Digitalization and Industry 4.0/5.0 Integration in Technical and Vocational Education and Training: A Review

Mohamad Ridzuan Jamli[1]*, Effendi Bin Mohamad[1], Mohd Akramin Mohd Romlay[2]

[1]Faculty of Industrial and Manufacturing Technology and Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

[2]Fakulti Teknologi Kejuruteraan Mekanikal dan Automotif, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

***Corresponding Author**

DOI: https://doi.org/10.47772/IJRISS.2026.100800322

Received: 09 August 2026; Accepted: 15 August 2026; Published: 03 September 2026

ABSTRACT

Technical and Vocational Education and Training (TVET) is under growing pressure to reconcile its hands-on, trade-specific pedagogy with the technological and human-centric demands introduced by the Fourth and Fifth Industrial Revolutions. While a substantial body of research now examines digital transformation in general education, evidence on how TVET systems absorb Industry 4.0 and Industry 5.0 technologies, competencies and governance arrangements remains fragmented across disciplines, regions and methodologies, making it difficult for institutions to know which interventions are worth prioritizing. This review synthesizes 59 peer-reviewed and institutional sources, published mainly between 2018 and 2026, to map how digitalization is reshaping TVET teacher competency, curriculum and institutional frameworks, student and graduate outcomes, technology adoption, industry-education-government partnership, and digital equity. Sources were drawn from databases including Scopus, Web of Science, ScienceDirect and IEEE Xplore, and from open-access outlets such as Sustainability and Frontiers in Education, and were synthesized thematically rather than statistically pooled, following a coding protocol adapted from established framework-synthesis practice. Findings show that curriculum and institutional competency frameworks dominate the literature (23.7%), followed by technology-adoption studies on digital twins, virtual reality and artificial intelligence (16.9%) and student and graduate-outcome studies (15.3%), while critical accounts of the persistent disconnect between TVET providers and industry remain scarce (1.7%), despite offering some of the most consequential findings in the corpus. Geographically, evidence clusters around Malaysia, wider Southeast Asia and cross-national bibliometric reviews, leaving Sub-Saharan Africa, South Asia and the Middle East thinly represented. A conceptual framework is proposed that positions technology-enhanced delivery as the mechanism converting Industry 4.0/5.0 inputs into employability, human-centric competencies and inclusive TVET outcomes, mediated by a policy and financing feedback loop. From the review, digitalization will not solve the structural misalignment between TVET and industry on its own; rather, it needs to go hand in hand with teacher development and curriculum evaluation, equity and policy coherence.

Keywords: TVET, Industry 4.0, Industry 5.0, Digitalization, Digital Competency

INTRODUCTION

Technical and Vocational Education and Training occupies an unusual position in the digital transformation debate. Unlike general academic education, where digitalization chiefly concerns content delivery and assessment, TVET is built around psychomotor skill formation, workshop-based practice and close proximity to industrial equipment (Jafar et al., 2020). The Fourth Industrial Revolution, characterized by cyber-physical systems, artificial intelligence, big data and the Internet of Things, has already reorganized the labor markets TVET graduates enter (Miah et al., 2024; Sigov et al., 2024). More recently, the European Union's articulation of Industry 5.0 has reframed the conversation, insisting human-centricity, sustainability and resilience must

accompany, not follow, technological capability (Oeij et al., 2024). For TVET institutions still consolidating Industry 4.0-aligned curricula, this second shift arrives before the first is complete.

The necessity of addressing the issue is not purely academic. UNESCO-UNEVOC estimates barely half of TVET practitioners have received training in delivering instruction through digital formats (X. Yang & Wu, 2024), and evidence from Pakistan, South Asia and South Africa shows TVET systems continuing to produce graduates in trades the labor market no longer wants while leaving unmet demand in others (Hassan & Anees, 2024; Magagula & Awodiji, 2024; Miah et al., 2024). Malaysia and other governments have made TVET digitalization an explicit policy priority, from the Malaysia Education Blueprint to frameworks such as HETVET at Universiti Teknologi MARA (Jamil et al., 2023; Saari et al., 2026; Seman et al., 2024). Whether this ambition is matched by evidence of what works, for whom, and under which conditions, is the gap this review addresses.

Existing reviews tend to examine either Industry 4.0 competency frameworks in isolation (Akgunduz & Mesutoglu, 2021; Jafar et al., 2020) or general higher-education digitalization without reference to TVET's distinct pedagogy (González-pérez & Ramírez-montoya, 2022; Wang et al., 2024; D. Yang et al., 2022). Few bring the teacher-competency, technology-adoption, partnership and equity literatures into a single account, and fewer extend the analysis to Industry 5.0 (Pelaez-Sanchez et al., 2024; Supriya et al., 2024). This matters: a recommendation from one strand alone, that closer industry engagement will automatically fix curriculum misalignment, can be undermined by evidence such engagement is frequently more rhetorical than real (Allais et al., 2025).

This review synthesizes 59 sources to answer three questions: how the literature is distributed across regions and themes; what frameworks, competencies and barriers recur across it; and what conceptual model can integrate these strands into guidance for TVET institutions, of which Universiti Teknikal Malaysia Melaka is one example, as they transition from Industry 4.0-era curricula toward Industry 5.0-era practice.

METHODOLOGY

This review adopts a narrative-thematic synthesis design rather than a formal meta-analysis, reflecting the heterogeneity of study designs, populations and outcome measures in the TVET digitalization literature. Fifty-nine sources published predominantly between 2018 and 2026 were compiled through database searching and citation snowballing across Scopus, Web of Science, ScienceDirect, IEEE Xplore, and open-access outlets including Sustainability and Frontiers in Education. Search terms combined "technical and vocational education and training" or "TVET" with "Industry 4.0", "Industry 5.0", "digitalization" and "digital competency", alongside terms such as "digital twin" and "employability".

Sources were included where they reported empirical, conceptual or review-based evidence directly relevant to digital technology adoption, competency development or policy in technical, vocational or closely adjacent professional education; were published in English in peer-reviewed journals, indexed proceedings or institutional reports; and provided sufficient detail for thematic coding. Sources on general schooling or industry sectors without an education component were retained only where they supplied a transferable construct treated as adjacent to TVET, consistent with comparable syntheses (Choudhary & Bansal, 2022; Yusop et al., 2022).

Each source was read in full and coded against geographic context, study design, reported frameworks, key findings and relevance to Industry 4.0/5.0-TVET integration, following the general logic of framework thematic synthesis (Shi & Bangpan, 2022) and protocols used by Miah et al. (2024) and Hassan et al. (2021). Eight themes emerged inductively: teacher and instructor competency; curriculum, assessment and institutional frameworks; student and graduate outcomes; technology adoption and barriers; industry-education-government partnership; digital divide and equity; conceptual and bibliometric background; and critical perspectives on the TVET-industry relationship. These themes, and the geographic spread of sources, are quantified in the Analysis section and underpin the framework proposed later.

