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A conceptual framework for a symbiotic integration of generative AI in post-secondary technical and vocational education and training (TVET): Bridging pedagogy, technology, and ethics

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Abstract

Generative Artificial Intelligence (GenAI) is poised to reshape Post-Secondary Technical and Vocational Education and Training (TVET), a sector critical for aligning formal education with industry demands. While the potential of GenAI is widely discussed, the literature lacks a holistic framework to guide its strategic and ethically sound integration. This paper addresses this gap by synthesizing existing research to develop a novel conceptual model for the symbiotic integration of GenAI in TVET.

This study employs an integrative literature review methodology. A purposive selection of recent, peer-reviewed literature (post-2020) was analyzed to synthesize key opportunities, such as hyper-personalized learning and immersive training, alongside significant systemic barriers, including infrastructural constraints, AI literacy gaps, and ethical risks. These insights were then structured into a multi-layered conceptual framework.

The review identifies three core domains of GenAI's impact: the evolution of pedagogy from standardization to personalization, the enhancement of learner engagement, and the reconceptualization of skills assessment. To navigate the complexities of implementation, the paper proposes the «Integrated Symbiotic Model». This model reframes GenAI integration as a collaborative «teacher-machine-student» ecosystem, structured across four interdependent layers: (1) foundational enablers (infrastructure, policy, AI literacy), (2) the core triad of actors (learner, educator, AI), (3) core pedagogical processes, and (4) the central objective of enhanced workforce readiness.

The primary contribution of this paper is the « Integrated Symbiotic Model », a novel framework designed to guide institutional leaders and educators in the strategic and ethically-grounded integration of GenAI. It moves beyond traditional technology adoption models to offer a pedagogically-focused, systemic roadmap for transforming TVET in the age of AI.

Keywords: Integrated Symbiotic Model, Generative AI, TVET, Pedagogical Transformation, Learner Engagement, Skills Assessment.

Classification JEL: O33, Q55, A20

Paper type: Theoretical Research

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1. Introduction

Arriving with significant velocity and societal impact, Generative Artificial Intelligence (GenAI) represents more than an incremental technological advance; it is widely regarded as a transformative force, with the field of education standing squarely at the epicenter of its transformative potential. Advanced technologies such as Large Language Models (LLMs), diffusion models for image generation, and sophisticated simulation engines are catalyzing a fundamental re-evaluation of how knowledge is created, disseminated, and validated. This technological sea change presents both unprecedented opportunities and profound challenges for educational systems worldwide (Bahroun et al., 2023; Francis et al., 2025).

Within this global transformation, Post-Secondary Technical and Vocational Education and Training (TVET) occupies a uniquely critical, yet often precarious, position. As the primary engine of workforce development, TVET serves as the vital conduit between formal education and the dynamic demands of industry. Its mission—to equip individuals with the practical skills and technical competencies essential for economic growth and personal prosperity—has never been more important (Yusop et al., 2023). These institutions are the wellspring of the skilled technicians, artisans, and professionals who form the backbone of a productive economy. Yet, many TVET systems, often built upon a pedagogical chassis designed for the industrial age, find themselves struggling to navigate the terrain of the 21st century. The challenge is no longer the simple transmission of established tradecraft but the cultivation of a more fluid and resilient skillset, including adaptive problem-solving, creativity, critical thinking, and digital fluency (Onatere-Ubrurhe & Ubrurhe, 2025). In an era of rapid automation and industrial change, the traditional model of lectures, static textbooks, and resource-limited workshops is proving increasingly inadequate for preparing learners for a future where agility and innovation are the currency of success.

It is at this very nexus of tradition and transformation that GenAI emerges as a powerful, if complex, agent of change. Unlike previous technological waves that primarily democratized access to information, GenAI possesses a fundamentally distinct capability: it can create, interact, and personalize at scale. It can generate strikingly realistic training scenarios, offer instantaneous and adaptive feedback on intricate practical tasks, and facilitate learning journeys meticulously tailored to individual aptitudes and industry specifications (Zary & Zary, 2025). The integration of GenAI into TVET is therefore not a mere upgrade; it signals a potential pedagogical revolution. AI can function as a «copilot for subject matter experts, instructional engineers, and trainers», dramatically accelerating the development and refinement of educational content (Shevchenko et al., 2024). This synergy promises to evolve TVET from a standardized, one-size-fits-all paradigm to a learner-centric ecosystem that is more dynamic, engaging, and ultimately, more effective.

However, this potential is accompanied by significant challenges that warrant careful consideration. The path toward a full, effective, and equitable integration is fraught with challenges that are at once technological, financial, human, and ethical. Issues of inadequate digital infrastructure, the prohibitive costs of implementation, the urgent need for upskilling both educators and learners, and profound ethical quagmires surrounding academic integrity, data privacy, and algorithmic bias must be navigated with strategic foresight and moral clarity (Francis et al., 2025; Lazimi, 2024). As a recent UNESCO (2024) report astutely observes, the rapid evolution of AI consistently outpaces the deliberative processes of policy and regulation, creating risks that demand vigilant and proactive management.

This literature review endeavors to provide a comprehensive and systematic cartography of the current landscape of GenAI in post-secondary TVET. While several excellent reviews have explored GenAI in the broader context of higher education, a dedicated synthesis focusing on the unique affordances and constraints of the vocational domain has been a notable gap. This paper seeks to fill that void. It moves beyond a simple inventory of impacts to propose a novel Integrated Symbiotic Model, a conceptual framework that reframes GenAI integration as a dynamic, "people-oriented" process involving a "teacher-machine-student" triad. This model is designed to guide a transformation that is at once innovative and responsible, addressing the following core research questions:

1. How does the integration of Generative AI fundamentally transform pedagogical practices within the specific contexts of TVET?

2. In what ways does Generative AI influence learner engagement, motivation, and the development of crucial self-regulated learning (SRL) skills?

3. How is Generative AI compelling a fundamental redesign of skills assessment methodologies to better capture the complex, multi-dimensional competencies required by the modern workforce?

By synthesizing a diverse body of recent literature, this paper aims to empower educators, institutional leaders, policymakers, and researchers to navigate the complexities of this new era, ensuring that the future of vocational training is not only technologically advanced but also profoundly human-centered.

