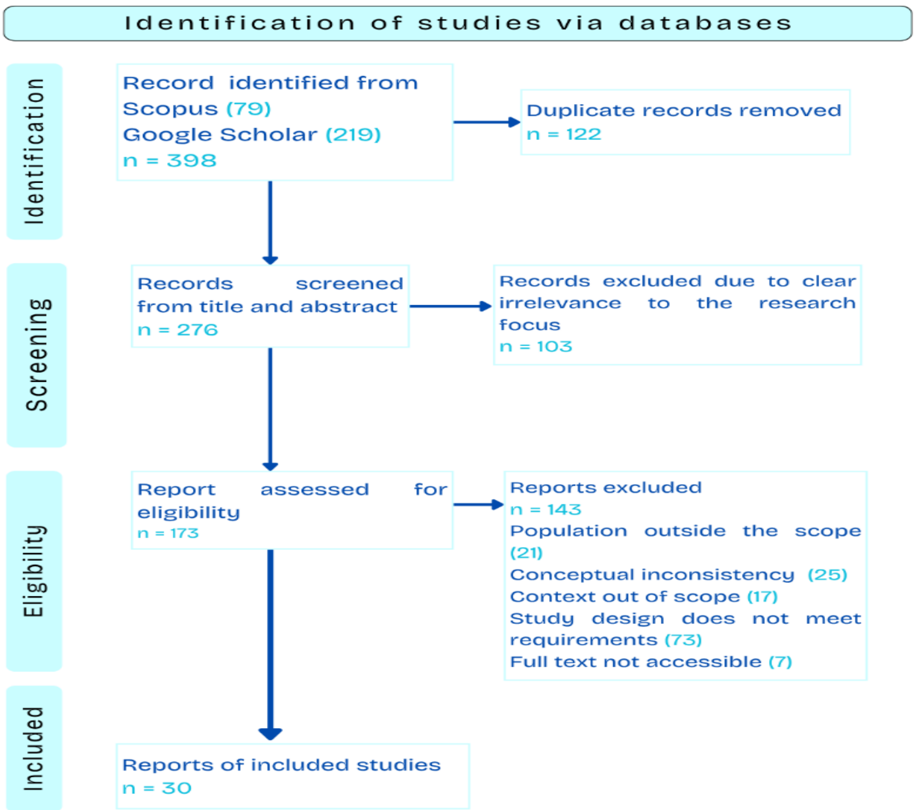

Figure 1: PRISMA flow diagram

Excluded articles were assigned a primary reason for exclusion, either population out of scope, conceptual inconsistency, context mismatch, ineligible study design, or full-text inaccessibility. In total 30 studies met the predefined inclusion criteria and were included in the final review. Data extraction was conducted manually using a structured Microsoft Excel form specifically developed for this review. The extraction form captured bibliographic information, study design and methodology, vocational specialization, pedagogical approaches implemented in the Merdeka Curriculum, integrated Industry 4.0 competencies, implementation challenges, strategic directions, and key findings.

The extracted data were synthesized using a thematic synthesis approach. Findings were initially coded inductively to identify recurring concepts and patterns across the included studies. Similar codes were refined into descriptive categories and subsequently organized into three analytical themes aligned with the review questions: Research question 1: pedagogical approaches applied in implementing the Merdeka Curriculum in vocational education; Research question 2: Industry 4.0 competencies integrated into vocational learning practices; and Research question 3: Implementation challenges and strategic directions for the transition toward Industry 5.0. This thematic synthesis enabled a systematic integration of evidence while maintaining conceptual alignment between the extracted findings, the review objectives, and the research questions.

4. Results

4.1 Pedagogical Approaches in the Merdeka Curriculum

4.1.1 Pedagogical Approaches Applied in Vocational Education

The reviewed literature reveals a pedagogical landscape dominated by PjBL and its STEM/STEAM-integrated variants, which appear independently or combined with other frameworks in more than half the corpus. This finding reflects the structural fit of PjBL with the dual mandate of vocational education, namely technical competency and development of 21st-century skills. Chrismondari et al. (2025) found project-based inquiry learning (PBIL) to be significantly superior to conventional instruction in electric motor installation on technical skills, problem-solving, and teamwork; Akmal et al. (2025) corroborated this finding through a quasi-experimental design showing integrated STEM-problem-based learning (PBL) improved the theoretical knowledge, practical skills, and 21st-century competencies of industrial automation students, and improved their engagement and motivation.

A qualitative case study at an SMK Center of Excellence (SMK PK) confirms that PjBL is a student-centered, adaptive model, though enactment optimization is still needed (Dzulkurnain et al., 2024). At the model-development level, Thaha et al. (2025) validated an Android-assisted STEAM-PjBL model (ADDIE) that improved all cognitive, affective, and psychomotor dimensions, plus the full 4C skillset. Yusuf et al. (2023), using structural equation modeling with 283 software engineering students, confirms the success of STEM-PjBL. 4C correlation with STEM-PjBL, while identifying communication as the weakest, least consistent outcome – a gap that recurs across the literature on STEM integration and signals that cognitive and creative competencies respond more readily to project-based designs than to the human-centered communication skills Industry 5.0 demands. TeFa constitutes the second major cluster, distinguished by embedding industrial production processes directly in school governance. Using partial least squares structural equation modeling (PLS-SEM), Tanjung et al. (2025) found that industry collaboration in the SMK PK framework significantly strengthens curriculum relevance, and has cascading effects on technical competency, work readiness, and soft skills such as problem-solving, teamwork, and discipline. Wahjusaputri and Bunyamin (2022) position TeFa as systemic institutional transformation rather than a stand-alone learning model; TeFA spans eight dimensions, from school management and human resources to workshop infrastructure and DUDI relationships. In an automotive-specific context, Ridho et al. (2025) found that TeFa-based curriculum innovation narrows the competency gap between SMK graduates and industry needs; they flag the need to extend TeFa into electric vehicle and connected vehicle domains.

A third cluster centers on technology-enhanced learning, particularly augmented reality. Sukatiman et al. (2026) linked a flipped PjBL model integrated with mockup media and augmented reality to learning motivation, media perception, and student activity and found them to be significant predictors of critical thinking. Efendi et al. (2025) validated an augmented reality mobile learning model (ADDIE, SEM-PLS) across vocational contexts and found gains in creativity and critical thinking but weaker effects on communication and collaboration, echoing the pattern already seen in the STEM-PjBL literature. A Toyota-collaborative Cooperative Learning Technopreneur for SMK by augmented reality model, similarly, improved creative thinking, communication, adaptability, and managerial capacity in automotive education (Purnomo, 2025), which suggests that augmented reality can offset the communication gap when design purposefully includes it.

Beyond PjBL and augmented reality, several innovative models extend the field: Mustaqim et al. (2025) combined problem-based flipped learning with STEM (87.9% student support) and improved critical thinking and collaboration but was constrained by infrastructure and teacher-preparation gaps; Ramdani et al. (2025) integrated digital literacy into PBL for electronic fuel injection (EFI) diagnosis, and found it improved creativity regarding fluency, originality, and elaboration; and Majuita et al. (2025) embedded AI directly in PBL to improve science literacy and vocational skill acquisition as an early but significant marker of AI-mediated pedagogy entering Indonesian vocational education.

Nurodanika and Gunadi (2026) applied mind mapping to visualize link-and-match (8+i) partnership components, thereby demonstrating its value as a diagnostic tool for identifying industry–school collaboration gaps. Longitudinal evidence from Prianto et al. (2022), who tracked four semesters of practical learning, found PjBL and school-based enterprise produced the strongest cumulative effects on deep learning competencies such as academic mindset, communication, content mastery, problem-solving and self-directed learning, to affirm that sustained experiential engagement outperforms shorter interventions.

As shown in Figure 2, the implementation of the Merdeka Curriculum in SMK is dominated by a project-based approach, TeFa and digital technology integration oriented toward strengthening Industry 4.0 competencies. However, the identified pedagogical transformation still tends to be technocentric and has not fully accommodated the human-centered, sustainability, and adaptive intelligence dimensions—the main characteristics of Industry 5.0.

