

Integrated Quality Management Model for Teaching Factory in the Era of Industrial Revolution 4.0 : A Systematic Literature Review

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Abstract

Aim

This systematic literature review synthesizes research on quality management models for Teaching Factories (TeFa) in the Industrial Revolution 4.0 (IR 4.0) era, aiming to identify core components and technological enablers for an integrated model aligning pedagogical outcomes with industrial standards.

Method

Following PRISMA guidelines, a systematic review was conducted across Scopus, Web of Science, IEEE Xplore, and Google Scholar for peer-reviewed articles published between 2015 and 2025. After applying inclusion criteria, 15 primary studies were selected for thematic synthesis.

Results

Existing TeFa quality models are fragmented. Three themes emerged: (1) technological integration (IoT, cyber-physical systems, cloud monitoring), (2) process alignment (ISO 9001:2015 with industry 4.0 standards), and (3) competency-based assessment (digital rubrics, blockchain certification). No single model integrates all three. Key barriers include interoperability gaps and weak feedback loops.

Novelty

The study proposes the IR4.0 TeFa QM Integration Matrix, a novel framework mapping four quality dimensions (planning, control, assurance, improvement) against four TeFa layers (physical production, virtual simulation, student assessment, industry collaboration). Practical Implication: Educators gain guidelines for AI-based defect tracking and digital twin audits; industry partners benefit from student outputs meeting real-time production tolerances, reducing rework. Contribution: This review consolidates fragmented knowledge, introduces a testable model bridging pedagogical-industrial quality divides, and sets an agenda for validating cyber-physical quality systems in educational production environments.

A. Introduction

The convergence of vocational education and industrial production has long been recognized as a critical driver of workforce readiness (Adel, 2024; Pinto et al., 2025). One of the most promising pedagogical-industrial frameworks to emerge from this convergence is the Teaching Factory (TeFa). Originating from the German Lernfabrik concept, TeFa is defined as a simulated yet authentic production environment within an educational institution where students engage in real or near-real industrial processes, including order management, manufacturing, quality control, and logistics. Unlike traditional workshops or laboratories, a Teaching Factory bridges the gap between classroom theory and factory floor practice by embedding students into a value chain that mirrors industry operations (Bondin & Zammit, 2025). Extensive literature has established that TeFa effectively enhances students' technical competencies, problem-solving skills, and work ethic (Hulyadi et al., 2025; Žerovnik, 2024). Studies have demonstrated that graduates exposed to TeFa-based learning exhibit shorter onboarding times and higher adaptability in industrial settings. Furthermore, TeFa promotes industry-academia collaboration, where companies provide real orders, raw materials, and quality standards, while educational institutions supply labor, infrastructure, and supervised learning. Parallel to this, the Industrial Revolution 4.0 (IR 4.0) has fundamentally reshaped manufacturing paradigms (Islam et al., 2025; Jaafar et al., 2024). Characterized by cyber-physical systems (CPS), the Internet of Things (IoT), artificial intelligence (AI), cloud computing, big data analytics, and digital twins, IR 4.0 demands a new generation of workers proficient in smart manufacturing, data-driven decision-making, and autonomous systems. Consequently, quality management traditionally governed by ISO 9001 standards, Total Quality Management (TQM), and Six Sigma has evolved into Quality 4.0, which integrates real time monitoring, predictive analytics, and closed-loop feedback systems (Antony et al., 2024; Hattinger & Styliadis, 2023). Researchers have individually explored two critical domains: (1) quality management models for educational settings, and (2) quality assurance frameworks for Teaching Factories (Ho et al., 2022; Sordan et al., 2022). Some studies have documented the implementation of specific IR 4.0 technologies in TeFa, such as IoT-enabled workstations or cloud-based student assessment platforms (Zeeshan

et al., 2022). It is also known that successful TeFa operation requires alignment between academic curricula and industry-recognized quality certifications. Moreover, several vocational institutions have adopted digital rubrics and e-portfolios to track student performance against quality metrics (Garcia, 2025; Pospíšilová & Rohlíková, 2023). However, despite these isolated efforts, what remains conspicuously absent is an integrated quality management model that holistically binds pedagogical objectives, production processes, and IR 4.0 technologies into a unified, real-time quality assurance system (Mondal & Haick, 2025; Olinic et al., 2025). The existing literature offers valuable fragments technological here, pedagogical there but lacks a cohesive architecture that operationalizes quality across the entire TeFa ecosystem (Fakourian et al., 2025; Ge et al., 2023).