To achieve these objectives, this study employs an integrative literature review methodology. An integrative review is a specific form of research that synthesizes representative literature on a topic to generate new frameworks and perspectives (Torraco, 2005). This strategy was deemed most appropriate for our goal, which was not to quantify research trends but to build a coherent theoretical argument and synthesize disparate concepts into a novel, holistic model.

The selection criteria focused on identifying recent (primarily post-2020), high-impact, peer-reviewed articles, and key institutional reports that address the intersection of generative AI, pedagogy, technology adoption, and ethics, with a specific focus on post-secondary and vocational education contexts. The corpus was constructed through targeted searches on academic databases and through citation chaining to identify foundational and influential works.

The remainder of this paper is structured as follows. First, we analyze the transformative impacts of GenAI on pedagogy, engagement, and assessment. Next, we discuss the systemic barriers to implementation. Finally, we introduce and detail our proposed conceptual framework, the Integrated Symbiotic Model, before offering concluding remarks.

2. The transformative impact of Generative AI on pedagogical practices in TVET

The arrival of Generative AI in TVET is not a matter of simply adding new tools to the instructional toolkit; it is a catalyst for a fundamental reconceptualization of pedagogy itself. The long-standing traditions of vocational instruction -often characterized by a unidirectional flow of information, standardized curricula, and delayed, summative feedback- are being challenged and augmented by AI-driven approaches. These new paradigms are inherently dynamic, interactive, and learner-centric, designed to foster active, hands-on learning in a way that is responsive to individual needs (Aswini et al., 2025). This evolution represents more than a technological shift; it is a pedagogical metamorphosis that recasts the learner from a passive recipient of knowledge into an active architect of their own competence (Hasynets et al., 2024).

2.1. From mass instruction to precision pedagogy: Personalization and adaptive learning

Perhaps the most profound pedagogical impact of GenAI lies in its ability to deliver personalized and adaptive learning experiences at a scale previously unimaginable. Within the TVET context, where student cohorts are typically characterized by a wide spectrum of prior experiences, practical skill levels, and learning paces, personalization is not a luxury but a

pedagogical imperative. GenAI offers a definitive break from the «one-size-fits-all» model, enabling the creation of truly bespoke learning pathways. An intelligent learning system can dynamically adapt the content, rhythm, and modality of instruction to the unique profile of each learner (Lazimi, 2024; Woolf, 2010).
In a practical setting, an adaptive learning platform can analyze a student's performance data in real-time. Consider an apprentice automotive technician working on a simulated engine diagnostics task. The AI can track not only whether the correct fault was identified but also the diagnostic path taken, the sequence of tests performed, and the time spent on each step. If the system detects a conceptual misunderstanding -for instance, a flawed grasp of the fuel injection system- it can immediately deploy a targeted intervention: a micro-learning video, an interactive 3D model of the system, or a set of remedial exercises. Conversely, for a student who demonstrates rapid mastery, the system can introduce more complex faults or advanced diagnostic scenarios, thereby preventing disengagement and fostering a state of continuous, challenging growth (Baharin et al., 2025). This capacity for precision tailoring is a powerful driver of student adoption. A study of TVET students found that «performance expectancy» -the belief that the technology would yield tangible improvements in their professional skills- was a primary determinant of their intention to use it, highlighting a clear demand for learning solutions that deliver demonstrable value (Baharin et al., 2025). This aligns with broader findings in higher education, where adaptive learning environments have been shown to enhance student engagement while mitigating cognitive overload (El-Sabagh, 2021; Li et al., 2021).

2.2. Enhancing efficiency: Automation in instructional design

Generative AI has the potential to significantly improve the efficiency and quality of instructional design within vocational education. The development of high-quality, relevant, and engaging learning materials is an intensely time-consuming endeavor for educators. GenAI can automate the creation of a vast array of resources, from detailed technical manuals and lesson plans to realistic, industry-specific case studies and extensive banks of assessment questions (Ranuharja et al., 2025; Shevchenko et al., 2024). This automation is not merely a time-saving measure; it liberates educators from repetitive, low-impact tasks, allowing them to redirect their expertise toward higher-value pedagogical activities. These include providing individualized mentorship, facilitating complex, project-based learning, and coaching students in the development of crucial non-technical skills like communication, teamwork, and problem-solving.
Furthermore, this capacity for automation enables the creation of curricula that are more dynamic, relevant, and continuously updated. A perennial challenge in TVET is the «curriculum lag»—the gap between what is taught in the classroom and the rapidly evolving needs of the labor market. GenAI can be deployed to continuously scan and analyze labor market data, including job postings, industry reports, and skills frameworks, to identify emerging competencies and skills in high demand. This intelligence can then be used to recommend or even auto-generate curricular updates in near real-time. This transforms the role of the educator from a simple "content deliverer" to a sophisticated «curriculum architect» or «learning experience designer». In this new role, the educator leverages AI as a powerful analytical and creative partner to design and maintain training pathways that are truly at the cutting edge of their industry.

2.3. The virtual workshop: Intelligent simulations and immersive training

In vocational education, where the mastery of psychomotor skills and hands-on practice is the ultimate goal, GenAI is unlocking revolutionary training possibilities through the development of sophisticated Intelligent Tutoring Systems (ITS) and immersive virtual simulations. AI-powered virtual labs and Extended Reality (XR) environments provide students with safe, controlled, and endlessly repeatable opportunities to practice complex technical procedures. This is invaluable in fields where real-world equipment is prohibitively expensive, inherently dangerous, or simply unavailable for novice training (e.g., aviation, surgery, industrial welding, high-voltage electrical work) (Johnson et al., 2020; Zary & Zary, 2025).

For instance, a study on an AI-guided welding simulator demonstrated significant improvements in both the precision and learning rate of apprentices compared to traditional instruction. The system could analyze the apprentice's hand stability, torch angle, and travel speed with superhuman precision, providing instantaneous, corrective haptic and visual feedback. Similarly, the use of Virtual Reality (VR) in TVET creates deeply immersive and interactive learning environments that effectively surmount the logistical and safety challenges of traditional hands-on training (Leong, 2024). These «AI teaching factories» and simulated worlds have proven their capacity to enhance technical proficiency, operational efficiency, and overall industry readiness, allowing students to practice procedures to the point of automaticity without risk or material cost (Chiang et al., 2022).