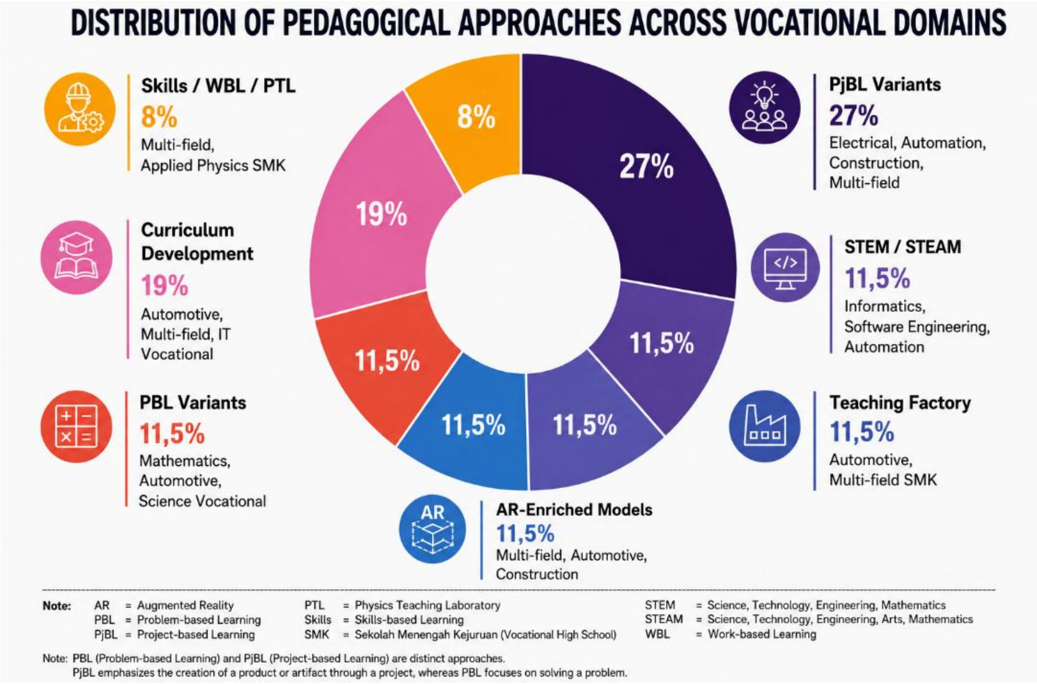

Figure 2: Distribution of pedagogical approaches across vocational domains

4.1.2 Merdeka Curriculum Practices in SMK

The institutional expression of the Merdeka Curriculum—through the SMK PK program and the operational curriculum of education units (KOSP)provides the policy context for nearly all innovations examined above. Most articles engage, explicitly or implicitly, with the core principles of the Merdeka Curriculum: student-centered and flexible pedagogy, DUDI collaboration formalized through link-and-match (8+i), development of the Pancasila Student Profile (P5), and school-level curriculum autonomy.

SMK PK provides the primary institutional architecture for this policy. Beyond the curriculum relevance and TeFa effects already noted (Tanjung et al., 2025), Usman et al. (2024), studying 22 SMK PK across Aceh Province through mixed methods involving 22 principals, 22 TeFa coordinators, and 110 students, found that integrating technopark activities in SMK PK drove a measurable shift toward dynamic, technology-based curricula, which improved both hard skills (technical competency) and soft skills (independence, teamwork, critical thinking).

The mind mapping tool used by Nurodanika and Gunadi (2026) indicates that SMK PK governance needs a systematic partnership-monitoring mechanism to track link-and-match implementation gaps. The philosophical core of the curriculum—student autonomy, experiential engagement, and contextual application is embodied in the active, inquiry- and project-based models reviewed throughout this review, several of which have direct institutional implications. Merdeka Belajar represents a broader educational reform agenda in Indonesia, within which the Merdeka Curriculum serves as a key curriculum framework. Jahudin et al. (2025) argue that meaningful implementation of the Merdeka Belajar reform application requires teachers to shift their orientation, from being content deliverers to being industry-engaged facilitators of transdisciplinary learning—a reconceptualization the P5 mechanism formally mandates but professional development infrastructure does not yet systematically guarantee.

Takiyudin et al. (2025) offer a concrete case: A curriculum for automotive engineering that is based on contextual teaching and learning strengthens hard and soft skills when it is grounded in real industrial workshop scenarios, consistent with the curriculum's locally relevant design principle. Majuita et al. (2025) and Perez et al. (2025) extend the same logic to digital technology by reporting that embedding technology tools in student-centered designs improves content mastery, digital literacy, and motivation.

Formal alignment between SMK curricula and industry competency requirements sits at the heart of the Merdeka Curriculum; this is addressed directly by most articles. Suhud (2025) found that systematic DUDI involvement in curriculum development narrowed the education–industry gap and increased local graduate absorption, thereby illustrating the potential of KOSP to produce industry-aligned curricula. Haifani et al. (2025) propose outcome-based education as a curricular framework for this alignment, by linking curriculum components to measurable, job-relevant outcomes and calling for periodic outcome reviews as a formal KOSP output.

Two studies reveal that the alignment gap is often categorical rather than incremental: Dwiyanti (2021) found logistics graduates lacked entire competency categories—digital supply chain management, AI-based inventory systems, smart warehouse automation—which reflects fundamental curriculum obsolescence, while Yulianto et al. (2025) and Wicaksono et al. (2025) identified the same pattern in accounting education, where cloud-based systems, AI-assisted bookkeeping, and digital financial reporting remain absent from curricula despite being baseline professional expectations. Saqinah et al. (2025), studying culinary and hospitality SMKs, confirmed that substantive—not merely administrative—link-and-match practice measurably improves graduate job prospects.

Despite the progressive design of the Merdeka Curriculum, its application faces recurring structural constraints, with teacher preparedness being the most consistently cited obstacle. Perez et al. (2025) found the integration of digital skills to be widely endorsed in principle but shallow in practice outside informatics programs, which reflects a systemic rather than individual capacity gap. Febrina and Sulasmi (2025) document that future skills—digital fluency, adaptive problem-solving, collaborative capacity—are insufficiently specified in the Indonesian vocational curriculum, which leaves teachers without a reliable basis for design or assessment. Wala and Wala (2025) show that entrepreneurship education can be implemented effectively in practice when teacher content knowledge and module quality are both high but noted that field-specific entrepreneurship materials are largely absent in other vocational fields. Mustaqim et al. (2025) identify teacher readiness as the binding constraint on problem-based flipped learning-STEM (PBFL-STEM practice, despite strong student support for its adoption (87.9%). Takiyudin et al. (2025) found that contextual teaching and learning in automotive education depended heavily on teachers' ability to connect instruction to current—rather than historical—industry practice.

Collectively, these findings show Merdeka Curriculum implementation in vocational schools converging on project-based pedagogy, DUDI collaboration, and TeFa/SMK PK-based ecosystems. Implementation quality, however, remains uneven and constrained by disparities in school capacity, teacher readiness, and the sustainability of industry partnerships, thereby leaving vocational pedagogical transformation structurally incomplete.

4.2 Integrated Industry 4.0 Competencies and Implementation Impact

The literature review reveals a set of Industry 4.0 competency clusters that consistently emerge as targets and outcomes of innovative learning models in SMK. Critical thinking is the most frequently mentioned competency, appearing explicitly or implicitly in nearly all 30 articles reviewed.

Empirical evidence for its development through innovative models is strong: Sukatiman et al. (2026) report the largest effect size in the corpus (η^2 = .329) for flipped PjBL-augmented reality, compared to conventional instruction, with analysis and explanation identified as the strongest subdimension; despite a relatively small sample (n = 20), Maknun and Herman (2024) found a high effect size (d = 0.83) for physics project team learning integrated with vocational worksheets; and Adit et al. (2025) demonstrate that work-based learning higher order thinking skills employability (WBL-HOTSE) achieved 80–90% practicality scores for development of critical thinking, even in a very limited technology environment in SMK in the 3T (Tertinggal, Terdepan, Terluar) region. The consistency of improvement in critical thinking across studies with diverse methodologies, from rigorous multi-school quasi-experiments to R&D practicality studies in remote areas, establishes it as a competency that reliably responds to active, inquiry-driven pedagogical interventions, regardless of the domain context.

Problem-solving competencies are closely related to critical thinking—an emphasis on generating applied solutions rather than analytical evaluation constitutes the second dominant competency cluster. Chrismondari et al. (2025) confirm significant problem-solving improvements when PBIL is used for electric motor installation; in that study, the experimental group significantly outperformed the control group in all skills dimensions. Akmal et al. (2025) corroborated this finding in the industrial automation domain through a quasi-experimental STEM-PBL experiment that found that problem-solving improvements were accompanied by improvements in theoretical knowledge and practical skills integration. The PBL integrated with digital literacy (PBL-DL) approach to EFI diagnosis demonstrates that creative problem-solving responds significantly to the integration of digital literacy in the PBL framework (Ramdani et al., 2025). The convergence of problem-solving improvements across PBIL, STEM-PBL, PBL-DL, and PBFL-STEM contexts strongly suggests that the active, inquiry-driven structure shared by these approaches is the mechanism at play and has implications for how pedagogical innovations should be designed and evaluated across vocational fields.

The 4C competencies (critical thinking, creativity, collaboration, and communication) serve as the primary lens for framing Industry 4.0 readiness in most Scopus articles. Through their STEAM-PjBL model, Thaha et al. (2025) report improvements across all four 4C dimensions at the cognitive, affective, and psychomotor levels. However, theoretically significant cross-model patterns of differing competency responses emerged from the corpus. Communication was consistently the weakest and most inconsistent improvement compared to the other three 4Cs. Yusuf et al. (2023) found that, although STEM-PjBL was positively correlated with all 4Cs, communication had the weakest association and was influenced by factors beyond the model's instructional design.