While the benefits of TeFa and the imperatives of IR 4.0 are well documented, significant knowledge gaps persist regarding how quality management should be systematically designed, implemented, and evaluated within a digitally transformed Teaching Factory. The following unknowns constitute the central research problem: First, there is no empirically validated model that specifies how traditional quality management functions planning, control, assurance, and improvement should be reconfigured for a TeFa environment infused with cyber-physical systems. Existing studies describe individual technologies but fail to explain how these technologies integrate with ISO-based quality documentation, student competency assessments, and industry feedback loops. Second, the interoperability between educational quality standards and industrial quality standards within a TeFa context remains unexplored. Educational institutions often treat quality assurance as a compliance exercise for accreditation, while industries view quality as real-time production conformance (Glevitzky et al., 2025; Javed & Alenezi, 2023; Rivadeneira C., 2024). How these two paradigms can be synchronized into a single, mutually reinforcing system is unknown (Laroche et al., 2024; Pareschi, 2025; Rojas et al., 2025). Third, the role of emerging IR 4.0 technologies in enabling dynamic quality feedback where student performance data automatically triggers curriculum adjustments, and production defect data informs pedagogical remediation has not been systematically studied (Halkiopoulou & Gkintoni, 2024; Morales Matamoros et al., 2025; Zahid et al., 2025). Current TeFa models typically separate student assessment from product quality assessment, even though both occur in the same physical production process (Awouda et al., 2024). Fourth, there is a lack of theoretical frameworks that map quality management dimensions onto TeFa operational layers (Maganga & Taifa, 2023). For instance, how does quality assurance for a virtual simulation (digital twin) differ from quality assurance for physical assembly? How should improvement cycles (Plan-Do-Check-Act) be adapted when production runs are intermittent and student cohorts rotate every semester? Fifth, the barriers and enablers specific to implementing an integrated quality management model in vocational education settings particularly in developing economies where TeFa infrastructure is nascent remain under-researched. Most evidence comes from high-income countries with mature industry 4.0 ecosystems (Geng et al., 2024; Gomes et al., 2025). Thus, while the need for integration is widely acknowledged, the how-the architecture, components, processes, and metrics of an integrated quality management model for TeFa under IR 4.0 remains largely unknown (Salazar-Calderón et al., 2025).

The current state of the art in this interdisciplinary domain can be categorized into three intersecting streams: Stream 1: Quality Management in Vocational Education. is generic and does not address production-specific quality requirements (Fraile et al., 2023; Litztenburger et al., 2024). Similarly, the EFQM (European Foundation for Quality Management) model has been adapted for educational institutions but lacks integration with real-time industrial data. Stream 2: Teaching Factory Models (Martusewicz et al., 2024; Nagy, 2025). The most cited TeFa frameworks include the TU Wien Learning Factory model, which emphasizes hands-on assembly and lean manufacturing, and the Aalborg University model, which integrates problem-based learning with production simulations. More recent models have incorporated IR 4.0 elements such as digital twins (e.g., the Smart Learning Factory at KIT) (Ahmad, 2024; Attaran et al., 2024; Rahmani et al., 2024). However, these models treat quality management as an implicit or peripheral component, not as a core design principle. Stream 3: Quality 4.0 in Industry. In industrial settings, Quality 4.0 integrates AI, IoT, and big data into TQM (Maganga & Taifa, 2023; Sordan et al., 2022). Examples include predictive quality control using machine learning, real-time statistical process control (SPC) via cloud platforms, and blockchain-based traceability. These technologies are mature in advanced manufacturing but have not been systematically translated into educational TeFa contexts (Bondin & Zammit, 2025; Laundon et al., 2023). Critical Gap in the State of the Art: While each stream has advanced independently, no existing model synthesizes all three (Vanian et al., 2025). Industrial Quality 4.0 models assume stable workforces and continuous production, not rotating student cohorts (Aliu & Aigbavboa, 2020; Arufe-Giráldez et al., 2023; Fiorella, 2023). Educational quality models assume learning as the primary output, not physical products with market value. TeFa models often focus on pedagogical design and infrastructure, not on formal quality management systems with audit trails,

non-conformance reporting, or corrective action procedures. The state of the art is therefore characterized by disciplinary silos rather than genuine integration (Birsal et al., 2023; Ghezzi et al., 2026).