CONCEPTUAL BACKGROUND: FROM INDUSTRY 4.0 TO INDUSTRY 5.0 IN TVET

Industry 4.0 originated in Germany's manufacturing strategy and denotes the fusion of cyber-physical systems, the Internet of Things, cloud computing and big data analytics into an interconnected production environment (Costa et al., 2022). Sigov et al. (2024) identify artificial intelligence, advanced connectivity and quantum computing as carrying Industry 4.0 into its next phase, while Tikhonova & Raitskaya (2023) trace a progression from Education 1.0's teacher-centered model toward a personalized Education 4.0 paradigm. Supriya et al. (2024) map Education 1.0 through 5.0 against Industry 1.0 through 5.0, identifying enabling technologies such as big data, blockchain, augmented and virtual reality and digital twins now appearing in smart-education contexts.

Industry 5.0, announced roughly a decade later, does not replace the earlier paradigm so much as correct its technocentrism. Oeij et al. (2024) organize it around three pillars, human-centricity, sustainability and resilience, arguing workforce skilling must be judged by whether technology remains under meaningful human control. Pelaez-Sanchez et al. (2024) operationalize this turn for education: of forty-six digital-competency assessment instruments published between 2013 and 2023, creativity, one of Industry 5.0's four core competencies, is measured in only fifteen.

For TVET specifically, this evolution carries a double burden. Arifin et al. (2020) argue the generic Technology-Pedagogy-Content-Knowledge model under-specifies the "work knowledge" vocational teaching requires, proposing an adapted model built around competency-cluster-specific learning. Hazrat et al., (2023) and Kumar Karanam & Hartman (2025) show digital-twin technologies, originally built for Industry 4.0 manufacturing, are already repurposed as Industry 5.0-era teaching tools. Hassan & Anees (2024) go furthest, naming digital-skills integration, sustainability, automation readiness, cross-disciplinary learning and continuous monitoring as the five pillars a TVET system must build to remain relevant.

Teacher and Instructor Competency for Industry 4.0/5.0

Teacher and instructor competency is the most mature strand of this literature, anchored by Jafar et al. (2020) five-construct framework, technical competency, soft skills, personal attributes, motive and self-concept, and mental and physical fitness. Wohlfart & Wagner (2023) umbrella review of twenty-three prior reviews confirms Technological Pedagogical Content Knowledge (TPACK) remains the dominant lens for teacher digital competency, yet notes eleven used no explicit theoretical framework, an unevenness echoed by (Teo et al., 2021) scoping review, which located only eighteen empirical studies on initial teacher training for Fourth Industrial Revolution skills across nearly a decade.

Two extensions of TPACK matter here. (Ning et al., 2024) test an AI-augmented TPACK model on 366 Chinese teachers and find technology-specific knowledge, not generic content or pedagogical knowledge, drives competence in AI-integrated teaching. Akgunduz & Mesutoglu (2021) supply matching evidence from Turkey, where a year-long professional-development programme raised teachers' Industry 4.0 content knowledge from zero to thirty-nine per cent at the "high" band, though gains were uneven, strong for three-dimensional printing, weak for virtual and augmented reality.

Rahman & Hossain (2025) survey of 586 Bangladeshi educators finds educators' own digital literacy, more than infrastructure, is the strongest predictor of community-level digital integration, while Zulu et al. (2023) study of United Kingdom construction leaders finds digitalization readiness mediated by dispositional traits, curiosity and openness, sitting outside any competency checklist. TVET instructor development for Industry 4.0/5.0 cannot be reduced to a static skills list.

Curriculum, Assessment and Institutional Frameworks

Curriculum, assessment and institutional-design studies form the largest single cluster in this review, unsurprising given that curriculum reform is the most direct lever institutions can pull. Costa et al. (2022) Triple Helix Education 4.0 framework, organizing industry, government and academia around shared training, technology, policy and research domains, remains influential, complemented by Hassan et al. (2021) seven-component TVET Training Cycle Framework. Applying that lens to 134 papers, Hassan et al. (2021) find Industry 4.0/5.0-aligned technologies barely register in TVET assessment (one per cent), career-guidance (four

per cent) or evaluation research (zero per cent), corroborated by Yusop et al. (2022) PRISMA review, which found competency-based assessment dominant in forty-four per cent of studies but none explicitly building Industry 4.0 skills.

At institutional level, named frameworks illustrate how curricula are being restructured. Seman et al. (2024) describe Universiti Teknologi MARA's HETVET framework, classifying 208 programmes into four practical-component-graded models. Chinedu et al. (2023) use a Delphi process with Asia-Pacific experts to derive a sustainability-literacy curriculum framework for Malaysian TVET teacher training, while Jamil et al. (2023) apply a fuzzy Delphi technique to validate digital-pedagogy policy objectives. Yusop et al. (2023) companion Delphi study validates 155 items embedding Industry 4.0 generic skills alongside conventional competencies. Magagula & Awodiji (2024)study of South African TVET lecturers identifies curriculum-equipment misalignment as a frequently raised implication, echoing González-pérez & Ramírez-montoya (2022) finding that Education 4.0 frameworks skew toward student-facing skills while teacher-facing frameworks remain neglected. Azofeifa et al., (2024) ShapingSkills platform keeps a skills taxonomy updated via natural-language processing, while Asmayawati et al. (2024) study of Indonesian educators shows curricular adaptation strengthens digital-literacy outcomes only when mediated by local cultural values.

Student and Graduate Outcomes: Employment, Entrepreneurship and Digital Literacy

The study of student and graduate outcomes extends the discussion of institutional inputs into individual outputs, with entrepreneurship being an alternative concept to traditional wage employment. Triyono et al. (2023) structural model of 757 Indonesian vocational students finds digital competence is the single strongest direct predictor of entrepreneurial intention, corroborated by Fawaid et al. (2022) study of 618 Yogyakarta students, where technological and digital-marketing competence shape entrepreneurial intention through self-efficacy and personality. Kholifah et al. (2025) survey of 2,587 Yogyakarta graduates situates digital communication and collaboration, not raw technical skill, as the strongest mediator converting digital competence into employability, while anxiety toward ICT suppresses this pathway.