Efendi et al. (2025) report a similar pattern for augmented reality mobile learning; they found that communication and collaboration were less responsive than creativity and critical thinking. This communication gap across models is not a minor or unique finding; it is a structural feature of project-centered and technology-mediated learning designs that prioritize artifact production and individual inquiry over dialogic exchange, peer-to-peer argumentation, and collaborative meaning-making through language. Given that communication, including human–machine communication, multi-stakeholder negotiation, and ethical discourse, is positioned as a central human-centered competency in the industry 5.0 vision. This gap demands explicit attention in instructional design for the future.

Digital literacy and AI-related competencies represent the fastest-growing and most strategically significant clusters in the reviewed literature. Integrating digital literacy in a PBL framework simultaneously enhances diagnostic creativity and improves students' access to learning resources—making digital tools both objects of learning and instruments for improving learning. The operationalization of AI integration in PBL for a science vocational context demonstrates that the AI-PBL model can be developed in a valid, practical, and effective manner in the SMK environment (Ramdani et al., 2025).

The results of the curriculum innovation analysis suggest that technology-based learning should be systematically integrated across all vocational fields rather than limited to informatics programs systemic design principle enabled by the flexible architecture of the Merdeka Curriculum but not yet enforced through curricular mechanisms (Perez et al., 2025). Employability and job readiness are key concerns in the academic corpus. Haifani et al. (2025) demonstrate that outcome-based education structurally reduces curriculum–industry mismatch by linking each curriculum component to measurable job-relevant outcomes;

however, gaps persist despite the presence of bridging and matching mechanisms. This finding demonstrates the inadequacy of administrative partnerships without substantial curriculum redesign.

Industry–school collaboration as a driver of structural competency, rather than pedagogical interventions, emerged in studies of TeFa, SMK PK, and DUDI partnerships, as an institutional factor that determines the quality of graduate competency. Industry collaboration has a direct positive effect on curriculum relevance and has cascading effects on competency outcomes (Tanjung et al., 2025). These findings position collaboration not only as contextual support but also as a core mechanism for competency development. Usman et al. (2024) corroborate this finding at the ecosystem level by reporting that technopark integration produces competency effects that go beyond what can be achieved by individual classroom interventions, by applying the architecture of school–industry–community knowledge flows.

Nurodanika and Gunadi (2026) add a diagnostic dimension in the form of mind mapping in collaborative learning, as a practical tool for visualizing the complete landscape of partnership components, such as curriculum alignment, utilization of teaching factories, and graduate absorption, as well as identifying which components function effectively and where implementation gaps remain, thus enabling evidence-based prioritization for partnership improvement efforts. Prianto et al. (2025) provides a longitudinal perspective and shows through observations over four semesters that cumulative participation in practical learning activities reinforces the view that the development of Industry 4.0 competencies is a continuous development process and not an outcome that can be achieved through separate instructional episodes.

4.3 Implementation Challenges and Strategic Directions for the Transition Toward Industry 5.0

Industry 5.0 extends and humanizes the industry 4.0 technological paradigm by emphasizing sustainability, resilience, and human-centered values alongside advanced digital intelligence, which demands a corresponding evolution in vocational education strategies. Although the articles reviewed in this study are largely framed in the context of Industry 4.0, they converge on a coherent set of forward-looking strategies that are organized at three levels: pedagogical, curricular–institutional, and system–policy, each of which is shadowed by a corresponding implementation challenge that constrains its realization in practice. Read together, these strategies and challenges chart both what SMK should pursue to prepare graduates for Industry 5.0, and the structural obstacles that future research and policy must resolve.

The most pressing pedagogical imperative identified in the literature is the integration of AI as both a learning context and a pedagogical instrument. Majuita et al. (2025) determined that an AI-PBL model can be effectively developed and implemented in SMK. These findings provide evidence that the AI-PBL concept should be expanded beyond the vocational science context to encompass automotive, informatics, logistics, and other high-need vocational fields. Perez et al. (2025), argue that the curricular mandate of digital tools, including AI applications, should be integrated in all vocational programs as systemic literacy rather than as specialist electives. The next logical step, implied by the PBL-DL model (Ramdani et al., 2025) and PBFL-STEM findings (Mustaqim et al., 2025), is the development of AI-augmented learning designs in which students learn to work alongside intelligent systems, interpret AI-generated output, and use human judgment in the context of AI-assisted vocational decision-making. That study proposes a competency profile that prepares graduates directly for human–AI collaboration in the Industry 5.0 workplace. Augmented reality and immersive learning environments constitute a second high-priority pedagogical direction:

Models enriched by augmented reality consistently produce significant cognitive and affective improvements in SMK contexts (Efendi et al., 2025; Purnomo, 2025; Sukatiman et al., 2026), which point toward digital twin- and metaverse-based environments in which students can simulate, iterate, and reflect complex sociotechnical scenarios that approximate future industrial realities. Realizing this potential at scale is, however, constrained by a concrete implementation barrier: the high cost of AR hardware limits the number of schools that can realistically adopt immersive technology models, which raises equity concerns about differential access (Efendi et al., 2025; Purnomo, 2025). The persistent communication and collaboration gap observed across augmented reality studies indicates that current designs underdevelop the very interpersonal competencies immersive learning is meant to strengthen.

Human-centered skills, including ethical reasoning, cultural competence, empathy, and social responsibility, emerge as systematically under-recognized skills in standard vocational pedagogy, despite their critical importance to the Industry 5.0 vision. Budhyani et al. (2025), using a transformative multicultural education model, demonstrated that design thinking and decision-making skills significantly improve when cultural diversity is treated as a generative pedagogical resource rather than a contextual variable. Jahudin et al. (2025) provides a theoretical framework for this direction and argues that industry-based transdisciplinary pedagogy creates conditions for human-centered competency development that subject-specific or purely technical instruction cannot achieve.

Wala and Wala (2025) demonstrate a parallel principle in the entrepreneurship domain: Integrating business legal literacy with fashion entrepreneurship produces genuine readiness for value-creating professional practice only when grounded in the learner’s authentic vocational identity. Set against these strategic directions, however, is a specific and persistent implementation gap: Reviewed studies report that communication performance is consistently subpar relative to the other 4C competencies (Efendi et al., 2025; Purnomo, 2025; Yusuf et al., 2023). Because the human-centered workplace envisioned by Industry 5.0 requires communication across human–machine boundaries, multi-stakeholder ethical discourse, and collaborative value creation through language, this finding represents the most acute competency deficit precisely where it will have the greatest impact.

At the curriculum level, evidence strongly supports a transition from a static, content-centered curriculum to a dynamic, outcomes-driven system that is capable of responding nimbly to industry evolution. Haifani et al. (2025) provides an outcome-based education framework for this transition and demonstrates that when curriculum components are grounded in measurable outcomes—and regularly reviewed against industry standards—chronic mismatches between curriculum content and industry expectations are systematically reduced.

The KOSP Merdeka Curriculum mechanism provides a structural opportunity for this agility, but gap analysis documents that this opportunity has not been consistently realized: Dwiyanti (2021) presents the most striking example, by reporting that the SMK logistics curriculum is missing entire competency categories—digital supply chain, AI inventory systems, smart warehousing—that are now standard expectations in Indonesia's logistics industry, while Yulianto et al. (2025) and Wicaksono et al. (2025) document similar categorical gaps in accounting (cloud systems, AI bookkeeping) and Ridho et al. (2025) in automotive engineering (electric vehicle systems, connected vehicle diagnostics).

These are gaps that reflect fundamental curriculum obsolescence in rapidly evolving sectors, and appear even where formal, interconnected, and appropriate industry partnerships exist. Nurodanika and Gunadi (2026) offer a practical diagnostic response and use collaborative learning mind mapping to systematically identify such gaps across the eight link-and-match (8+i) components and enable evidence-based curriculum prioritization in the KOSP framework. TeFa, when implemented with full institutional governance, represents the most mature mechanism currently available for embedding Industry 5.0 readiness in SMK structures.

Wahjusaputri and Bunyamin (2022) report that its effectiveness spans all institutional dimensions, such as management, human resources, workshop infrastructure, learning patterns, and DUDI relationships, and, therefore, requires systemic institutional transformation rather than isolated adoption. A crucial next step is to expand TeFa to emerging domains such as electric vehicle systems, smart manufacturing, healthcare technology, sustainable logistics, and green energy, thereby directly aligning SMK preparation with the sustainability and technological imperatives of Industry 5.0 (Ridho et al., 2025; Takiyudin et al., 2025).