2.4. The evolving educator: From sage on the stage to guide on the side

The integration of GenAI inevitably catalyzes a profound mutation of the educator's role in TVET. The traditional model of the teacher as the sole repository of knowledge -the «sage on the stage»- becomes functionally obsolete. The educator of the AI era must evolve into a multifaceted professional: a facilitator of learning, a designer of learning experiences, a sophisticated technology integrator, and, most critically, an ethical guide. This represents a fundamental shift from the «sage on the stage» to the «guide on the side». The educator's primary function is no longer to transmit information but to help students navigate complex information ecosystems, to critically evaluate AI-generated content, to master the art of effective prompting, and to apply their skills in a manner that is both creative and ethically sound.

This is not an easy or automatic transition; it is a significant professional development challenge. It demands a massive and sustained investment in upskilling educators to enhance their AI literacy, their pedagogical adaptability, and their confidence in using these powerful new tools (Lazimi, 2024; Zabolotska et al., 2021). As a systematic review by Bittle and El-Gayar (2025) starkly concludes, a primary obstacle is the «insufficiency of the digital and pedagogical skills necessary to integrate AI into their professional practices». Without robust training, ongoing support, and a culture that encourages pedagogical experimentation, the risk of cultural resistance and superficial adoption is high, potentially leaving the transformative power of GenAI largely untapped.

3. Impact on learner engagement and motivation

Learner engagement stands as a cornerstone of educational achievement, a factor that is magnified in TVET, where the intrinsic motivation to master complex practical skills is paramount. Generative AI is proving to be a powerful force in this domain, capable of transforming learning experiences from passive and monotonous to active, immersive, and deeply motivating. While traditional vocational training can sometimes struggle to sustain high levels of student engagement, GenAI addresses this by engineering dynamic and personalized interactions that captivate learners and forge a more profound connection with the subject matter (Jayalath & Esichaikul, 2021).

3.1. From passive consumption to active co-construction

The most fundamental shift in the learning experience driven by GenAI is the transition from the passive consumption of content to the active participation in, and co-construction of,

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knowledge. No longer is the learner confined to reading a static manual or listening to a lecture. Now, a student can engage in a sophisticated dialogue with an AI-powered conversational agent to clarify doubts, collaboratively solve complex problems, and receive instant, contextualized explanations. A compelling study in TVET institutions revealed that using ChatGPT had a significant positive impact on students' comprehension and engagement, effectively transforming the learning process into a more exploratory and conversational journey (Ab Hamid et al., 2023). In parallel, AI-driven simulations and virtual labs demand that students actively apply their theoretical knowledge to solve realistic problems, a process that enhances not only their technical competence but also their self-confidence and problem-solving abilities (Leong, 2024). This hands-on, interactive methodology is perfectly aligned with the practical nature of vocational skills and is instrumental in forging a deeper cognitive link with the material, a key prerequisite for long-term knowledge retention.

3.2. The power of immediacy: feedback and gamification

Feedback is arguably the single most powerful influence on learning, and GenAI makes it immediate, personalized, and omnipresent. In a traditional educational setting, the feedback loop can be painfully long, with students often waiting days or weeks for a response on their work. With AI-based systems, that loop is closed in seconds. An apprentice mechanic using an engine repair simulator receives real-time, corrective feedback on every single action. This continuous stream of information is a potent motivational engine. Learners can visualize their progress, pinpoint their weaknesses with precision, and practice until mastery is achieved. This process directly nurtures a sense of competence and self-efficacy, two of the most critical pillars of intrinsic motivation.

To further amplify this motivational effect, many AI-driven educational platforms are integrating sophisticated gamification elements. The awarding of digital badges for mastering new skills, the use of leaderboards to foster a sense of healthy competition, and the creation of interactive quizzes with points and rewards have all proven highly effective in boosting student engagement (Arce & Cuadros Valdivia, 2020; Li et al., 2024). These ludic elements render the learning process more interactive and enjoyable, stimulating both intrinsic motivation (the joy of overcoming challenges) and extrinsic motivation (the desire for recognition and reward) (Xiao & Hew, 2024a).

3.3. Fostering autonomy: Self-Regulated Learning (SRL)

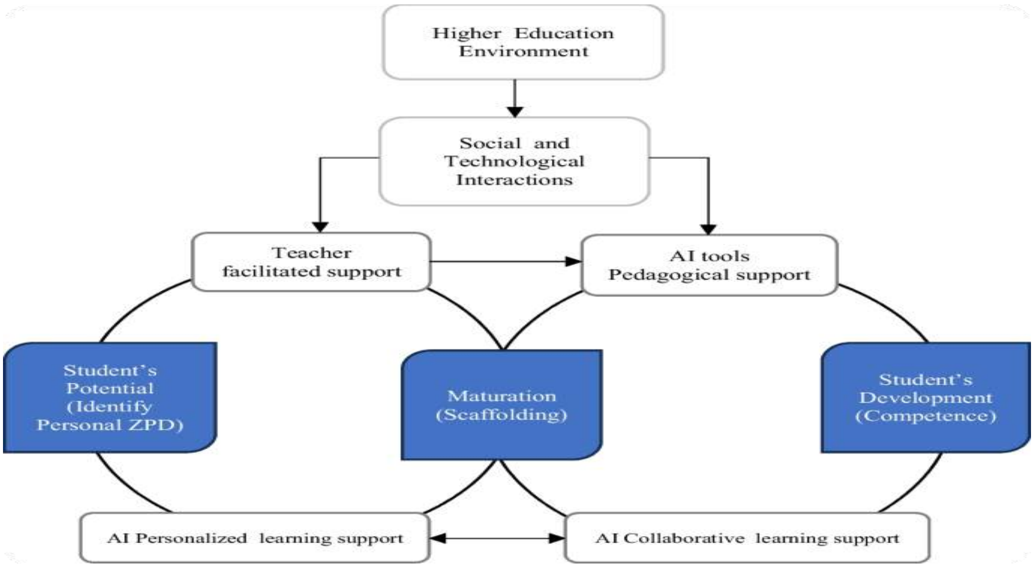
An effective learner is not merely a vessel for knowledge, but a skilled navigator of their own learning journey. Self-Regulated Learning (SRL) refers to the set of metacognitive skills that allow an individual to actively manage their learning process - setting goals, monitoring progress, and adapting strategies. A systematic review of the literature indicates that GenAI can have a significant positive impact on the development of these crucial skills (Sardi et al., 2025). By providing personalized scaffolding and intuitive tracking tools, AI systems can empower students to better plan their work, recognize when they need assistance, and reflect critically on their own learning processes. A personalized dashboard, for instance, can visually map a student's progress against their stated goals, clearly highlighting areas of strength and opportunities for improvement.