Employer-side evidence complicates a purely skills-supply narrative. Wong et al. (2025) survey of 180 Malaysian digital-technology employers finds industry-specific knowledge and digital skills predict graduate employability directly, but adaptability shows no significant effect, contradicting models that treat soft skills as automatically transferable. Omar & Abdullah (2025) study of 658 GIATMARA entrepreneurs finds industry collaboration contributes more to competency development than job-training alone. Silor & Silor (2025) randomised experiment with Philippine pre-service teachers shows embedding TVET-based instruction into a literacy course produces significantly larger digital-competence gains than traditional instruction, while Khampirat (2021) model of 1,313 Thai engineering students shows workplace-oriented ICT competency explaining eighty-three per cent of variance in engineering competency across genders. Shi & Bangpan (2022) review of thirty-one qualitative studies should remind this stream of research of the ways in which the gains of TVET are not merely financial, since cultural capital, social capital, aspiration and well-being all emerge as key outcomes for disadvantaged youths especially.

Technology Adoption: Digital Twins, VR/AR, AI and Simulation-Based Learning

Studies of technology adoption provide the most concrete quantitative data and comprehensive listing of barriers to implementation for this review. A quasi-experiment by Erdei et al. (2022) conducted with engineering students in Hungary concluded that trainees using digital twins to prepare for a training on a six-axis robot cell performed a similar practical task with nearly twice the speed as students relying on traditional documentation. The study by Kumar Karanam & Hartman (2025) combining various cases of digital twins use concludes about similar improvement rates up to twenty per cent higher results in tests, stressing the fact that implementation is possible not because of technology itself but due to the required infrastructure and cooperation with industry. Cai et al. (2025) review of 158 research papers on artificial intelligence in higher education describes this phenomenon with reference to Vygotsky's zone of proximal development, in which AI can be viewed as scaffolding.

Evidence sector-wise goes further to include the manufacturing sector. The work of Kamis et al. (2026) which brings together 39 references on maritime technical and vocational education and training reveals the use of

simulation techniques and smart glasses for remote monitoring of activities. It includes Malaysia's 2023 reform that admits vocational certificate holders for officers training without academic qualifications. Leong, 2025 comparison of traditional and AI-enabled TVET finds roughly seventy-five per cent of European TVET institutions adopting artificial-intelligence tools against sixty-eight per cent in Asia, consistent with the disparity Setyadi et al. (2025) document from manufacturing, where Internet-of-Things adoption reaches ninety-two per cent in Europe against roughly fifty per cent in Asia-Pacific.

Barriers are well documented. Choudhary & Bansal (2022) review of eighty-six digital-literacy programmes proposes a four-level barrier taxonomy, administrative, training, learner and community, echoed in Mhlanga (2024) account of poverty and policy fragmentation limiting Fourth Industrial Revolution learning in emerging markets, and in Rajamanickam et al. (2025) review of Malaysian on-the-job training, identifying instructor skills deficits and equipment mismatches as persistent obstacles.

Industry-Education-Government Partnership and Policy Models

Partnership and policy studies address the institutional plumbing connecting TVET providers to the labor markets they serve. X. Yang & Wu (2024) case study of the UNESCO Chair on Digitalization in TVET at Shenzhen Polytechnic University identifies four cooperation mechanisms, policy dialogue, resource sharing, training exchanges and ecosystem partnerships, framed through a three-part digital divide of access, skills and benefits. Miah et al. (2024) analysis of forty-eight South Asian studies distils nine driving factors behind successful Industry 4.0 adoption and six challenge categories, of which training and development account for twenty-eight per cent, the largest share.

Sector-specific research on partnerships enriches the literature with a more subtle understanding than found in the official discourse. For instance, the findings of the survey conducted by Zheng et al. (2024) among 184 Chinese companies working in the field of hydrogen energy revealed that the probability of cooperation with educational institutions is positively associated with the perception of resources' advantages and negatively associated with the perception of costs risks, and the latter effect can be counterbalanced with government subsidies, but the former cannot. The same mechanism was uncovered by Napathorn (2022) when analyzing four firms operating in Thailand and their efforts to train greener skills in absence of environmental subjects within vocational college curricula. In terms of governance, Nie et al. (2020) identify the four criteria for evaluation of the Russian e-learning market (effectiveness, efficiency, economy and equity), and (Saari et al., 2026) argue that Malaysia's governance of its readiness to Fourth Industrial Revolution includes much more than purchasing technologies.

Digital Divide, Equity, Gender and Marginalization

Equity research poses questions about any simplistic assumption regarding the inherent inclusivity of digitalization. According to Wignall et al. (2023), the participatory study undertaken in Cameroon and Sierra Leone reveals that TVET can reinforce rather than disrupt patriarchal labor market arrangements: despite their training, young women still experience harassment, unsafe travel and exclusion from formal employment, while girls constitute only 34.2 per cent of Cameroonian TVET enrollment. The authors distinguish "transversal" skills from "transgressive" skills capable of actively disrupting gender norms, arguing only the latter produce genuine transformation. Ahmad et al. (2024) conceptual review of nine Industry 4.0 technologies for inclusive learning catalogues how each might serve learners with disabilities or from diverse backgrounds, though without examining implementation barriers.

At a more structural level, Meng et al. (2024) scientometric review of thirty-five studies proposes six dimensions of digital inequity, access, usage and skill, quality of experience, content, economic standing and gender, several reappearing in Ekrem et al. (2025)cluster analysis of thirty-two European countries, which finds higher national digital-literacy levels accompany lower youth NEET rates, with female NEET status clustering into a more heterogeneous pattern than male. Smit et al. (2025) ethnographic study of seventy-three low-literacy Dutch adults finds marginalized users develop informal "bypass" tactics, family support, translation software, to participate digitally regardless. Ventrella & Cotnam-Kappel (2024) Canadian case study closes the loop: teachers' own uneven digital confidence directly compounds the digital divide their students experience.

Critical Perspectives: The Persistent TVET-Industry Disconnect

A smaller but analytically important strand interrupts the optimistic tone of the studies reviewed above. Allais et al., (2025) mixed-methods study across six low-income and middle-income countries surveyed 847 manufacturing firms and conducted 117 interviews to test whether industry engagement with TVET is what policymakers assume. This is an awkward response: the employment of TVET graduates by the company in terms of their hiring practices varies between about seventeen percent at general worker level to seventy-six percent at the technician level; moreover, the firms that give positive responses to TVET graduates on closed-ended questions turn out to be quite negative on open-ended questions, a discrepancy which the authors refer to as "espoused support versus revealed critique".

This sits alongside Hassan & Anees (2024) diagnostic data from Pakistan, where TVET output exceeds industry demand by more than double yet leaves specific trades in chronic shortage, and barely thirty-eight percent of graduates secure employment at all. Together, these sources caution against a recurring assumption elsewhere in this review: that digitalizing curricula, or encouraging more industry consultation, will by itself close the gap between what TVET produces and what labor markets need.