At a systemic level, inadequate technological infrastructure emerged as the most consistently cited barrier to realizing pedagogical innovation, and investment in infrastructure is correspondingly identified as a prerequisite for that innovation to reach equitable scale (Efendi et al., 2025; Mustaqim et al., 2025; Purnomo, 2025). The barrier persists even in urban SMK contexts, where students rely on personal smartphones in the absence of dedicated technology (Mustaqim et al., 2025), thereby revealing a gap between the requirements of innovative models and the realities of institutional provision that improvised adaptation cannot close. This equity challenge reaches its most critical expression in 3T regions, where the WBL-HOTSE model, designed for offline and low-bandwidth integration, documents the most extreme manifestation of infrastructure inequity (Adit et al., 2025). Students in underserved geographic contexts are systematically denied access to the digital and immersive learning capabilities available to their urban peers, thereby producing a stratification of digital competencies that undermines both the equity goals of the Merdeka Curriculum and the inclusion mandate of Industry 5.0.

A second major structural challenge is the gap between the pedagogical sophistication that innovative models demand and the professional preparation of the average SMK teacher. Professional development systems have not adequately prepared teachers for the level of curriculum autonomy, technology integration, and learning design sophistication demanded by Merdeka Belajar (Febrina & Sulasmi, 2025; Mustaqim et al., 2025; Perez et al., 2025; Takiyudin et al., 2025). Jahudin et al. (2025) argue that meaningful, industry-based transdisciplinary pedagogy requires a fundamental reconceptualization of teachers' professional identity that episodic in-service training cannot achieve but that a sustained professional learning community throughout a teacher's career can.

Because the gap between the competency-development potential of innovative models and the quality of their actual implementation is largely a teacher capacity gap, future policy should invest in structured professional learning communities at the inter-school level of the SMK PK system, develop a validated teacher readiness Industry 5.0 pedagogy assessment instrument, and create incentive structures that reward continuous pedagogical innovation over mere curriculum compliance. Correspondingly, the field currently has strong evidence on model effectiveness in supported or experimental settings but very limited evidence on what configurations of professional development produce sufficient teacher competencies to sustain innovation at scale in the absence of researcher support.

Underlying all the strategies in the reviewed literature is a structural condition that identifies as a precondition for their success: multi-stakeholder governance involving government, industry, higher education, and community actors. Formalized and well-managed industry partnerships consistently produce better competency outcomes than schools operating without structured collaboration (Nurodanika & Gunadi, 2026; Tanjung et al., 2025; Usman et al., 2024), which suggests that policy should shift from merely encouraging DUDI collaboration, toward institutionalizing it through long-term, multi-year partnership contracts with shared accountability, joint curriculum committees, and industry-funded professional development programs.

A further structural gap this finding identifies is a persistent replication problem. Local innovations from SMK PK schools rarely generate system-wide impact. Developing a national SMK innovation knowledge management system that captures, validates, and disseminates curriculum and pedagogical innovations from SMK PK to the broader system would address this gap directly, and convert isolated pockets of good practice into a durable, scalable foundation for Indonesia's vocational education transition toward Industry 5.0.

5. Discussion

5.1 Pedagogical Transformation of the Merdeka Curriculum for Vocational Education Oriented Toward Industry 4.0

The predominance of PjBL and its STEM/STEAM-integrated variants indicates that implementation of the Merdeka Curriculum in SMK is increasingly characterized by learner-centered and competency-oriented pedagogies. Rather than functioning merely as a project assignment, PjBL facilitates authentic learning experiences that integrate technical knowledge, practical problem-solving, collaboration, and workplace simulation (Akmal et al., 2025; Chrismondari et al., 2025; Prianto et al., 2022).

This interpretation is consistent with recent systematic reviews that found that project-oriented vocational learning is most effective when authentic industry contexts and competency-based assessment are embedded in curriculum application, rather than treated as supplementary activities. This interpretation aligns with recent systematic reviews that demonstrate that project-based vocational learning yields stronger learning outcomes when projects are situated in authentic industrial contexts, supported by external stakeholders, and accompanied by competency-based assessment integrated throughout curriculum application (Kasili et al., 2025; Waheed, 2026).

TeFa represents a qualitatively different form of pedagogical innovation because its effectiveness extends beyond classroom instruction to institutional transformation. The reviewed studies demonstrate that TeFa strengthens competency development through the integration of curriculum, industrial production, school management, and partnerships with industry (Tanjung et al., 2025; Wahjusaputri & Bunyamin, 2022). This interpretation is supported by recent systematic reviews that identify industry collaboration, institutional governance, teacher expertise, infrastructure readiness, and sustainable partnerships as the principal determinants of successful TeFa implementation. Rather than operating solely as a production-based learning model, TeFa functions as an institutional ecosystem that connects vocational education with authentic industrial practice (Putra et al., 2025; Siagian et al., 2025).

The present findings suggest, furthermore, that technology-enhanced pedagogies should be interpreted as complementary mechanisms rather than alternative instructional models. Across the reviewed studies, augmented reality consistently enhanced students' conceptual understanding, practical performance, and learning motivation by supporting experiential and visualization-based learning (Purnomo, 2025; Sukatiman et al., 2026). Recent systematic reviews, similarly, conclude that immersive technologies produce the greatest educational benefits when they are integrated with active learning strategies rather than used as stand-alone instructional tools. Their effectiveness depends primarily on well-designed pedagogical activities, appropriate instructional design, and effective teacher facilitation, rather than on the immersive technology itself (Liu et al., 2024; Mohamad et al., 2024; Selvakumar & Sivakumar, 2025).

Collectively, these findings suggest that the effectiveness of pedagogical innovation under the Merdeka Curriculum depends not only on the selection of instructional models but also on the alignment between curriculum design, instructional implementation, digital technologies, teacher capability, institutional governance, and industry engagement. Conceptualized curriculum transformation is a system-level process that requires coherent coordination across educational, organizational, and industry stakeholders to achieve sustainable vocational education reform (Mende et al., 2025; Mustakim et al., 2024).

5.2 Integrating Industry 4.0 Competencies in Vocational Learning: Implications for Competency Development

The findings indicate that the integration of Industry 4.0 competencies in Indonesian vocational education extends beyond technical proficiency and increasingly incorporates transversal competencies required for technology-enabled workplaces. Across the reviewed studies, critical thinking, problem-solving, collaboration, creativity, and digital literacy emerged as the competencies most consistently embedded in vocational learning (Efendi et al., 2025; Maknun & Herman, 2024; Sukatiman et al., 2026; Yusuf et al., 2023).

This pattern suggests that vocational education has gradually shifted from preparing students for routine occupational tasks toward developing adaptive capabilities required to respond to rapidly changing industrial environments (Ortiz-Terrinches et al., 2026). Such a transition reflects the evolving nature of Industry 4.0: Occupational performance depends not only on technical expertise but also on the ability to analyze information, solve complex problems, collaborate across disciplines, and continuously adapt to technological change (Imama et al., 2025; Vázquez-Villegas & Borrego, 2026).

Despite the overall improvement in Industry 4.0 competencies, the reviewed studies consistently indicate that communication remains the least-developed competency in diverse vocational learning contexts (Akmal et al., 2025; Efendi et al., 2025; Prianto et al., 2022; Usman et al., 2024; Yusuf et al., 2023). This recurring pattern suggests that the current implementation of competency-based vocational learning tends to emphasize technical problem-solving, project completion, and individual task performance, while providing fewer opportunities for structured dialogue, collaborative reflection, negotiation, and professional communication. This finding is particularly significant because effective communication has become a core competency for interdisciplinary collaboration, knowledge sharing, and human–technology interaction in Industry 5.0 workplaces (Taqwa et al., 2026; Vázquez-Villegas & Borrego, 2026).

Digital transformation has expanded the competency profile required of vocational graduates beyond technical expertise to include communication, teamwork, collaborative problem-solving, and the ability to work effectively in technology-mediated and multidisciplinary environments (Ma & Ismail, 2025). This interpretation reinforces the argument of Jahudin et al. (2025) that the integration of digital technologies into vocational education requires graduates not only to master technical and digital competencies but also to communicate effectively in multidisciplinary teams and digitally connected workplaces. Therefore, strengthening communication should not be viewed as a complementary aspect of vocational learning but as a core competency that supports the successful application of technical and digital expertise in increasingly collaborative industrial settings.

Recent international reports consistently indicate that workforce readiness is increasingly shaped by the integration of technical, digital, cognitive, and transversal competencies rather than by excellence in any single competency domain (OECD, 2025; World Economic Forum, 2025). Workers are expected to integrate digital literacy, critical thinking, communication, collaboration, and lifelong learning with occupational expertise to navigate increasingly complex, technology-mediated, and multidisciplinary work environments (Zeng & Della, 2025). This shift reflects a broader transition from occupation-specific competence toward adaptive and transferable competency profiles that enable individuals to respond effectively to continuous technological and organizational change (Kurnia et al., 2026; Lecours et al., 2026).

Consequently, competency integration in vocational education should be understood not as the accumulation of discrete knowledge and skills but as the development of an interconnected competency profile that enables graduates to apply, transfer, and continuously adapt their capabilities across diverse workplace contexts. Such an orientation is increasingly recognized as essential for aligning vocational education with contemporary labor market expectations, according to which sustainable workforce performance depends on the dynamic interaction of technical, digital, cognitive, and interpersonal competencies.