However, the same body of research sounds a critical note of caution regarding the risk of over-reliance. If AI tools become a crutch, providing all the answers and guiding every step without prompting independent thought, they can paradoxically stifle the very metacognitive skills they are meant to support. The pedagogical goal must be to use AI to foster autonomy, not to create dependency (Li & An, 2023). The educator's role here is indispensable; they must design learning activities that compel students to engage with AI as a critical and reflective partner, not as an infallible oracle.

3.4. A catalyst for collaboration

While often lauded for its power to individualize learning, GenAI can also serve as a potent catalyst for collaborative learning, an essential competency in virtually every modern workplace. AI algorithms can be used to strategically assemble student teams, balancing or grouping them based on complementary skill profiles, learning styles, or specific project needs to maximize group synergy. Beyond team formation, AI tools can facilitate the entire collaborative workflow. They can provide shared virtual workspaces, AI-assisted brainstorming tools to overcome creative blocks, and even conversational agents programmed to help mediate conflicts or ensure the project remains on track. The conceptual model proposed by Cai et al. (2024), which illustrates the interplay between teacher facilitation, personalized support, and AI-driven collaboration, captures this dynamic effectively. By simulating the collaborative, technology-mediated environments that define modern professional life, GenAI can make learning more social, more relevant, and more engaging.

Figure 1: Interplay between teacher support and AI tools



Source: Cai et al., 2024, « Exploring the impact of integrating AI tools in higher education »

3.5. Augmenting human creativity and critical thinking

A primary objective of modern TVET is to cultivate not just competent technicians, but also agile innovators capable of adapting and creating. In this quest, GenAI can be a powerful ally. Students can leverage these tools for divergent thinking, using them as a brainstorming partner to generate a vast array of ideas. They can act as a co-creator, helping to rapidly develop and iterate on prototypes. They can even function as an intellectual «sparring partner». challenging assumptions and helping to explore alternative solutions (Wu, J., 2025). A graphic design student, for example, could use an image generation model to visualize dozens of logo concepts in minutes, allowing them to focus their human creativity on refining the most promising avenues. This process fosters a culture of creative exploration, rapid iteration, and intellectual risk-taking in a low-stakes environment.

However, the indispensable corollary to this creative potential is the cultivation of critical thinking. Educators bear the crucial responsibility of teaching students to be discerning consumers and critical evaluators of AI-generated content. This means equipping them with the skills to identify potential biases, factual inaccuracies (or «hallucinations»), embedded stereotypes, and logical fallacies in the outputs they receive. Students must learn that the output of a GenAI model is not an endpoint, but a starting point for their own analysis, synthesis, and value-added creation (Francis et al., 2025). As UNESCO (2024) emphasizes, the goal is to use

AI to augment and support human intellect and decision-making, not to supplant it. The ultimate value lies not in the answer the AI provides, but in the quality of the critical dialogue and deep reflection it inspires.

4. Redefining skills assessment with Generative AI

Assessment is the bedrock upon which learning is validated and certified. Generative AI is catalyzing a revolution in this domain, moving beyond static, traditional methods to offer more dynamic, authentic, and comprehensive ways to evaluate competence. This technological shift forces a fundamental reappraisal not only of *how* we assess but, more profoundly, of *what* we value as evidence of learning. For decades, traditional assessment methods have struggled to adequately measure the so-called 21st-century skills -creativity, innovation, collaboration, and complex problem-solving- (Onatere-Ubrurhe & Ubrurhe, 2025). The advent of GenAI makes this reassessment an urgent necessity, compelling us to redefine what constitutes meaningful proof of competence in the digital age (Audran, 2024).

4.1. The shift to authentic, performance-based assessment

The traditional assessment paradigm in TVET, often characterized by its reliance on multiple-choice questions, short-answer recall, and decontextualized practical exams, reveals its profound limitations in the era of AI. Such methods tend to measure rote memorization of facts rather than the fluid application of skills in authentic, real-world contexts. GenAI enables a decisive pivot towards authentic, performance-based assessment-evaluation that mirrors the complex, multifaceted challenges that professionals encounter in their daily work. AI-driven simulations can assess a student's ability to troubleshoot an intermittent fault in a complex hydraulic system, manage a project with shifting deadlines and resource constraints, or navigate a difficult customer service interaction. These systems can capture a rich tapestry of data that goes far beyond the final outcome. They can log the entire problem-solving process: the hypotheses formulated, the information sources consulted, the decisions made, and the iterative adjustments performed along the way (Salinas-Navarro et al., 2024).

These systems facilitate the evaluation of complex, open-ended tasks and long-term projects, providing a far more holistic and nuanced portrait of a learner's capabilities than is possible with standardized, static tests (Onatere-Ubrurhe & Ubrurhe, 2025). As UNESCO (2024) powerfully suggests, assessment itself should evolve towards a model of dialogue and defense, where learners are required to articulate and justify their reasoning in real-time a process that reveals a depth of understanding that AI struggles to replicate authentically.

4.2. The feedback loop: Automated, Granular, and Real-Time

One of the most immediate and impactful applications of GenAI in assessment is its capacity to deliver automated, detailed, and instantaneous feedback. In language-intensive trades, Natural Language Processing (NLP) models can evaluate not just grammar and syntax, but also the coherence, structure, and argumentative force of a technical report (Wu, J., 2025). In technical domains, sensor-equipped simulators can provide granular feedback on a student's psychomotor skills, measuring, for example, the precise angle of a cutting tool or the consistency of pressure applied. This real-time feedback loop is an incredibly powerful learning accelerant. It transforms assessment from a summative, end-of-unit event into a continuous, formative process woven into the fabric of learning itself. Students can immediately identify and correct their errors, understand the nature of their misconceptions, and iteratively refine their skills through practice (Onatere-Ubrurhe & Ubrurhe, 2025; Razouki et al., 2025).