ANALYSIS OF THE REVIEWED LITERATURE

Table 1 summarizes the geographic distribution of the 59 sources reviewed. Malaysian-based or Malaysian-authored studies account for the largest national share (eleven sources, 18.6%), reflecting this review's institutional vantage point, followed by other Southeast Asian contexts (eight sources, 13.6%), Europe (eight sources, 13.6%), and East Asia, the Americas and Oceania combined (eight sources, 13.6%). Sub-Saharan Africa and South Asia remain thin at three and two sources respectively, and no source is set in the Middle East, a genuine gap given the region's own Industry 4.0/5.0 investment. The largest single category is cross-national systematic reviews and bibliometric studies (nineteen sources, 32.2%), consistent with a field still more comfortable mapping itself than generating primary evidence in any one setting.

Table 1. Geographic Distribution of the 59 Reviewed Sources

Region / Country	Sources (n)	Percentage
Malaysia	11	18.6%
Other Southeast Asia (Indonesia, Philippines, Thailand)	8	13.6%
Europe	8	13.6%
East Asia, Americas and Oceania	8	13.6%
Sub-Saharan Africa	3	5.1%
South Asia	2	3.4%
Middle East	0	0.0%
Cross-national / bibliometric reviews	19	32.2%

Table 2 and Figure 1 present the thematic distribution. Curriculum, institutional and competency-framework studies are the largest category (fourteen sources, 23.7%), followed by technology-adoption studies (ten sources, 16.9%) and student and graduate-outcome studies (nine sources, 15.3%). Teacher competency and industry-education-government partnership are evenly matched at seven sources each (11.9%), digital-divide and equity studies account for six sources (10.2%), and conceptual or bibliometric background studies account for five (8.5%). Critical or structural perspectives on the TVET-industry relationship supply only a single

source (1.7%), the smallest category by a wide margin.

The rapid growth of the wider digital-education literature helps explain why TVET-specific evidence still trails behind. Wang et al. (2024) bibliometric analysis of 588 digital-education studies (2000-2022) identifies professional development and digital transformation as the fastest-growing frontiers after 2020, corroborated by D. Yang et al. (2022) citation-network analysis of 368 studies, which flags educational equity and governance as under-researched. Chakraborty et al. (2023) mapping of Industry 4.0 and Education 4.0 constructs across 1,965 engineering-education articles reaches a similar conclusion: no standardized framework yet links the two literatures, and developed countries still publish sixty-three per cent of available

Education 4.0 output despite TVET's disproportionate relevance in developing economies.

Table 2. Thematic Distribution of the 59 Reviewed Sources

Theme	Sources (n)	Percentage
Curriculum, assessment and institutional frameworks	14	23.7%
Technology adoption (digital twins, VR/AR, AI)	10	16.9%
Student and graduate outcomes	9	15.3%
Teacher and instructor competency	7	11.9%
Industry-education-government partnership	7	11.9%
Digital divide, equity and gender	6	10.2%
Conceptual and bibliometric background	5	8.5%
Critical / structural perspectives	1	1.7%

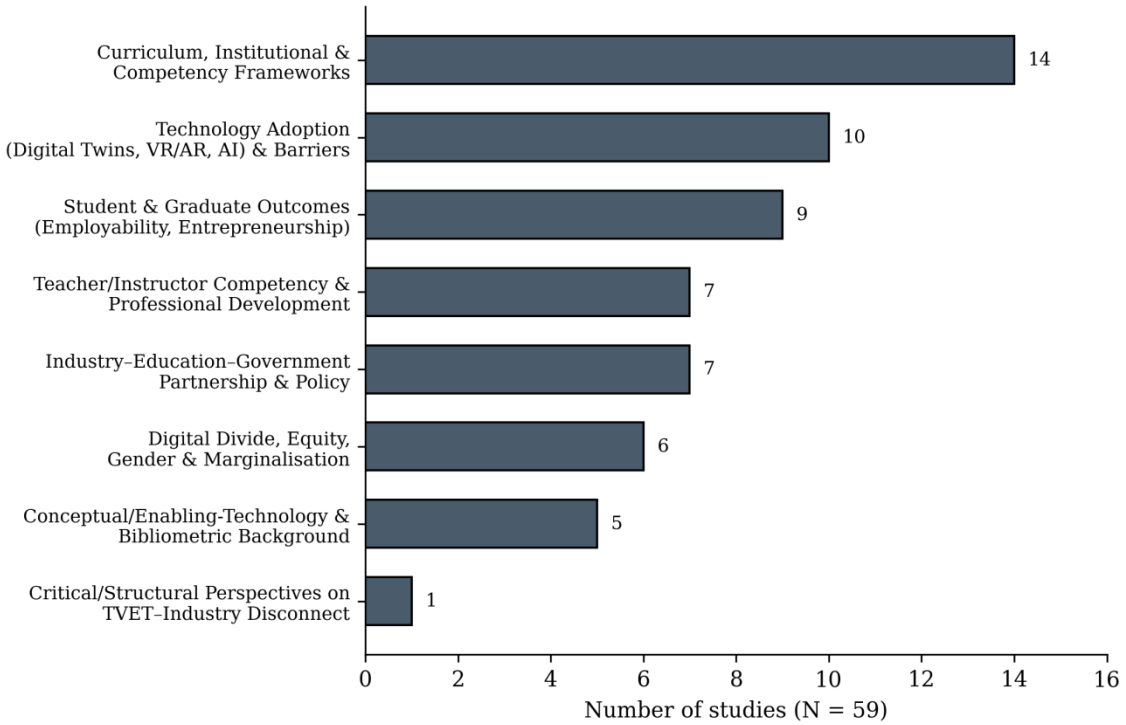

Figure 1. Thematic Distribution of the 59 Reviewed Sources

Two patterns deserve emphasis. First, the dominance of curriculum and framework papers alongside the near-absence of critical, structural analysis suggests the field is better at proposing what TVET systems should look like than at testing why reforms succeed or fail once implemented. Second, the concentration of evidence in

Malaysia, Southeast Asia and cross-national reviews, against thin African and South Asian representation, means the framework proposed next is most strongly evidenced for middle-income, rapidly-industrializing contexts.

PROPOSED CONCEPTUAL FRAMEWORK

Drawing on the eight thematic clusters identified above, Figure 2 proposes an integrative framework for how Industry 4.0/5.0 digitalization translates into TVET outcomes. The framework treats Industry 4.0/5.0 enabling technologies and human-centric, sustainable values (Oeij et al., 2024; Supriya et al., 2024) as the input layer, flowing into four interdependent pillars: teacher and instructor competency (Jafar et al., 2020; Ning et al., 2024), curriculum and institutional frameworks (Costa et al., 2022; Hassan et al., 2021), industry-education government partnership (X. Yang & Wu, 2024; Zheng et al., 2024), and digital equity, gender and inclusion (Meng et al., 2024; Wignall et al., 2023). These converge on a shared mechanism, technology-enhanced TVET delivery through digital twins, virtual and augmented reality and simulation- or work-integrated learning (Erdei et al., 2022; Kamis et al., 2026; Kumar Karanam & Hartman, 2025), the point where most concrete quantitative gains documented in this review are actually realized.