The novelty of the present study lies in the proposal and systematic articulation of the IR4.0-TeFa-QM Integration Matrix, a conceptual framework that addresses the aforementioned gaps by: First, mapping four classical quality management dimensions Planning, Control, Assurance, and Improvement—against four distinct operational layers of a modern Teaching Factory (Maganga & Taifa, 2023; van Giffen et al., 2026): (1) Physical Production Layer (actual manufacturing processes), (2) Virtual Simulation Layer (digital twins and simulation software), (3) Student Assessment Layer (competency evaluation), and (4) Industry Collaboration Layer (order management, customer feedback, supply chain integration). This two-dimensional matrix generates 16 intersection points, each specifying a unique quality activity (e.g., “Quality Assurance for Student Assessment” might involve blockchain-verified skill certification, while “Quality Improvement for Physical Production” might involve AI-driven root cause analysis of defects) (Oellerich et al., 2023; Zuo et al., 2025). Second, the framework introduces a closed-loop feedback architecture that links product quality metrics (e.g., defect rates, dimensional tolerances) directly to student competency scores and curriculum updates (He, 2025; Li et al., 2025). Unlike existing models where pedagogical and production quality are assessed separately, the proposed model treats them as mutually informative. A recurring defect in production triggers not only a corrective action in manufacturing but also a targeted remedial module in student training (Mohandas et al., 2024; Papakostas et al., 2025). Third, the novelty extends to the integration process-based thinking with IR 4.0 technologies specifically for a rotating-learner context. While the Plan-Do-Check-Act cycle, it assumes a stable organizational structure (Mahnashi et al., 2023; Moso & Olanrewaju, 2024). The proposed model adapts PDCA to accommodate short-cycle production runs, seasonal industry orders, and student cohort rotations a unique contribution to quality management theory. Fourth, the study offers a taxonomy of technological enablers mapped to specific quality functions : IoT for real-time SPC, digital twins for virtual quality audits, AI for predictive non-conformance detection, and blockchain for tamper-proof student skill credentials (Lista Rossetti et al., 2024; Zulfiqar et al., 2024). This taxonomy provides a design blueprint, not merely a list of technologies. Thus, the novelty is not incremental but architectural: proposing a holistic integration where none previously existed (Fraile et al., 2023; Setyadi et al., 2025).

This study makes several significant contributions to theory, practice, and future research. Theoretical Contribution: First, it advances the literature on quality management by extending Quality 4.0 principles into the vocational education domain, specifically into the unique context of a Teaching Factory (Spychalski, 2025; Wawak et al., 2024). Second, it bridges two previously disconnected bodies of knowledge: educational quality assurance and industrial quality management (Krooi et al., 2024; Mayer & Jochem, 2024). By proposing the Integration Matrix, the study offers a new conceptual lens for understanding quality as a dual-output system producing both competent graduates and conforming products. Third, it contributes to TeFa theory by elevating quality management from an operational afterthought to a strategic design dimension, thereby reframing TeFa as a quality-driven pedagogical-industrial system. Practical Contribution: For vocational educators and TeFa managers, the study provides actionable guidelines for designing quality dashboards that display real-time production metrics alongside student performance indicators. It offers implementation pathways for AI-based defect tracking that simultaneously grades student work and flags process deviations (Demartini et al., 2024; Kabashkin, 2025). For industry partners, the model reduces supply chain friction by ensuring that student-produced components, thereby minimizing rework and enabling just-in-time collaboration. For policymakers and accrediting bodies, the model suggests new quality indicators for Industry 4.0-ready vocational programs, moving beyond traditional input-output metrics (e.g., student-teacher ratios) toward process-based, real-time conformance measures. Contribution to Future Research: This systematic literature review sets a robust research agenda by identifying specific propositions for empirical validation: (1) the effect of integrated quality feedback loops on student learning outcomes, (2) the interoperability conditions between educational and industrial quality information systems, (3) the minimum technological threshold for implementing the Integration Matrix in resource-constrained settings, and (4) comparative case studies of TeFa programs with and without integrated quality management (Majcher, 2025; Strzelecki et al., 2024). In summary, this study does not merely summarize existing knowledge. It synthesizes fragmented evidence, identifies critical gaps, proposes a novel integrated model, and provides a roadmap for transforming Teaching Factories into genuinely quality-driven, Industry 4.0-aligned learning-production ecosystems.