Interestingly, research indicates a complementary relationship between AI and human feedback. While students continue to perceive feedback from their teachers as more trustworthy and nuanced, they deeply value the feedback from GenAI for its immediacy, 24/7 availability, and its non-judgmental nature (Henderson et al., 2025). This points to an optimal division of labor: AI can manage the high volume of formative, iterative feedback at scale, liberating the human educator to provide higher-level, holistic evaluations that focus on aspects the machine cannot perceive, such as intent, creativity, ethical judgment, and professional disposition.

4.3. Precision and equity through adaptive testing

GenAI is a key enabler of Computerized Adaptive Testing (CAT), a form of assessment where the difficulty of tasks is dynamically adjusted in real-time based on the test-taker's performance. If a student correctly answers a question or successfully completes a task, the system presents a more challenging one; if they struggle, the system offers a simpler task or provides scaffolding to support them. This dynamic approach yields a far more precise and efficient measurement of a student's true competency level compared to static tests where every student receives the same set of items, regardless of their ability (Onatere-Ubrurhe & Ubrurhe, 2025). By tailoring the assessment experience to the individual, adaptive testing can also reduce the overall time required for testing, mitigate test-related anxiety (by avoiding questions that are demoralizingly difficult or boringly easy), and provide a more positive and motivating assessment experience for the learner (Kulik & Fletcher, 2016).

4.4. The ethical minefield: Academic integrity and algorithmic bias

The immense power of GenAI in assessment is mirrored by the gravity of the ethical challenges it presents. Chief among these is the threat to academic integrity. The facility with which students can generate sophisticated essays, functional code, or intricate designs using AI raises profound questions about plagiarism, authorship, and the authenticity of student work (Bittle & El-Gayar, 2025; Jess, 2024). This has ignited an urgent debate and a call to action for the fundamental redesign of assessment. The focus must shift away from the final product, which can be easily generated by a machine, and towards the process of creation. This means designing assessments that prioritize skills that AI cannot easily replicate: critical reflection, oral defense of one's work, and in-person demonstrations of practical skills (Verdicchio, 2025). A study in Côte d'Ivoire starkly illustrated this dilemma, finding that while educators were using GenAI to design assessments, their students were using the same tools to complete them, thereby undermining the validity of the entire process (Coulibaly & Fofana, 2025).

Furthermore, ensuring the fairness, validity, and reliability of AI-driven assessment systems is a critical, non-negotiable imperative (Hao et al., 2024). A significant and tangible risk is that of algorithmic bias. If an AI assessment model is trained on historical data that reflects existing societal biases, it can learn to perpetuate and even amplify those biases. This could lead to systems that unfairly disadvantage students based on their gender, socio-economic background, linguistic patterns, or other characteristics (UNESCO, 2024). To counter this, the development of transparent and explainable AI models («Explainable AI»), coupled with robust ethical frameworks and validation protocols like the AI Assessment Scale (AIAS), is absolutely essential. These measures are necessary to ensure that AI is deployed as a tool for promoting equity, not as an unwitting instrument of discrimination (Perkins et al., 2023). The word cloud below, derived from an analysis of ethical considerations in TVET, highlights the central importance of concepts such as transparency, fairness, privacy, and accountability (Omeh et al., 2025).

However, this profound redesign of skills assessment, much like the transformation of pedagogy and engagement, collides with significant systemic obstacles that we will now examine.

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Figure 2: A word cloud emphasizing key ethical considerations for the application of AI in TVET.

Source: Omeh et al., 2025, « Application of artificial intelligence (AI) technology in TVET education»

5. Overarching challenges and systemic barriers to implementation

While the potential of Generative AI to revolutionize TVET is undeniable, the path from promising pilot projects to successful, scaled implementation is strewn with considerable systemic barriers. These obstacles are not merely technical; they are deeply intertwined with human, financial, and institutional realities. A critical reading of the literature reveals a consistent set of fundamental challenges that must be strategically and holistically addressed to bridge the chasm between technological promise and the practical realities of educational institutions (Lazimi, 2024; Zary & Zary, 2025).

5.1. The foundational barrier: Infrastructure and financial constraints

The most foundational barrier is the lack of adequate technological infrastructure. This issue is particularly acute in developing regions, but it is also a persistent reality in underfunded institutions and rural areas within developed nations. Many TVET institutions operate with outdated computer hardware, unreliable or low-bandwidth internet connectivity, and a general absence of the robust digital ecosystem required to support sophisticated AI-driven platforms (Lazimi, 2024; Onatere-Ubrurhe & Ubrurhe, 2025). This «digital divide» creates a landscape of inequity, where access to transformative educational technologies becomes a function of geography and economic status (OECD, 2020).

This infrastructural deficit is compounded by the often-prohibitive costs associated with AI implementation. The licensing or development of advanced simulators, adaptive learning systems, and automated assessment platforms represents a significant capital investment. Furthermore, the total cost of ownership extends far beyond the initial purchase. Recurring expenses for software maintenance, regular updates, specialized staff training, and the substantial energy consumption of the required server infrastructure create a long-term financial burden that many institutional budgets are ill-equipped to handle (Alenezi, 2023). Without a clear strategy for significant and sustained investment from governmental bodies and industry partners, the large-scale adoption of these technologies will remain an elusive goal for a vast number of institutions (World Bank, 2019).

5.2. The human dimension: Competency gaps and cultural resistance

A technology, no matter how powerful, is only as effective as the people who wield it. A critical human-centric barrier is the pervasive digital competency gap among both educators and learners (Baharin et al., 2025). Despite a growing ambient awareness of AI, a significant portion of the TVET teaching workforce lacks the specific training and pedagogical knowledge required to effectively and critically integrate GenAI into their teaching and assessment practices (Eickelmann et al., 2019; Razouki et al., 2025). This lack of expertise can breed a lack of confidence, foster technological anxiety, and lead to a strong reluctance to move beyond familiar, traditional methods. Similarly, learners may lack the foundational digital literacy needed to fully exploit the potential of GenAI tools, leading to unequal access and a limited understanding of how these tools can be used effectively and ethically in an academic context (Baharin et al., 2025).