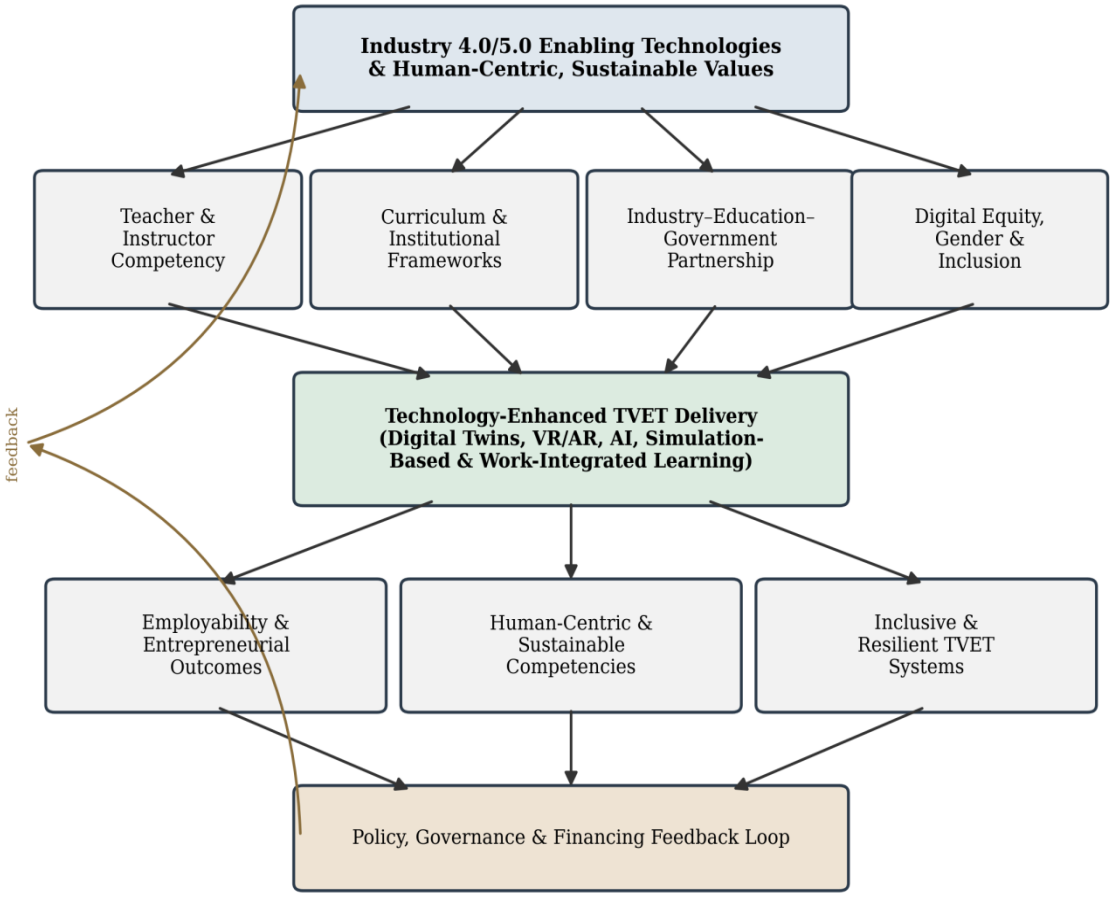

Figure 2. Proposed Conceptual Framework for Digitalization and Industry 4.0/5.0 Integration in TVET

This mechanism produces three outcome domains: employability and entrepreneurial outcomes (Omar & Abdullah, 2025; Triyono et al., 2023; Wong et al., 2025), human-centric competencies consistent with Industry 5.0 (Napathorn, 2022; Pelaez-Sanchez et al., 2024), and inclusive, resilient TVET systems (Ahmad et al., 2024; Shi & Bangpan, 2022). The final element in the model takes the form of a feedback loop, going back to policy and finance considerations (Nie et al., 2020; Saari et al., 2026). This is due to the demonstration by Allais et al. (2025) and Hassan & Anees (2024) of how achievements made during one round of funding can be silently eroded if not continually kept in mind.

The critical idea underlying this framework is that the line from enabling technology to outcome is never a

straight one. For each and every example of success cited here - whether from Erdei et al. (2022) digital-twin robots training or Ning et al. (2024) AI-ready Chinese teachers - there is at least one institutional block involved before it becomes an outcome. Considering digitalization as a matter of technology procurement, and not of teachers, curricula, partnerships and equity, is precisely the reason for underperformance in such cases.

DISCUSSION

Several implications can be drawn from the synthesis for TVET institutions like Universiti Teknikal Malaysia Melaka and their regional counterparts when it comes to planning ahead of their curriculum in light of Industry 4.0. Firstly, there is a consensus in the literature on teachers' competency that generic digital literacy training is less efficient than targeted, continuous professional development of the instructors, which was discussed in the works by Akgunduz & Mesutoglu (2021) and Ning et al. (2024).

Secondly, although the literature on curriculum and framework is very abundant in the models of curriculums

and frameworks, there is very little discussion of the effects of adoption of any of them. Several frameworks have been named explicitly and include HETVET (Seman et al., 2024), TVET Training Cycle (Hassan et al., 2021), and Triple Helix Education 4.0 model (Costa et al., 2022). However, there is virtually no literature on the adoption and validation of the framework in relation to Industry 4.0 (Hassan et al., 2021; Yusop et al., 2022).

Thirdly, the literature on equity suggests that digitalization does not guarantee inclusivity. Wignall et al. (2023) finding that TVET can reproduce rather than dismantle patriarchal labor-market structures, and Ventrella & Cotnam-Kappel (2024) finding that teachers' own digital inequality compounds their students', suggest equity needs designing into strategy from the outset.

Fourth, and most consequential for policy, the critical-perspectives literature, though numerically small, should not be read as marginal. Allais et al. (2025) six-country evidence that industry engagement is frequently more rhetorical than real, and Hassan & Anees (2024) demonstration that Pakistan's TVET system oversupplies some trades while starving others, imply digitalization layered onto a structurally disconnected relationship may improve delivery mechanics without resolving the underlying mismatch.

Finally, the regional concentration identified earlier means the framework proposed here is a starting hypothesis for under-represented regions rather than a validated model.