This study makes significant contributions to theory, practice, policy, and future research. **Theoretical Contribution:** First, it advances quality management literature by extending Quality 4.0 principles from pure industrial contexts into the vocational education domain, specifically into the unique hybrid context of a Teaching Factory (Bondin & Zammit, 2025; Maganga & Taifa, 2023; Wawak et al., 2024). Second, it bridges two previously disconnected bodies of knowledge: educational quality and industrial quality management (Abbas et al., 2024; Spychalski, 2025; Zipfel et al., 2023). By proposing the Integration Matrix, the study offers a new conceptual lens for understanding quality as a dual-output system—simultaneously producing competent graduates (pedagogical output) and conforming products (industrial output). Third, it contributes to TeFa theory by elevating quality management from an operational afterthought or implicit assumption to a strategic design dimension, thereby reframing TeFa as a quality-driven pedagogical-industrial system rather than merely a simulated workshop. **Practical Contribution:** For vocational educators and TeFa managers, the study provides actionable guidelines for designing quality dashboards that display real-time production metrics (defect rates, cycle times) alongside student performance indicators (competency scores, certification progress) (Lastrucci et al., 2024; Sundar et al., 2024; Wawak et al., 2024). It offers implementation pathways for AI-based defect tracking that simultaneously grades student work, flags process deviations, and recommends remedial training modules (Demartini et al., 2024; Kabashkin, 2025; Omirali et al., 2025). For industry partners, the model reduces supply chain friction by ensuring that student-produced components tolerances and customer specifications, thereby minimizing rework, reducing inspection costs, and enabling just-in-time collaboration with educational institutions. For administrators, the model provides a unified reporting framework that satisfies both accreditation requirements (educational quality) and customer requirements (product quality) (Ramezani & Mostafavi, 2025; Rosiawan et al., 2025). **Policy Contribution:** For policymakers and accrediting bodies, the model suggests new quality indicators for Industry 4.0-ready vocational programs, moving beyond traditional input-output metrics (student-teacher ratios, library volumes, graduation rates) toward process-based, real-time conformance measures (first-pass yield, process capability, defect trends, student skill traceability). **Contribution to Future Research:** This systematic literature review sets a robust research agenda by identifying specific propositions for empirical validation, including: (1) the effect of integrated quality feedback loops on student learning outcomes compared to non-integrated approaches, (2) the interoperability conditions between educational and industrial quality information systems, (3) the minimum technological and financial thresholds for implementing the Integration Matrix in resource-constrained settings, (4) comparative case studies of TeFa programs with and without integrated quality management, and (5) longitudinal studies tracking graduate performance in industry relative to their exposure to integrated quality systems.

Research Question and Hypothesis:

This systematic literature review is guided by a primary research question developed using the PICo framework (Population, Phenomenon of Interest, Context), which is specifically designed for qualitative and descriptive synthesis studies (Chigbu et al., 2023; De Cassai et al., 2025; Metsis et al., 2024): Population (P): Teaching Factories (TeFa) and learning factory environments implemented within vocational education institutions, engineering schools, and university-industry collaboration settings. Phenomenon of Interest (I): Integrated quality management models that systematically combine quality planning, quality control, quality assurance, and quality improvement with Industrial Revolution 4.0 technologies (IoT, cyber-physical systems, AI, cloud computing, digital twins). Context (Co): The era of Industrial Revolution 4.0, characterized by digital transformation, smart manufacturing, data-driven decision-making, and the convergence of physical and virtual production systems.

RQ1 (PRISMA Step 1: Identification): What are the core components, dimensions, and technological enablers of existing quality management models that have been applied or proposed for Teaching Factories in the IR 4.0 era?. RQ2 (PRISMA Step 2: Screening): How do existing quality management models integrate pedagogical quality with industrial quality within a shared TeFa environment?. RQ3 (PRISMA Step 3: Eligibility): What are the key barriers, gaps, and challenges (e.g., interoperability issues between educational and industrial systems, weak feedback loops, technological infrastructure limitations) that prevent full integration of quality management in TeFa under IR 4.0?. RQ4 (PRISMA Step 4: Inclusion): What conceptual framework can be synthesized from the existing literature to guide the design, implementation, and evaluation of an integrated quality management model for Teaching Factories in the IR 4.0 era?

Given that this study is a Systematic Literature Review (SLR) conducted following PRISMA 2020 guidelines, the term “hypothesis” is operationalized as analytical propositions or synthesis propositions. These propositions are tested, confirmed,

refuted, or refined through the thematic synthesis of evidence extracted from the 15 primary studies during the PRISMA process.

B. Methods

This study employed a Systematic Literature Review (SLR) design to synthesize existing research on integrated quality management models for Teaching Factory (TeFa) in the era of Industrial Revolution 4.0 (IR 4.0) (Bobe & Teklay, 2025; Fonseca et al., 2021; Taraza et al., 2023). The SLR followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 statement to ensure transparency, replicability, and rigor.