5.3 Addressing Implementation Challenges and Transitional Strategies Toward Industry 5.0

The reviewed studies collectively indicate that the transition toward Industry 5.0 is constrained by systemic implementation challenges that extend beyond classroom pedagogy. Although diverse pedagogical innovations have demonstrated positive effects on students' competency development, their implementation remains uneven because schools differ substantially in institutional readiness, technological infrastructure, teacher capability, and the quality of industry partnerships (Tanjung et al., 2025; Usman et al., 2024; Wahjusaputri & Bunyamin, 2022). These findings suggest that pedagogical innovation alone is insufficient to sustain curriculum transformation. Addressing these challenges requires a system-wide implementation strategy that simultaneously strengthens institutional capacity, expands industry collaboration, and aligns curriculum implementation with local resource conditions, rather than assuming that successful instructional models can be uniformly transferred across vocational schools (Mende et al., 2025; Nidhom et al., 2025).

Unequal access to digital infrastructure represents one of the most significant barriers to equitable implementation. While immersive technologies such as augmented reality have demonstrated considerable potential for improving vocational learning, their high implementation costs limit adoption, particularly by schools with constrained financial and technological resources (Purnomo, 2025; Sukatiman et al., 2026). Similarly, the WBL-HOTSE model illustrates that vocational schools in remote and underserved (3T) regions require infrastructure-adaptive learning models rather than technology-intensive approaches that were developed for well-resourced schools (Adit et al., 2025). Therefore, addressing this challenge requires differentiated implementation strategies that are responsive to local contexts rather than uniform approaches to digitalization.

Recent evidence suggests that effective technology integration depends on aligning digital innovation with institutional readiness, teacher capacity, infrastructure availability, and local resource conditions (Amemasor et al., 2025; Kurnia et al., 2026). Accordingly, policymakers should prioritize scalable and context-responsive learning models that combine online, offline, and low-bandwidth solutions, while progressively strengthening digital infrastructure across regions. Such an approach would reduce disparities in students' opportunities to acquire Industry 50 competencies and better support equitable vocational education transformation.

A second implementation challenge concerns the conceptual orientation of curriculum reform. Most reviewed studies continue to evaluate vocational education using Industry 4.0 indicators that emphasize digitalization, automation, and technical competency development, whereas considerably less attention is given to human-centered innovation, sustainability, resilience, ethical decision-making, and human–technology collaboration (Jahudin et al., 2025; Wahjusaputri & Bunyamin, 2022). This imbalance indicates that curriculum transformation remains predominantly technology-driven despite the broader aspirations of Industry 5.0. Addressing this gap requires vocational curricula to explicitly integrate human-centered competencies alongside digital and technical competencies.

Rather than treating these competencies as complementary outcomes, curriculum designers should embed them in learning objectives, authentic assessment, and industry-based learning experiences to ensure that graduates are prepared for increasingly collaborative and sustainable industrial environments. This perspective aligns with emerging evidence that Industry 5.0 demands integrated competency frameworks in which human-centric capabilities, including collaboration, adaptability, ethical decision-making, and systems thinking, are developed concurrently with technical and digital expertise (Carminati et al., 2025; Fernando et al., 2025)

A synthesis of the reviewed evidence suggests that the transition toward Industry 5.0 should be approached through four interrelated implementation priorities. First, infrastructure investment should focus on ensuring equitable access to technology-enhanced learning across diverse regional contexts. Second, curriculum renewal should continuously integrate emerging industrial technologies while strengthening human-centered, ethical, and sustainability-oriented competencies. Third, teacher professional development should evolve from episodic training to sustained professional learning communities supported by industry partnerships and continuous updating of technology. Finally, governance mechanisms should institutionalize long-term collaboration among schools, industry, government, and professional organizations to ensure that curriculum innovation remains responsive to workforce transformation.

6. Conclusion

The purpose of this systematic literature review is to synthesize evidence on pedagogical approaches, Industry 4.0 competency integration, and implementation challenges related to the implementation of the Merdeka Curriculum in SMK. The findings indicate that active and industry-oriented pedagogical approaches, particularly PjBL, TeFa, and technology-mediated learning, strengthen students' technical, digital, and higher order thinking competencies. However, competency development remains uneven, and communication consistently emerges as the least-developed competency in the reviewed studies.

The review, furthermore, demonstrates that successful curriculum implementation depends not only on pedagogical innovation but also on institutional readiness, teacher capability, curriculum responsiveness, industry collaboration, and equitable access to digital infrastructure. Collectively, these findings suggest that preparing vocational education for Industry 5.0 requires a systemic transformation that integrates pedagogical, institutional, and technological dimensions, rather than relying solely on curriculum reform or instructional innovation.

This review is subject to several limitations. First, the literature search was limited to the Scopus and Google Scholar databases and to publications published between 2021 and 2026. Although these sources were selected to ensure broad coverage of peer-reviewed and relevant scholarly literature, potentially eligible studies indexed in other databases or published outside the selected timeframe may not have been captured. Second, the available evidence was predominantly derived from short-term intervention studies conducted at Indonesian vocational schools; we found little longitudinal evidence examining graduates' competency transfer into workplace settings. Furthermore, most studies were framed by Industry 4.0 perspectives and provided relatively limited evidence of the implementation of human-centered and sustainability-oriented competencies associated with Industry 5.0.

Future research should, therefore, investigate longitudinal competency development, evaluate graduates' workplace performance in different industrial sectors, and examine how communication, collaboration, sustainability, and human-centered competencies can be systematically integrated in vocational curricula and authentic learning environments. Comparative studies across regions and vocational disciplines are also needed to identify implementation strategies that are responsive to diverse institutional capacities and technological contexts.

Conflict of Interest
The authors declare that there are no conflicts of interest regarding the publication of this article.

7. Acknowledgments
The authors acknowledge the limited use of generative AI tools, including paraphrasing and language enhancement applications (e.g., QuillBot and Grammarly), solely for the purpose of language refinement in the preparation and editing of this work. The authors are solely responsible for all ideas, analyses, interpretations, and conclusions expressed in this research.

8. References
Abbu, H., Khan, S., Mugge, P., & Gudergan, G. (2025). Building digital-ready leaders: Development and validation of the human-centric digital leadership scale. *Digital*, *5*(1), 7. https://doi.org/10.3390/digital5010007

Adit, F., Aryanto, J., Fitra Andikos, A., & Andre, L. (2025). Practicality of developing the work-based learning higher order thinking skills employability (WBL-HOTSE) model to improve critical thinking ability in 3T regional vocational high schools. *Data and Metadata*, *4*. https://doi.org/10.56294/dm2025654

Ahmanda, W., Maulana, A., Murtinugraha, R. E., & Arifah, S. (2022). Implementasi program SMK pusat keunggulan dilihat dari konsep 8+i link and match [Implementation of the SMK Center of Excellence Program seen from the 8+i Link and Match concept]. *Jurnal Pendidikan Teknik Bangunan*, *2*(2), 59–74. https://doi.org/10.17509/jptb.v2i2.51290

Akmal, A., Ambiyar, A., Usmeldi, U., & Fadillah, R. (2025). Developing and assessing the impact of an integrated STEM project-based learning model in vocational education for enhanced competence and employability. *Salud, Ciencia y Tecnología, 5,* Article 1786. https://doi.org/10.56294/saludcyt20251786

Amemasor, S. K., Oppong, S. O., Ghansah, B., Benuwa, B.-B., & Essel, D. D. (2025). A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, *10*. https://doi.org/10.3389/feduc.2025.1541031

Azahar, R., Hilhamsyah, H., Alim, M. I., Hartati, H., & Dirmayani, T. (2025). Fihsbone analysis: Challenges and strategies for implementing Merdeka Curriculum in vocational high schools. *Jurnal Riset dan Inovasi Pembelajaran*, *5*(2), 628–644. https://doi.org/10.51574/jrip.v5i2.3361

Badan Pusat Statistik. (2026). *Tingkat pengangguran terbuka berdasarkan tingkat pendidikan 2025 [Open unemployment rate by education level 2025]*. https://www.bps.go.id/id/statistics-table/2/MTE3OSMy/tingkat-pengangguran-terbuka-berdasarkan-tingkat-pendidikan.html

Barboutidis, G., & Stiakakis, E. (2023). Identifying the factors to enhance digital competence of students at vocational training institutes. *Technology, Knowledge and Learning*, *28*(2), 613–650. https://doi.org/10.1007/s10758-023-09641-1

Budhyani, I. D. A. M., Widiastini, N. W. E., Puger, I. G. N., & Yudiana, I. K. E. (2025). Strategies to enhance decision making and design thinking skills for industrial design. *Jurnal Ilmiah Ilmu Terapan Universitas Jambi*, *9*(3), 1319–1331. https://doi.org/10.22437/jiituj.v9i3.46287