LIMITATIONS OF THE REVIEW

This review has several limitations. As a narrative-thematic rather than statistical synthesis, it cannot quantify effect sizes across studies using markedly different designs and outcome measures, and the thematic categorization in Table 2, though grounded in careful reading of all 59 sources, necessarily involved judgement calls about studies spanning two or three clusters at once. The corpus was compiled iteratively rather than through a single pre-registered protocol, and English-language publication bias almost certainly under-represents relevant work in other languages, particularly from Latin America, the Middle East and parts of Africa. Several technology-adoption statistics, particularly those drawn from conference proceedings such as Leong (2025), rely on self-reported figures with limited transparency and should be treated as illustrative rather than definitive. Future reviews would benefit from a registered protocol and, where feasible, a quantitative meta-analytic component.

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This review has synthesized fifty-nine sources to map how digitalization and the emerging Industry 5.0 agenda are reshaping Technical and Vocational Education and Training across teacher competency, curriculum design, student outcomes, technology adoption, industry partnership and equity. The evidence base is uneven: curriculum and institutional frameworks are proposed far more often than evaluated after adoption, technology-adoption studies supply the clearest quantitative gains, and critical, structural analysis of the

TVET-industry relationship remains almost entirely absent despite delivering some of the review's most consequential findings. Geographically, the literature clusters around Malaysia, Southeast Asia and cross-national bibliometric reviews, leaving Sub-Saharan Africa, South Asia and the Middle East thinly evidenced.

The conceptual framework proposed here positions technology-enhanced delivery, not technology procurement alone, as the mechanism converting Industry 4.0/5.0 inputs into employability, human-centric competency and inclusive outcomes, contingent on simultaneous investment in teacher competency, curriculum design, industry partnership and equity, sustained by a policy and financing feedback loop. Its central caution, that digitalization without attention to structural disconnection risks improving delivery mechanics without closing labor-market mismatch, follows from the smallest but most sobering cluster of evidence reviewed.

Future research should prioritize three directions: longitudinal studies tracking named frameworks beyond adoption into outcome; primary research from under-represented regions, particularly the Middle East and Sub-Saharan Africa; and further critical research in the tradition of Allais et al. (2025) and Hassan & Anees (2024), examining whether Industry 5.0's human-centric aspirations can be embedded into TVET systems that have not yet resolved their Industry 4.0-era disconnection from industry.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for their direct and indirect contributions to this work.

ETHICAL CONSIDERATIONS

This article is a narrative-thematic literature review that did not involve the recruitment of human participants, animal subjects, or the collection of primary personal data. No ethical approval was therefore required for the conduct of this study. All findings reported are drawn from previously published, publicly available peer-reviewed and institutional sources, each of which is fully cited in the reference list.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise, in relation to the preparation and publication of this article.

DATA AVAILABILITY STATEMENT

The dataset underpinning this review, comprising the coded thematic classification, geographic distribution and bibliographic details of the 59 sources analyzed, was compiled by the authors from the publicly available published articles cited in the reference list and is available from the corresponding author upon reasonable request.

REFERENCES

1. Ahmad, I., Sharma, S., Singh, R., Gehlot, A., Gupta, L. R., Thakur, A. K., Priyadarshi, N., & Twala, B. (2024). Inclusive learning using industry 4.0 technologies: addressing student diversity in modern education. Cogent Education, 11(1). https://doi.org/10.1080/2331186X.2024.2330235
2. Akgunduz, D., & Mesutoglu, C. (2021). Science, Technology, Engineering, and Mathematics Education for Industry 4.0 in Technical and Vocational High Schools: Investigation of Teacher Professional Development. Science Education International, 32(2), 172–181. https://doi.org/10.33828/sei.v32.i2.11
3. Allais, S., Schöer, V., Maurer, M., Behre, H., Khammounty, B., Shimu, S. S., Nguyen, T. T., Veung, N., Marock, C., & Morlock, M. (2025). Disconnection or delusion? complexities of employer-engagement with TVET in six LMICs. Journal of Education and Work, 38(1–4), 19–41. https://doi.org/10.1080/13639080.2025.2562507

4. Arifin, Z., Nurtanto, M., Priatna, A., Kholifah, N., & Fawaid, M. (2020). Technology andragogy work content knowledge model as a new framework in vocational education: Revised technology pedagogy content knowledge model. TEM Journal, 9(2), 786–791. https://doi.org/10.18421/TEM92-48
5. Asmayawati, Yufiarti, & Yetti, E. (2024). Pedagogical innovation and curricular adaptation in enhancing digital literacy: A local wisdom approach for sustainable development in Indonesia context. Journal of Open Innovation: Technology, Market, and Complexity, 10(1), 100233. https://doi.org/10.1016/j.joitmc.2024.100233
6 Azofeifa, J. D., Rueda-Castro, V., Camacho-Zuñiga, C., Chans, G. M., Membrillo-Hernández, J., & Caratozzolo, P. (2024). Future skills for Industry 4.0 integration and innovative learning for continuing engineering education. Frontiers in Education, 9(July 2020). https://doi.org/10.3389/feduc.2024.1412018
7. Cai, L., Msafiri, M. M., & Kangwa, D. (2025). Exploring the impact of integrating AI tools in higher education using the Zone of Proximal Development. In Education and Information Technologies (Vol. 30, Number 6). Springer US. https://doi.org/10.1007/s10639-024-13112-0
8. Chakraborty, S., Gonzalez-Triana, Y., Mendoza, J., & Galatro, D. (2023). Insights on mapping Industry 4.0 and Education 4.0. Frontiers in Education, 8(April), 1–19. https://doi.org/10.3389/feduc.2023.1150190
9. Chinedu, C. C., Saleem, A., & Wan Muda, W. H. N. (2023). Teaching and Learning Approaches: Curriculum Framework for Sustainability Literacy for Technical and Vocational Teacher Training Programmes in Malaysia. Sustainability (Switzerland), 15(3). https://doi.org/10.3390/su15032543
10. Choudhary, H., & Bansal, N. (2022). Addressing Digital Divide through Digital Literacy Training Programs: A Systematic Literature Review. Digital Education Review, 1(41), 224–248. https://doi.org/10.1344/DER.2022.41.224-248
11. Costa, A. C. F., Santos, V. H. D. M., & de Oliveira, O. J. (2022). Towards the Revolution and Democratization of Education: A Framework to Overcome Challenges and Explore Opportunities through Industry 4.0. Informatics in Education, 21(1), 1–32. https://doi.org/10.15388/infedu.2022.01
12. Ekrem, B., Muhammet, B., & Neagu, G. (2025). BRIDGING NEET STATUS AND EMPLOYABILITY THROUGH DIGITAL LITERACY: IMPLICATIONS FOR TVET POLICIES IN THE DIGITAL AGE. Revista Calitatea Vieții, 36(1), 5–22. https://doi.org/10.46841/RCV.2025.01.01
13. Erdei, T. I., Krakó, R., & Husi, G. (2022). Design of a Digital Twin Training Centre for an Industrial Robot Arm. Applied Sciences (Switzerland), 12(17). https://doi.org/10.3390/app12178862
14. Fawaid, M., Triyono, M. B., Sofyan, H., Nurtanto, M., Mutohhari, F., Jatmoko, D., Majid, N. W. A., & Rabiman, R. (2022). Entrepreneurial Intentions of Vocational Education Students in Indonesia: PLS-SEM Approach. Journal of Technical Education and Training, 14(2 SPECIAL ISSUE), 91–105. https://doi.org/10.30880/jtet.2022.14.02.009
15. 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), 1–31. https://doi.org/10.3390/su14031493
16. Hassan, R. H., & Anees, T. (2024). TVET-SCon: A Unified Catalyst Framework for Enhancing Youth Employability. VFAST Transactions on Software Engineering, 12(4), 37–58. https://doi.org/10.21015/vtse.v12i4.1958
17. Hassan, R. H., Hassan, M. T., Naseer, S., Khan, Z., & Jeon, M. (2021). ICT Enabled TVET Education: A Systematic Literature Review. IEEE Access, 9, 81624–81650. https://doi.org/10.1109/ACCESS.2021.3085910
18. Hazrat, M. A., Hassan, N. M. S., Chowdhury, A. A., Rasul, M. G., & Taylor, B. A. (2023). Developing a Skilled Workforce for Future Industry Demand: The Potential of Digital Twin-Based Teaching and Learning Practices in Engineering Education. Sustainability (Switzerland), 15(23). https://doi.org/10.3390/su152316433
19. Jafar, D. S. A., Saud, M. S., Hamid, M. Z. A., Suhairom, N., Hisham, M. H. M., & Zaid, Y. H. (2020). TVET teacher professional competency framework in industry 4.0 era. Universal Journal of Educational Research, 8(5), 1969–1979. https://doi.org/10.13189/ujer.2020.080534
20. Jamil, M. R. M., Hashim, A. T. M., Othman, M. S., Ahmad, A. M., Noh, N. M., & Kamal, M. F. M. (2023). Digital Pedagogy Policy in Technical and Vocational Education and Training (TVET) in Malaysia: Fuzzy Delphi Approach. Journal of Technical Education and Training, 15(2), 1–10.