This skills deficit is often intertwined with a deeper cultural resistance within educational institutions. The academic and administrative staff may be deeply invested in established practices and may harbor skepticism or fear regarding the adoption of new technologies. Legitimate concerns that AI might supplant the role of the teacher, dehumanize the educational experience, or erode the quality of human interaction are widespread and must be addressed with empathy and open dialogue (Lazimi, 2024). Overcoming this cultural inertia requires more than just technical training; it demands a comprehensive change management strategy that includes clear communication of the pedagogical benefits, strong leadership, and the active involvement of all stakeholders in the integration process (Fullan, 2016).

5.3. The ethical and legal imperative

The deployment of AI in educational settings raises profound ethical and legal questions that must be proactively addressed to build trust and ensure a responsible implementation. A paramount concern is data privacy and security (Baharin et al., 2025; Floridi et al., 2018). The very systems that enable personalized learning do so by collecting and analyzing vast quantities of sensitive student data-performance metrics, interaction patterns, error logs, and even behavioral indicators. This raises a host of critical questions: How is this data collected, stored, used, and protected? Who has ownership of it? In many parts of the world, existing legal frameworks for data protection, such as the GDPR in Europe, are struggling to keep pace with the rapid advancements in AI capabilities, often leaving students and institutions navigating a legal gray area that exposes them to potential vulnerabilities (Mittelstadt et al., 2016).

The ethical challenge of algorithmic bias, as previously discussed, also looms large. If AI systems are trained on historical data that contains latent societal biases, they will inevitably learn and reproduce those biases, potentially leading to discriminatory outcomes in assessment, feedback, or learning pathway recommendations (UNESCO, 2024). Ensuring the transparency, accountability, and fairness of these complex algorithms is a significant technical and ethical challenge, but it is a non-negotiable prerequisite for any ethical deployment of AI in education (Jobin et al., 2019). Operationally, this requires institutions to establish concrete governance mechanisms, such as (1) internal ethics review boards for the procurement of AI tools, (2) regular algorithmic audits to detect and mitigate bias, particularly in assessment systems, and (3) the development of transparent data management policies that are clearly communicated to all stakeholders. The evaluation of equity must be translated from a theoretical concern into a set of auditable processes and clear lines of accountability.

5.4. The systemic lag: Curriculum, policy, and technology

Finally, a significant systemic barrier is the inherent lag between the exponential pace of technological change and the often-glacial pace of curricular and policy adaptation within educational systems. Current TVET curricula may fail to reflect the new competencies demanded by an AI-infused workplace, such as prompt engineering, data literacy, human-machine collaboration, and applied AI ethics (Popenici & Kerr, 2017). The process of updating official study programs is typically complex, bureaucratic, and requires consensus among a wide range of stakeholders, including educational institutions, industry advisory boards, certification bodies, and government ministries.

This challenge is often exacerbated by the absence of clear, coherent national strategies for the integration of AI into vocational education. This policy vacuum frequently results in a fragmented, ad-hoc approach, characterized by isolated pilot projects with limited impact and a duplication of effort (Lazimi, 2024). Without a strategic, top-down vision, supported by clear public policies and adequate, long-term funding, the truly transformative potential of GenAI in the TVET sector risks remaining largely unrealized (European Commission, 2020).

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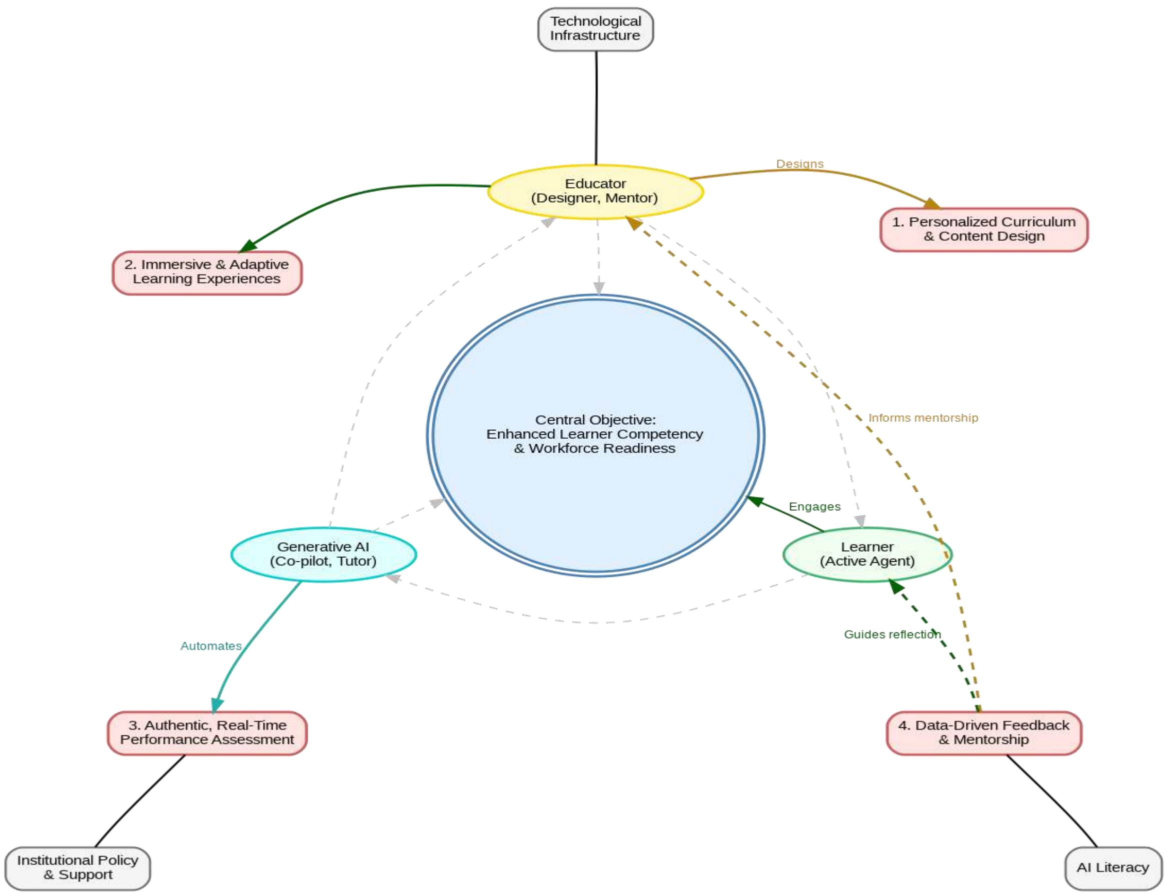
6. An Integrated Symbiotic Model for Generative AI in TVET