Carminati, L., Lagorio, A., Cimini, C., Pirola, F., Jurczuk, A., & Boucher, X. (2025). Integrative skills framework for Industry 5.0: Insights from a systematic literature review and a European survey study. *Journal of Environmental Management 394,* Article 127425. https://doi.org/10.1016/j.jenvman.2025.127425

Chen, X., & Chan, S. (2024). Implementing digital pedagogy in TVET: A connectivist perspective. *Vocation, Technology & Education*, *1*(2). https://doi.org/10.54844/vte.2024.0595

Chigbu, B. I., & Makapela, S. L. (2025). AI in education, sustainability, and the future of work: An integrative review of Industry 5.0, Education 5.0, and Work 5.0. *Journal of Open Innovation: Technology, Market, and Complexity*, *11*(4), Article 100645. https://doi.org/10.1016/j.joitmc.2025.100645

Chrismondari, Simatupang, W., Waskito, Fadillah, R., & Rianto, B. (2025). Implementation of a project-based inquiry learning model for electrical motor installation: Evaluating its effectiveness in vocational education. *Data and Metadata*, *4*, Article 1079. https://doi.org/10.56294/dm20251079

Ditjen Pendidikan Vokasi PKPLK. (2024). *Gencarkan kolaborasi dengan industri,Kkurikulum Merdeka tingkatkan pembelajaran di SMK [Merdeka Curriculum boosts collaboration with industries, improves learning in vocational schools]*. Kementerian Pendidikan Dasar dan Menengah [Ministry of Primary and Secondary Education]. https://vokasi.kemendikdasmen.go.id/read/b/gencarkan-kolaborasi-dengan-industri-kurikulum-merdeka-tingkatkan-pembelajaran-di-smk

Dwiyanti, V. (2021). Penguatan penyiapan kompetensi lulusan smk teknik logistik yang dibutuhkan industri logistik [Strengthening the preparation of vocational high school graduates' competencies in logistics engineering needed by the logistics industry]. *Lentera Karya Edukasi*, *1*(2), 61–69. https://doi.org/10.17509/lekaedu.v1i2.35943

Dzulkurnain, M. I., Aminuddin, A., Hammood, W. A., Abdullah, K. H., & Alam Miah, M. B. (2024). Optimizing students' practical skills through project-based learning: Case study in vocational high schools. *International Journal of Evaluation and Research in Education*, *13*(5), Article 3151. https://doi.org/10.11591/ijere.v13i5.28694

Efendi, R., Ambiyar, Estuhono, & Wulandari, R. A. (2025). Bridging the Industry 4.0 skills gap: An immersive augmented reality mobile learning approach for vocational education. *International Journal of Interactive Mobile Technologies*, *19*(06), 60–74. https://doi.org/10.3991/ijim.v19i06.53825

Elragal, A., & Habibipour, A. (2025). Operationalizing Education 4.0: A structured method for course materials and assessment alignment. *Frontiers in Education*, *10*. https://doi.org/10.3389/feduc.2025.1694545

Febrina, I., & Sulasmi, E. (2025). Pendekatan inovatif untuk mempersiapkan siswa menghadapi dunia kerja dalam kurikulum berbasis keterampilan [An innovative approach to preparing students for the world of work in a skills-based curriculum]. *Serunai : Jurnal Ilmiah Ilmu Pendidikan*, *11*(2). https://doi.org/https://doi.org/10.37755/sjip.v11i2.2076

Fernando, A. R., Ghazali, N. E. b., Phang, F. A., & Rahman, N. F. A. (2025). Competencies of a holistic engineer: Towards the development of a competency model and curriculum framework for future-proof engineers. *European Journal of Engineering Education*, *50*(6), 1305–1345. https://doi.org/10.1080/03043797.2025.2584067

Ghamrawi, N., Shal, T., Ghamrawi, N. A. R., Abu-Tineh, A., Alshaboul, Y., & Alazaizeh, M. A. (2025). A step-by-step approach to systematic reviews in educational research. *European Journal of Educational Research*, *14*(2), 549–566. https://doi.org/10.12973/eu-jer.14.2.549

González-Pérez, L. I., & Ramírez-Montoya, M. S. (2022). Components of Education 4.0 in 21st century skills frameworks: Systematic review. *Sustainability (Switzerland)*, *14*(3), Article 1493. https://doi.org/10.3390/su14031493

Guzmán Hernández, R. (2024). TVET pedagogy: Towards an innovative and sustainable educational model. *Revista Scientific*, *9*(31), 10–20. https://doi.org/10.29394/Scientific.issn.2542-2987.2024.9.31.0.10-20

Haifani, M. F., Wijayanti, R., Sutopo, A., & Sutama. (2025). Integration of vocational high school curriculum with industry needs based on outcome-based education. *El Midad: Jurnal Jurusan PGMI*, *17*(3), 859–871. https://ftkjournal-uinmataram.id/index.php/elmidad/article/view/14677

Hamdi, S., Triatna, C., & Nurdin, N. (2022). Kurikulum Merdeka dalam perspektif pedagogik [The independent curriculum from a pedagogical perspective]. *Susunan Artikel Pendidikan*, *7*(1). https://doi.org/10.30998/sap.v7i1.13015

Handito, T., Mulyono, H., & El Khuluqo, I. (2026). Teaching factory and computational thinking in Asian vocational education: A bibliometric analysis of the Scopus database 2015–2025. *Discover Education, 5*(1). https://doi.org/10.1007/s44217-026-01521-x

Hongli, Z., & Wai Yie, L. (2024). Industry 5.0 and Education 5.0: Transforming vocational education through intelligent technology. *Journal of Innovation and Technology*, *2024*(1). https://doi.org/10.61453/joit.v2024no16

Imama, D. D., Ismara, K. I., Sudira, P., & Maryadi, T. H. T. (2025). Bridging the digital skills gap: A systematic literature review of technology adaptability in vocational education and training. *International Journal of Research and Innovation in Social Science*, *8*, 2983–2999. https://doi.org/10.47772/IJRISS.2025.906000219

Indarta, Y., Jalinus, N., Waskito, Samala, A. D., Riyanda, A. R., & Adi, N. H. (2022). Relevansi Kurikulum Merdeka Belajar dengan Model pembelajaran abad 21 dalam perkembangan era Society 5.0 [The relevance of the independent learning curriculum with 21st century learning models in the development of the Society 5.0 era]. *Edukatif: Jurnal Ilmu Pendidikan*, *4*(2), 3011–3024.

International Labor Organization. (2024). *Global employment trends for youth 2024: Decent work, brighter futures* (20th anniversary ed.). https://doi.org/10.54394/ZUUI5430

Jaedun, A., Nurtanto, M., Mutohhari, F., Saputro, I. N., & Kholifah, N. (2024). Perceptions of vocational school students and teachers on the development of interpersonal skills towards Industry 5.0. *Cogent Education*, *11*(1). https://doi.org/10.1080/2331186X.2024.2375184

Jahudin, A. A., Amelia, A., & Madhakomala, R. (2025). Pedagodik transformatif berbasis industri: Pendekatan transdisipliner dalam implementasi Merdeka Belajar. *Jurnal Manajemen Pendidikan,* *13*(02), 191–200. https://journal.unpak.ac.id/index.php/JMP/article/view/12279

Jumani-Alwani, S. S. J. (2025, November 13). Comparison on vocational education and training across different national and international contexts. The Education And Development Forum (UKFIET). https://www.ukfiet.org/2025/comparison-on-vocational-education-and-training-across-different-national-and-international-contexts/

Kasili, M., Pramudibyo, S., Rahmandan, H., Lahamutu, M. R. A., Aldio, T., Yanino, R. M., & Umar, A. (2025). Systematic literature review (SLR) evaluasi implementasi kurikulum merdeka pada sekolah menengah kejuruan dalam menghadapi tantangan Industri 4.0 [Systematic literature review (SLR) on the evaluation of the implementation of the Merdeka curriculum in vocational high schools in facing the challenges of Industry 4.0.]. *Jambura Journal of Engineering Education*, *4*(2). https://doi.org/10.37905/jjee.v4i2.36061

Kholifah, N., Nurtanto, M., Sutrisno, V. L. P., Majid, N. W. A., Subakti, H., Daryono, R. W., & Achmadi, A. (2025). Unlocking workforce readiness through digital employability skills in vocational education graduates: A PLS-SEM analysis based on human capital Theory. *Social Sciences and Humanities Open*, *11*. https://doi.org/10.1016/j.ssaho.2025.101625

Kurnia, R., Syafar, A. M., & Oyovwi, E. O. (2026). Integrating digital skills in technical and vocational education: A systematic review in the context of Industry 4.0. *Journal of Vocational, Informatics and Computer Education*, *4*(2), 106–120. https://doi.org/10.66053/voice.v4i2.475