https://doi.org/10.30880/jtet.2023.15.02.001

21. Kamis, A. S., hmad Fuad, A. F., Ali, S. A., Wan Mansor, W. N., Syed Ahmad, S. Z. A., & Akhbar, A. F. (2026). Maritime TVET in Transition: Global Trends, Institutional Innovation, and Strategic Reform. TransNav, 20(1), 131–144. https://doi.org/10.12716/1001.20.01.14
22. Khampirat, B. (2021). Relationships between ICT competencies related to work, self-esteem, and self-regulated learning with engineering competencies. PLoS ONE, 16(12 December), 1–24. https://doi.org/10.1371/journal.pone.0260659
23. 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(1), 101625. https://doi.org/10.1016/j.ssaho.2025.101625
24. Kumar Karanam, S. A., & Hartman, N. W. (2025). A systematic review of Digital Twin (DT) and virtual learning environments (VLE) for smart manufacturing education. Manufacturing Letters, 44, 1597–1608. https://doi.org/10.1016/j.mfglet.2025.06.179
25. Leong, W. Y. (2025). Artificial Intelligence, Automation, and Technical and Vocational Education and Training: Transforming Vocational Training in Digital Era †. Engineering Proceedings, 103(1), 1–8. https://doi.org/10.3390/engproc2025103009
26. Magagula, M. M., & Awodiji, O. A. (2024). The implications of the fourth industrial revolution on technical and vocational education and training in South Africa. Social Sciences and Humanities Open, 10. https://doi.org/10.1016/j.ssaho.2024.100896
27. Meng, Y., Xu, W., Liu, Z., & Yu, Z. G. (2024). Scientometric analyses of digital inequity in education: problems and solutions. Humanities and Social Sciences Communications, 11(1), 1–13. https://doi.org/10.1057/s41599-024-03480-w
28. Mhlanga, D. (2024). Digital transformation of education, the limitations and prospects of introducing the fourth industrial revolution asynchronous online learning in emerging markets. Discover Education, 3(1). https://doi.org/10.1007/s44217-024-00115-9
29. Miah, M. T., Erdei-Gally, S., Dancs, A., & Fekete-Farkas, M. (2024). A Systematic Review of Industry 4.0 Technology on Workforce Employability and Skills: Driving Success Factors and Challenges in South Asia. Economies, 12(2). https://doi.org/10.3390/economies12020035
30. Napathorn, C. (2022). The development of green skills across firms in the institutional context of Thailand. Asia-Pacific Journal of Business Administration, 14(4), 539–572. https://doi.org/10.1108/APJBA-10-2020-0370
31. Nie, D., Panfilova, E., Samusenkov, V., & Mikhaylov, A. (2020). E-learning financing models in Russia for sustainable development. Sustainability (Switzerland), 12(11), 3–6. https://doi.org/10.3390/su12114412
32. Ning, Y., Zhang, C., Xu, B., Zhou, Y., & Wijaya, T. T. (2024). Teachers' AI-TPACK: Exploring the Relationship between Knowledge Elements. Sustainability (Switzerland), 16(3). https://doi.org/10.3390/su16030978
33. Oeij, P., Dhondt, S., Sorko, S. R., & Warhurst, C. (2024). A Conceptual Framework for Workforce Skills for. Journal of Innovation Management, 12 (1)(July), 205–233. https://www.researchgate.net/publication/382124058_A_Conceptual_Framework_for_Workforce_Skills_for_Industry_50_Implications_for_Research_Policy_and_Practice
34. Omar, M., & Abdullah, M. (2025). The impact of TVET-based entrepreneurship training program on student employability: The case of GIATMARA institution in Malaysia. Multidisciplinary Science Journal, 7(Supplementary Issue). https://doi.org/10.31893/multiscience.2025ss0233
35. Pelaez-Sanchez, I. C., Glasserman-Morales, L. D., & Rocha-Feregrino, G. (2024). Exploring digital competencies in higher education: design and validation of instruments for the era of Industry 5.0. Frontiers in Education, 9(October). https://doi.org/10.3389/feduc.2024.1415800
36. Rahman, M. M., & Hossain, M. E. (2025). Digital dynamics in technology adoption: Exploring socio-economic development through technology and education. Technology in Society, 82(September 2024), 102906. https://doi.org/10.1016/j.techsoc.2025.102906
37. Rajamanickam, S., Rus, R. C., & Raji, M. N. A. (2025). Navigating complexities in on-the-job training at vocational institutions: a systematic literature review. International Journal of Evaluation and Research in Education, 14(3), 1856–1869. https://doi.org/10.11591/ijere.v14i3.31977
38. Saari, M. A., Jalaludin, N. A., Rasul, M. S., Mhd Salim, M. H., & Mohamed Ashari, Z. H. (2026).