The preceding review of the literature reveals a clear consensus: the successful integration of Generative AI into TVET is not a simple matter of adopting new technological tools. It is a complex, systemic challenge that involves a dynamic interplay between technological capabilities, institutional readiness, pedagogical innovation, and unwavering ethical oversight. A fragmented or technology-centric approach is destined to yield suboptimal results, failing to unlock the transformative potential of GenAI. To synthesize these interconnected elements and to offer a clear, strategic roadmap for future research and institutional practice, we propose a new conceptual model for the effective and ethical integration of GenAI in TVET.

6.1. Rationale for an integrated symbiotic model

This model builds upon established theoretical frameworks, such as the Unified Theory of Acceptance and Use of Technology (UTAUT), which explains user intentions to use an information system (Baharin et al., 2025). However, while UTAUT is powerful in predicting user acceptance, it is less equipped to explain the complex, post-adoption dynamics of symbiotic integration into pedagogical processes. Our Integrated Symbiotic Model extends beyond the antecedents of intention to use - the core of UTAUT - to create a holistic, ecosystem-level framework. It shifts the focus to the ongoing, dynamic interplay between the educator, the learner, and the AI within the learning process itself, conceptualizing AI not merely as a "system" to be "used", but as an active agent in a "teacher-machine-student" triad. This approach offers a more granular and pedagogically-grounded perspective than traditional adoption models.

Figure 3: An integrated symbiotic model.



Source: Elaborated by the authors on the basis of the scientific literature mentioned

It is crucial to acknowledge, however, that the implementation of this model is highly context-dependent. While conceptually universal, its layers will manifest differently across diverse cultural and institutional settings. The "Institutional policy and support" enabler, for instance, will be shaped by national educational policies, while "AI literacy" will depend on the pre-existing digital divide. The model should therefore be viewed not as a rigid blueprint, but as an adaptable framework whose components must be tailored to local realities. We suggest that future empirical research should focus on testing and adapting the model in various contexts to explore its transferability and identify the key contextual factors that moderate its effectiveness.

6.2. Deconstructing the Model: Components and dynamics

The model is designed to be both descriptive and prescriptive, illustrating the necessary components and their dynamic relationships for a successful GenAI ecosystem in TVET.

6.2.1. Layer 1: The foundational enablers

These three elements form the bedrock upon which any successful AI integration strategy must be built. They are external to the core learning process but are essential prerequisites that enable it. They are interdependent and mutually reinforcing; a weakness in one will compromise the entire structure.

- ***Technological infrastructure:***

This extends beyond the mere availability of modern hardware and high-speed internet. It encompasses access to relevant, effective, and secure GenAI software, platforms, and specialized simulations. Crucially, it also includes the robust technical support necessary to maintain these systems, ensure data integrity, and assist users, preventing technological frustrations from becoming pedagogical barriers (Lazimi, 2024).

- ***Institutional policy & support:***

Strong, visionary leadership is critical. This component involves the strategic allocation of dedicated funding for technology and training, the creation of clear and fair policies on the acceptable use of AI (for both staff and students), the revision of assessment regulations to permit and encourage innovation, and the active promotion of an organizational culture that encourages experimentation, tolerates failure as a learning opportunity, and actively supports educators in their professional transition (Francis et al., 2025; European Commission, 2020).

- ***AI literacy:***

This is a comprehensive requirement for all stakeholders. For educators and learners alike, AI literacy must transcend basic operational skills. It must include advanced competencies such as prompt engineering, the ability to critically evaluate the accuracy, bias, and reliability of AI outputs, a deep understanding of the ethical dimensions of AI use, and the capacity to creatively integrate AI into teaching and learning workflows (Zabolotska et al., 2021; UNESCO, 2021).

6.2.2. Layer 2: The core triad of actors

At the heart of the learning process are three interconnected agents whose roles and interactions are transformed by the integration of GenAI.

- ***The learner (active agent):***

The model explicitly positions the learner not as a passive recipient of information but as an active agent in their own learning. The learner engages directly with the learning experiences, uses AI tools for reflection and practice, and co-constructs their understanding.

- ***The educator (designer, mentor):***

The educator's role undergoes a profound shift from a «sage on the stage» to a «guide on the side». In this model, they are the primary "Designer" of the learning ecosystem, curating content and architecting immersive experiences. They are also the expert "Mentor", using data-driven insights to provide targeted, human-centric guidance that AI cannot replicate.

- ***Generative AI (co-pilot, tutor):***

The AI is positioned as a powerful assistant, not a replacement. As a "Co-pilot", it aids the educator in content creation and automates routine tasks. As a "Tutor", it provides learners with personalized scaffolding, instant feedback, and tireless opportunities for practice.

6.2.3. Layer 3: The four core processes

These four processes represent the primary activities within the AI-enhanced TVET ecosystem, driven by the actors and enabled by the foundations.

- ***Personalized curriculum & content design:***

The educator, leveraging their AI literacy and the available tools, designs personalized curricula. GenAI acts as a co-pilot, helping to generate diverse and relevant content that can be tailored to individual learner pathways.

- ***Immersive & adaptive learning experiences:***

The educator also designs the overarching learning activities, which are increasingly immersive (e.g., VR simulations) and adaptive. The learner actively engages with these experiences, which are mediated and personalized by the GenAI tutor.

- ***Authentic, real-time performance assessment*:**

As the learner interacts with these experiences, their performance is continuously assessed. GenAI automates this process, capturing rich data on not just outcomes but the processes used. This assessment is authentic, as it occurs within realistic, performance-based scenarios.