Lecours, A., Laribi, S., Laliberté, M., & Kiki, G. M. (2026). Mapping transversal competences for vocational education learners in response to transformations in the world of work: A scoping review. *Education + Training*, *68*(3), 323–340. https://doi.org/10.1108/ET-08-2025-0678

Lin, T.-C., Lee, Y.-S., & Ye, J.-H. (2024). A study on Taiwan's vocational senior high school teachers' teaching identity and teaching transformation when facing a new competency-based curriculum. *Frontiers in Psychology*, *15*. https://doi.org/10.3389/fpsyg.2024.1290551

Liu, Y., Zhan, Q., & Zhao, W. (2024). A systematic review of VR/AR applications in vocational education: Models, affects, and performances. *Interactive Learning Environments*, *32*(10), 6375–6392. https://doi.org/10.1080/10494820.2023.2263043

Ma, H., & Ismail, L. (2025). Bibliometric analysis and systematic review of digital competence in education. *Humanities and Social Sciences Communications*, *12*, Article 185. https://doi.org/10.1057/s41599-025-04401-1

Mafarja, N., Mohamad, M. M., Affandi, H. M., Ali, R. H. R. M., & Ahmad, A. (2025). Promoting thinking skills and inventive problem-solving skills through cybergogy approach for TVET learners. *Sage Open*, *15*(3). https://doi.org/10.1177/21582440251357150

Majuita, S., Hakim, L. E., & Ristanto, R. H. (2025). Pengembangan model pembelajaran problem-based learning (PBL) terintegrasi artificial intelligence untuk meningkatkan literasi sains dan keterampilan vokasional siswa. *CARONG: Jurnal Pendidikan, Sosial dan Humaniora*, *2*(4), 567–579. https://doi.org/10.62710/fqwaqf32

Maknun, J., & Herman, N. D. (2024). Developing critical thinking skills in vocational high school students through the application of physics project team learning model integrated with vocational-based worksheets. *Revista de Gestão Sociale Ambiental*, *18*(7), Article e05188. https://doi.org/10.24857/rgsa.v18n7-042

Mende, C., Oswald-Egg, M. E., & Caves, K. (2025). Vocational education and training (VET) system governance: A systematic literature review. *Journal of Vocational Education & Training*, *77*(5), 1419–1453. https://doi.org/10.1080/13636820.2025.2461586

Mohamad, S. A., Zaharudin, R., Ariffin, H. F., & Abdullah, S. (2024). A systematic review exploring the impact of augmented reality on teaching modules in vocational education. *Journal of Contemporary Social Science and Education Studies*, *4*(3), 177–189. https://doi.org/10.5281/zenodo.14064593

Mujiburrahman, M., Ratnaya, I. G., Parwata, I. G. L. A., & Budhyani, I. D. A. M. (2025). Evaluation of the merdeka curriculum in educational institutions: A systematic literature review of strategies, challenges, and student learning outcomes. *Jurnal Paedagogy*, *12*(4), 1255–1268. https://doi.org/10.33394/jp.v12i4.17078

Muliadi, M., Sutadji, E., Isnandar, I., & Widiyanti, W. (2025). Analysis of the mental readiness of technology and engineering students before industrial work practice. *Jurnal Inovasi Teknologi Pendidikan*, *12*(4). https://doi.org/10.21831/jitp.v12i4.85420

Mustakim, W., Giatman, M., Maksum, H., Abdullah, R., & Refdinal, R. (2024). Integration of policy and technology in vocational educational leadership: A systematic literature review. *Jurnal Pendidikan Teknologi Informasi dan Vokasional*, *6*(2), 131–146. https://doi.org/10.23960/jptiv.v6i2.33016

Mustaqim, B., Akhyar, M., Joyoatmojo, S., & Roemintoyo. (2025). A study of problem-based flipped learning of indonesian vocational high school students. *Journal of Teaching and Learning*, *19*(2), 80–97. https://doi.org/10.22329/jtl.v19i2.9292

Nayernia, H., Bahemia, H., & Papagiannidis, S. (2022). A systematic review of the implementation of Industry 4.0 from the organisational perspective. *International Journal of Production Research*, *60*(14), 4365–4396.

https://doi.org/10.1080/00207543.2021.2002964

Nidhom, A. M., Kamaruzaman, F. M., & Omar, M. B. (2025). A systematic review of factors shaping vocational teacher professional education implementation. *International Journal of Learning, Teaching and Educational Research*, *24*(4), 592–615. https://doi.org/10.26803/ijlter.24.4.27

Nurjanah, I., Ana, A., & Masek, A. (2022). Work readiness of vocational high school graduates in facing the Industrial 4.0 era. *Jurnal Pendidikan Teknologi dan Kejuruan*, *28*(2). https://doi.org/10.21831/jptk.v28i2.48552

Nurodanika, M., & Gunadi, G. (2026). Mind mapping in a collaborative learning model: Strengthening link-and-match (8+i) partnerships in center of excellence vocational schools. *Takuana: Jurnal Pendidikan, Sains, dan Humaniora*, *4*(4), 1505–1520. https://doi.org/10.56113/takuana.v4i4.352

OECD. (2025). *OECD Skills Outlook 2025: Building the skills of the 21st century for all*. OECD Publishing. https://doi.org/10.1787/26163cd3-en

Ortiz-Terrinches, J.-F., Sánchez-Cabrero, R., & Sandoval-Mena, M. (2026). Assessment and development of soft skills for workplace internships in vocational education and training: A systematic literature review. *Administrative Sciences*, *16*(7), Article 318. https://doi.org/10.3390/admsci16070318

Perez, C., Khasanah, F. N., Ismiyanti, Y., & Herman, H. (2025). Curriculum innovation and technology-based learning for digital skills in vocational education. *Jurnal MENTARI : Manajemen, Pendidikan dan Teknologi Informasi*, *4*(1), 94–104. https://doi.org/10.33050/mentari.v4i1.904

Pharamela, S., & Singh-Pillay, A. (2025). Technical and vocational education and training college lecturers and 21st-century skills: A wareness and implications for teaching practices. *Journal of Technical Education and Training*, *17*(2), 182–196. https://doi.org/10.30880/jtet.2025.17.02.013

Prianto, A., Firman, F., Mayasari, D., & Widoyoningrum, S. (2025). Teaching factory-based learning and its impact on students' employability skills. *International Journal of Learning, Teaching and Educational Research*, *24*(12), 215–240. https://doi.org/10.26803/ijlter.24.12.10

Prianto, A., Qomariyah, U. N., & Firman, F. (2022). Does student involvement in practical learning strengthen deeper learning competencies? *International Journal of Learning, Teaching and Educational Research*, *21*(2), 211–231. https://doi.org/10.26803/ijlter.21.2.12

Purnomo, S. (2025). Development of cooperative learning by technoprenuer for vocational schools-augmented reality model to improve the survival skills. *International Journal of Information and Education Technology*, *15*(9), 1884–1892. https://doi.org/10.18178/ijiet.2025.15.9.2389

Putra, R. C., Barliana, M. S., Komaro, M., & Hamdani, A. (2025). Bridging theory and practice: A systematic review of work-integrated learning frameworks in vocational education. *Journal of Vocational Education Studies*, *8*(2), 368–386. https://doi.org/10.12928/joves.v8i2.12766

Ramdani, S. D., Nurtanto, M., Supriyatna, D., Mutohhari, F., Sutrisno, V. L. P., Setiadi, B. R., Pratiwi, H., & Fatin, N. N. (2025). Embedding digital literacy into problem-based learning to foster creativity in diagnosing EFI systems: A vocational education innovation. *Salud, Ciencia y Tecnologia, 5,* Article 1938. https://doi.org/10.56294/saludcyt20251938

Rehman, N., Huang, X., Mahmood, A., AlGerafi, M. A. M., & Javed, S. (2024). Project-based learning as a catalyst for 21st-century skills and student engagement in the math classroom. *Heliyon*, *10*(23), Article 39988. https://doi.org/10.1016/j.heliyon.2024.e39988

Ridho, N. A., Shaffiyyah, R., Z, S. S., Putri, T. A., & Arifah, U. N. (2025). Inovasi kurikulum teaching factory di sekolah menengah kejuruan program keahlian teknik kendaran ringan [Curriculum innovation for teaching factories in vocational high schools with a light vehicle engineering program]. *Integrative Perspectives of Social and Science Journal*, *2*, 8662–8683. https://ipssj.com/index.php/ojs/article/view/1009

Saqinah, N., Andriani, C., Elida, E., & Siregar, J. (2025). Imlementation of the curriculum of state vocational school 9 Padang by preparing graduates who are ready to work. *Jurnal Pendidikan Tata Boga dan Teknologi*, *6*(3), Article 426. https://doi.org/10.24036/jptbt.v6i3.26990

Sarıışik, G., & Demir, S. (2025). Industry 5.0: A human-centric paradigm for sustainable and resilient industrial transformation. *Journal of Social Perspective Studies*, *2*(2), 50–66. https://doi.org/10.5281/zenodo.15358434