Policies and governance for skills development in the fourth industrial revolution. International Journal of Evaluation and Research in Education, 15(2), 1079–1090. https://doi.org/10.11591/ijere.v15i2.29177

39. Seman, N., Sulaiman, S., Tahir, W., Jamil, A. A., Samad, M. F., & Ramli, S. S. (2024). Enhancing TVET Education in Malaysia Via HETVET @UiTM Framework. 2024 IEEE 13th International Conference on Engineering Education: Dissemination and Advancement of Engineering Education Using Artificial Intelligence, ICEED 2024, 1–6. https://doi.org/10.1109/ICEED62316.2024.10923816
40. Setyadi, A., Soekotjo, S., Lestari, S. D., Pawirosumarto, S., & Damaris, A. (2025). Trends and Opportunities in Sustainable Manufacturing: A Systematic Review of Key Dimensions from 2019 to 2024. Sustainability (Switzerland), 17(2), 1–34. https://doi.org/10.3390/su17020789
41. Shi, Y., & Bangpan, M. (2022). Young people's participation experiences of technical and vocational education and training interventions in low- and middle-income countries: a systematic review of qualitative evidence. Empirical Research in Vocational Education and Training, 14(1). https://doi.org/10.1186/s40461-022-00136-4
42. Sigov, A., Ratkin, L., Ivanov, L. A., & Xu, L. Da. (2024). Emerging Enabling Technologies for Industry 4.0 and Beyond. Information Systems Frontiers, 26(5), 1585–1595. https://doi.org/10.1007/s10796-021-10213-w
43. Silor, A. C., & Silor, F. S. C. (2025). Harnessing TVET for New Literacies: An Experimental Study on Enhancing 21st Century Competencies. International Journal of Learning, Teaching and Educational Research, 24(11), 144–160. https://doi.org/10.26803/ijlter.24.11.7
44. Smit, A., Swart, J., & Broersma, M. (2025). Bypassing digital literacy: Marginalized citizens' tactics for participation and inclusion in digital societies. New Media and Society, 27(6), 3127–3145. https://doi.org/10.1177/14614448231220383
45. Supriya, Y., Bhulakshmi, D., Bhattacharya, S., Gadekallu, T. R., Vyas, P., Kaluri, R., Sumathy, S., Koppu, S., Brown, D. J., & Mahmud, M. (2024). Industry 5.0 in Smart Education: Concepts, Applications, Challenges, Opportunities, and Future Directions. IEEE Access, 12(June), 81938–81967. https://doi.org/10.1109/ACCESS.2024.3401473
46. Teo, T., Unwin, S., Scherer, R., & Gardiner, V. (2021). Initial teacher training for twenty-first century skills in the Fourth Industrial Revolution (IR 4.0): A scoping review. Computers and Education, 170(April), 104223. https://doi.org/10.1016/j.compedu.2021.104223
47. Tikhonova, E., & Raitskaya, L. (2023). Education 4 . 0 : The Concept , Skills , and. Journal of Language and Education, 9(1), 5–11.
48. Triyono, M. B., Mutohhari, F., Kholifah, N., Nurtanto, M., Subakti, H., & Prasetya, K. H. (2023). Examining the Mediating-Moderating Role of Entrepreneurial Orientation and Digital Competence on Entrepreneurial Intention in Vocational Education. Journal of Technical Education and Training, 15(1), 116–127. https://doi.org/10.30880/jtet.2023.15.01.011
49. Ventrella, F. M., & Cotnam-Kappel, M. (2024). Examining digital capital and digital inequalities in Canadian elementary Schools: Insights from teachers. Telematics and Informatics, 86(July 2023), 102070. https://doi.org/10.1016/j.tele.2023.102070
50. Wang, C., Chen, X., Yu, T., Liu, Y., & Jing, Y. (2024). Education reform and change driven by digital technology: a bibliometric study from a global perspective. Humanities and Social Sciences Communications, 11(1). https://doi.org/10.1057/s41599-024-02717-y
51. Wignall, R., Piquard, B., & Joel, E. (2023). Up-skilling women or de-skilling patriarchy? How TVET can drive wider gender transformation and the decent work agenda in Sub-Saharan Africa. International Journal of Educational Development, 102. https://doi.org/10.1016/j.ijedudev.2023.102850
52. Wohlfart, O., & Wagner, I. (2023). Teachers' role in digitalizing education: an umbrella review. Educational Technology Research and Development, 71(2), 339–365. https://doi.org/10.1007/s11423-022-10166-0
53. Wong, L. C., Tiong, Y. Y., Tee, P. K., Song, B. L., Zin, N. A. M., & Wong, S. F. (2025). Enhancing Digital Technology Graduates' Employability in the Fourth Industrial Revolution from Employers' Perspective. Paper Asia, 41(5), 1–18. https://doi.org/10.59953/paperasia.v41i5b.620
54. Yang, D., Zhou, J., Shi, D., Pan, Q., Wang, D., Chen, X., & Liu, J. (2022). Research Status, Hotspots, and Evolutionary Trends of Global Digital Education via Knowledge Graph Analysis. Sustainability (Switzerland), 14(22). https://doi.org/10.3390/su142215157

55. Yang, X., & Wu, W. (2024). Advancing digital transformation in TVET through international cooperation: Approaches by the UNESCO Chair on Digitalization in TVET. Vocation, Technology and Education, 1(2), 1–14. https://doi.org/10.54844/vte.2024.0585
56. Yusop, S. R. M., Rasul, M. S., Yasin, R. M., Hashim, H. U., & Jalaludin, N. A. (2022). An Assessment Approaches and Learning Outcomes in Technical and Vocational Education: A Systematic Review Using PRISMA. Sustainability (Switzerland), 14(9). https://doi.org/10.3390/su14095225
57. Yusop, S. R. M., 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
58. Zheng, W., Zheng, X., & Zhu, X. (2024). Promoting integration of industry and vocational education: Exploring stakeholder intentions of hydrogen energy industry. International Journal of Hydrogen Energy, 52, 454–464. https://doi.org/10.1016/j.ijhydene.2023.06.072
59. Zulu, S. L., Saad, A. M., & Gledson, B. (2023). Individual Characteristics as Enablers of Construction Employees' Digital Literacy: An Exploration of Leaders' Opinions. Sustainability (Switzerland), 15(2). https://doi.org/10.3390/su15021531