- ***Data-driven feedback & mentorship:***

This is the crucial feedback loop that powers the model. The performance data generates two streams of insight. First, it provides immediate, data-driven feedback directly to the learner, which guides their reflection and self-correction. Second, it provides synthesized insights to the educator, which informs their mentorship, allowing them to intervene precisely when and where their human expertise is most needed.

6.2.4. Layer 4: The central objective

All of these components and processes work in synergy towards a single, overarching goal: Enhanced Learner Competency & Workforce Readiness. This objective is not merely about passing exams but about developing deep, robust, and applicable vocational skills, along with the adaptive 21st-century competencies that ensure graduates are not just ready for their first job but are prepared for a lifetime of career evolution. The success of the entire system is measured by its ability to achieve this central objective.
In essence, this model proposes that for TVET institutions to achieve the desired outcome of a future-ready workforce, they must move beyond piecemeal adoption of AI tools. They must commit to a systemic transformation: investing strategically in the foundational enablers, re-imagining the roles of and interactions between educators and learners, and governing the entire process through a robust ethical framework. True success lies in the alignment and integration of these layers.

7. Discussion

7.1. Synthesis of key findings and tensions

This literature review has systematically explored the multifaceted impacts of Generative AI on post-secondary TVET, revealing some landscape rich with opportunity but also fraught with significant challenges. The evidence clearly indicates that GenAI is not a fleeting trend but a transformative force with the potential to fundamentally redefine vocational education by enhancing pedagogical practices, deepening learner engagement, and creating more authentic and accurate methods of skills assessment (Zary & Zary, 2025; Onatere-Ubrurhe & Ubrurhe, 2025; Baharin et al., 2025).

A central finding of this review is that the effectiveness of digital technologies hinges less on the tools themselves and more on their thoughtful and critical integration into rigorous pedagogical practices (Timotheou et al., 2022). The core pedagogical shift enabled by GenAI is from standardization to personalization (Lazimi, 2024). However, the literature also reveals a critical tension between the promise of technology and the complexities of its implementation. For instance, while a significant body of research extols the virtues of immersive VR simulations for technical training (e.g., Leong, 2024; Chiang et al., 2022), other studies caution against a purely techno-optimist view. Albus et al. (2021), for example, highlight the risk of cognitive overload in poorly designed VR environments, suggesting that the pedagogical effectiveness of these tools is contingent upon careful instructional design, not just technological sophistication.

This illustrates a broader theme: the success of GenAI integration is highly context-dependent, moderated by factors such as the specific vocational domain, the digital readiness of the institution, the pedagogical culture, and the characteristics of the student population (Lazimi, 2024; Zary & Zary, 2025). The variability in findings across studies highlights the absence of a singular, universally applicable solution and underscores the imperative for tailored approaches grounded in robust empirical data and informed by deep pedagogical reflection. The proposed conceptual model attempts to provide a framework for navigating this complexity, emphasizing the foundational elements that must be in place regardless of the specific context.

7.2. Identification of gaps in the research

While research on GenAI in education is exploding, several critical gaps remain, particularly within the TVET context. Addressing these gaps is essential for building an evidence base to guide future policy and practice.

- ***Lack of longitudinal data:***

The vast majority of studies are short-term, focusing on immediate impacts on engagement or performance in a single course or module. There is a pressing need for longitudinal research that evaluates the long-term impact of GenAI interventions on skill retention, professional development, and career trajectories of graduates (Zary & Zary, 2025). Do the benefits observed in a semester-long course translate into greater competence and adaptability five years into a career?

- ***Under-exploration of socio-emotional aspects:***

The literature tends to focus on cognitive and behavioral outcomes (e.g., test scores, task completion times). The psycho-affective dimensions of learning with AI—such as its impact on student anxiety, sense of belonging, self-efficacy, and potential for social isolation—remain insufficiently studied (Van Laar et al., 2020). Understanding these aspects is crucial for designing AI systems that are not only effective but also supportive of student well-being.

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- ***Limited focus on practical and non-cognitive skills assessment:***

While the potential for assessing practical skills is often touted, there are few rigorous studies evaluating how effectively digital tools can measure and develop non-cognitive skills like collaboration, communication, resilience, and professional ethics in a vocational setting. Developing and validating digital assessment tools for these crucial competencies is a significant area for future research.

- ***The educator's perspective:***

Much of the research focuses on student outcomes. More studies are needed that focus on the educator's experience: the challenges they face in adapting their practice, the types of professional development and support they find most effective, and how their professional identity and workload evolve in an AI-integrated environment (Zabolotska et al., 2021).

7.3. Limitations of the present review

This review, while aiming for comprehensiveness, has its own limitations. The field of generative AI is evolving at an unprecedented pace, meaning that any review is a snapshot in time and may quickly be outdated by new technological developments and research findings. There is also a potential for publication bias, where studies with positive or significant findings are more likely to be published than those with null or negative results, which could skew the overall picture of effectiveness. Finally, the synthesis of studies from diverse contexts (e.g., developed vs. developing nations, different vocational fields from healthcare to manufacturing) requires careful interpretation, as findings may not be universally generalizable.

8. Conclusion

The journey toward the full and equitable integration of Generative AI in TVET is complex but necessary. It holds the promise of cultivating a workforce that is not only technically proficient but also highly adaptable, innovative, and prepared to thrive in an increasingly automated world. This review confirms that GenAI can be a powerful catalyst for transforming pedagogy, engagement, and assessment in vocational education. However, its success is not a technological inevitability; it is a function of strategic planning, pedagogical innovation, and an unwavering ethical commitment.

Realizing this potential requires a concerted, collaborative effort from all stakeholders. The proposed conceptual model offers a framework for this effort, emphasizing that technological tools must be supported by foundational enablers-infrastructure, policy, and literacy-and governed by a robust ethical framework that permeates every layer of the system. The ultimate goal is not simply to integrate AI, but to leverage it to achieve superior learning outcomes: enhanced vocational skills, greater workforce readiness, and the cultivation of lifelong learning capabilities.

In conclusion, generative AI offers a unique opportunity to revolutionize post-secondary technical and vocational education. The path forward requires vision, investment, and collective action to overcome the existing barriers and fully realize AI’s potential. With strategic planning and stakeholder engagement, TVET systems can harness these powerful tools to shape a more effective, engaging, and relevant future for vocational training, preparing learners to thrive in the digital era.

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