Setiawan, M. D., Kiong, T. T., Hikmahyanti, Singh, C. K. S., Wulansari, R. E., & Ichwanto, M. A. (2024). Evaluation of the implementation of the merdeka curriculum at vocational high school using cipp model. *Online Journal for TVET Practitioners*, *9*(2), 25–48. https://doi.org/10.30880/ojtp.2024.09.02.003

Siagian, M., Hantono, H., Haloho, R. H., Arisandy, D., & Simaremare, A. (2025). Implementation of teaching factory in Indonesian vocational high schools: A bibliometric and systematic literature review. *Formosa Journal of Multidisciplinary Research*, *4*(9), 4521–4538. https://doi.org/10.55927/fjmr.v4i9.483

Selvakumar, S., & Sivakumar, P. (2025). Immersive learning technology for teacher education: A systematic literature review. *Journal of Learning for Development*, *12*(1), 56–75. https://doi.org/10.56059/jl4d.v12i1.1500

Singaram, S., Mayer, C.-H., & Oosthuizen, R. M. (2023). Leading higher education into the fourth industrial revolution: an empirical investigation. *Frontiers in Psychology*, *14*. https://doi.org/10.3389/fpsyg.2023.1242835

Siti, S. R., Rasul, M. S., Mohammad Yasin, R., & Hashim, H. U. (2023). Identifying and validating vocational skills domains and indicators in classroom assessment practices in TVET. *Sustainability (Switzerland)*, *15*(6). https://doi.org/10.3390/su15065195

Subrahmanyam, S., & Slaiby, W. (2025). Navigating the future: Emerging trends in soft skills for Industry 4.0 manufacturing. In F. Ortiiz-Rodriguez (Ed.), *Developing soft skills for manufacturing in Industry 4.0*. (pp. 79–111). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3373-0892-0.ch005

Suhud, S. N. A. (2025). Curriculum innovation at SMKN 3 Bandung: Bridging education and industry. *Hipkin Journal of Educational Research*, *2*(2), 177–188. https://doi.org/10.64014/hipkin-jer.v2i2.158

Sukatiman, Saputro, I. N., & Budiarto, M. K. (2026). Improving critical thinking skills through a flipped project-based learning model integrated with mockup media and augmented reality. *Electronic Journal of e-Learning*, *24*(1), 61–74. https://doi.org/10.34190/ejel.24.1.4176

Takiyudin, A., Suranti, P., Narimo, S., & Sumardjoko, B. (2025). Pengembangan kurikulum program keahlian teknik otomotif berbasis contextual teaching and learning (CTL) dalam penguatan hard skills dan soft skills siswa SMK Pontren Darussalam Demak [Development of an automotive engineering vocational program curriculum based on contextual teaching and learning (CTL) to strengthen the hard skills and soft skills of students at SMK Pontren Darussalam Demak]. *Pendas: Jurnal Ilmiah Pendidikan Dasar*, *10*(4), 222–231. https://journal.unpas.ac.id/index.php/pendas/article/view/39789

Tanjung, D., Syahwani, A. K. I., Ayuningtyas, G., Sholihah, W., & Rivtryana, D. A. (2025). Evaluating the impact of the teaching factory model on vocational high school student competencies in the SMK Centre of Excellence program. *BIO Web of Conferences*, *171*. https://doi.org/10.1051/bioconf/202517104015

Taqwa, M. R. A., Roozafzai, Z. S., & Suhendi, E. (2026). Communication, collaboration, critical thinking, and creative (4Cs) in TVET: A bibliometric analysis and systematic literature review. *Universal Education Journal of Teaching and Learning*, *3*(1), 1–22. https://doi.org/10.63081/uejtl.v3i1.94

Thaha, Ghafara, S., Ambiyar, A., Giatman, M., Jalinus, N., Rizal, F. A., & Fadhillah, F. (2025). Development of an android-assisted STEAM-based project-based learning model in informatics subjects at vocational high schools. *Salud, Ciencia y Tecnología*, 1826. https://doi.org/10.56294/saludcyt20251826

Tjahjono, B., Hermawan, D., Millah, S., & Evans, R. (2025). Bridging the skills gap curriculum transformation for automation industries and the role of digital technopreneurship. *Aptisi Transactions on Technopreneurship*, *7*(2). https://doi.org/10.34306/att.v7i2.620

Wahyuni, S. T., Yensy, N. A., & Danim, S. (2026). Towards a vocational education ecosystem framework: A systematic literature review of industry partnership, curriculum alignment, educational financing, and employability in SMK and TVET. *Journal of Advanced Sciences and Mathematics Education*, *6*(2), 178–203. https://doi.org/10.58524/jasme.v6i2.1253

Usman, N., AR, M., Irani, U., Mylostyvyi, R., & Siswanto, I. (2024). Technoparks as catalyst for sustainable future innovative ecosystem in vocational schools. *Jurnal Ilmiah Peuradeun*, *12*(1), 203–222. https://doi.org/10.26811/peuradeun.v12i1.1042

Vázquez-Villegas, P., & Borrego, M. (2026). The global gap between the skills of technical-vocational school graduates and the manufacturing industry's needs: A 2020-2025 scoping literature systematic review. *International Journal for Research in Vocational Education and Training*, 24–71. https://doi.org/10.13152/IJRVET.14.1.2

Vimbelo, S., & Bayaga, A. (2024). Transforming mathematics education into TVET colleges through humanising pedagogy: An exploration of teaching approaches, student engagement, and real-life examples. *IETE Journal of Education*, *65*(2), 139–154. https://doi.org/10.1080/09747338.2024.2324808

Waheed, Z. (2026). Implementation of competency-based assessment in technical and vocational education and training (TVET): A systematic review of models, quality assurance, and learner outcomes. *Social Science and Human Research Bulletin*, *3*(3), 334–343. https://doi.org/10.55677/SSHRB/2026-3050-0314

Wahjusaputri, S., & Bunyamin, B. (2022). Development of teaching factory competency-based for vocational secondary education in Central Java, Indonesia. *International Journal of Evaluation and Research in Education*, *11*(1), Article 353. https://doi.org/10.11591/ijere.v11i1.21709

Wala, G. N., & Wala, A. N. (2025). Pengembangan modul pembelajaran hukum bisnis fashion untuk meningkatkan kesiapan berwirausaha siswa SMK jurusan tata busana. *Jurnal Pendidikan Siber Nusantara*, *3*(2), 70–78. https://doi.org/10.38035/jpsn.v3i2.361

Wicaksono, M. A., Salsabila, K. N., Salsabila, Z., & Maya, M. (2025). Curriculum implementation in accounting major at SMK Pajajaran Bandung. *Hipkin Journal of Educational Research*, *2*(1), 1–22. https://doi.org/10.64014/hipkin-jer.v2i1.35a

Wickramasinghe, G., & Wickramasinghe, V. (2024). Institutional implementation of Industry 4.0 competencies in TVET programmes in the Indo-Pacific: Critical success factors. *Journal of Vocational, Adult and Continuing Education and Training*, *7*(1), 27. https://doi.org/10.14426/jovacet.v7i1.382

World Bank, Unesco, & International Labour Organization. (2023, July 12). *Building better formal TVET systems: Principles and practice in low- and middle-income countries*. https://doi.org/10.1596/978-92-2-039357-4

World Economic Forum. (2025). *The Future of Jobs Report 2025*. World Economic Forum. https://www.weforum.org/publications/the-future-of-jobs-report-2025/

Yani, I. P., Ahzari, S., & Novitra, F. (2024). Technology integration in the project-based learning model: Bibliometric analysis 2015-2024. *Pillars of Physics Education*, *17*(2), 143–149. https://doi.org/10.48550/arXiv.2601.09149

Yulianto, M. D., Amalia, D., Nazhirah, H. M., & Alghefira, R. R. (2025). Observing accounting curriculum development in vocational schools for job-ready graduates. *Hipkin Journal of Educational Research*, *2*(1), 139–150. https://doi.org/10.64014/hipkin-jer.v2i1.44

Yusuf, A. R., Marji, M., Sutadji, E., & Sugandi, M. (2023). Integration of STEM project-based learning into 21st century learning and innovation skills (4Cs) in vocational education using SEM model analysis. *Hacettepe University Journal of Education*. https://doi.org/10.16986/HUJE.2023.499

Yusvana, R. (2025). Addressing the skills gap in technical and vocational training for sustainable socio-economic growth and development. *International Journal of Research and Innovation in Social Science*, *8*, 6311–6325. https://doi.org/10.47772/ijriss.2024.803474s

Zeng, S., & Della, C. (2025). A systematic review of professional communication skills in English for specific purposes in vocational education within the new media era. *Eurasian Journal of Educational Research*, 226–249. https://doi.org/10.14689/ejer.2024.114.013

Zhong, Z., & Juwaheer, S. (2024). Digital competence development in TVET with a competency-based whole-institution approach. *Vocation, Technology & Education*, *1*(2). https://doi.org/10.54844/vte.2024.0591