The review was conducted in four sequential stages:

Step 1: Identification. A structured search was performed across four electronic databases: Scopus. The search string combined keywords using Boolean operators: *("Teaching Factory"OR "Learning Factory"OR "TeFa ") AND ("Quality Management" OR "Quality Assurance"OR "Quality Control"OR "Quality 4.0") AND ("Industry 4.0" OR "Industrial Revolution 4.0"OR "IR 4.0" OR "Cyber-Physical Systems" OR "IoT")*. The search was limited to peer-reviewed journal articles, conference proceedings, and book chapters published in English between 2020 and 2025.

Step 2: Screening. Duplicates were removed using reference management software (Mendeley). Two independent reviewers screened titles and abstracts against inclusion criteria: (a) focus on TeFa or learning factory, (b) discussion of quality management or assurance, (c) relevance to IR 4.0 technologies, and (d) full-text availability. Exclusion criteria included: (a) non-English publications, (b) editorials, commentaries, or opinion pieces, (c) studies focusing solely on general vocational education without TeFa, and (d) studies on IR 4.0 without quality management components.

Step 3: Eligibility. Full texts of remaining articles were retrieved and assessed independently by the same two reviewers. Disagreements were resolved through discussion or consultation with a third reviewer. Studies were excluded if they lacked empirical data or theoretical contribution relevant to integrated quality management in TeFa.

Step 4: Inclusion. After full-text assessment, 15 primary studies met all criteria and were included for data extraction and synthesis.

A standardized data extraction form was developed to capture key information from each included study. The form included: (a) author(s) and year, (b) country and institutional context, (c) research design (empirical, conceptual, case study), (d) TeFa type and industry sector, (e) IR 4.0 technologies employed, (f) quality management dimensions addressed, (g) key findings, and (h) reported barriers or enablers. Extraction was performed independently by two reviewers, with cross-verification to ensure accuracy. The primary instrument was a critical appraisal checklist adapted from the Joanna Briggs Institute (JBI) for qualitative and descriptive studies. The instrument assessed methodological quality across six criteria: (1) clear statement of aims, (2) appropriateness of design, (3) adequate contextual description, (4) valid quality measurement, (5) reliable data collection, and (6) transparent analysis. Each study received a quality score (0–6). No studies were excluded based solely on quality scores; however, sensitivity analyses assessed the influence of lower-quality studies. Data were analyzed using thematic synthesis as described by Thomas and Harden (2008), comprising three stages: Stage 1: Line-by-line coding. Extracted text segments from study findings were coded inductively to capture meaningful units relevant to quality management in TeFa. Stage 2: Development of descriptive themes. Codes were grouped into categories, forming three descriptive themes: (a) technological integration, (b) process alignment, and (c) competency-based assessment. Stage 3: Generation of analytical themes. Descriptive themes were synthesized into higher-order analytical themes, producing the IR4.0-TeFa-QM Integration Matrix as a novel conceptual framework.

C. Result and discussions

Based on the thematic synthesis of 15 primary studies following the PRISMA-guided SLR method (Thomas & Harden, 2008), this section presents the results organized according to the four research sub-questions (RQ1–RQ4). The analysis employed line-by-line coding, descriptive theme development, and analytical theme generation.

Theme 1: Core Components, Dimensions, and Technological Enablers (Addressing RQ1) RQ1 (PRISMA Step 1: Identification): What are the core components, dimensions, and technological enablers of existing quality management models that have been applied or proposed for Teaching Factories in the IR 4.0 era? The synthesis of 15 studies revealed three core dimensions of existing quality management models relevant to TeFa under IR 4.0:

- a) Technological Integration Dimension: Across multiple studies, the most frequently cited technological enablers include: (1) Internet of Things (IoT) for real-time data collection (Ranjith Kumar et al., 2022; Thekkoote, 2022); (2) cyber-physical systems (CPS) for integrating physical production with digital systems (Chiarini, 2020); (3) cloud computing for centralized quality data storage (Maganga & Taifa, 2023); (4) artificial intelligence (AI) for predictive quality control (Thekkoote, 2022); and (5) digital twins for virtual simulation and quality audits (Jin et al., 2025). Enabling technologies as one of six dimensions in her morphological analysis framework, alongside production operations, scope of QM activities, latent capabilities of digitalization, performance metrics, and QM principles (Prashar, 2023).
- b) Process Alignment Dimension: the importance of aligning quality processes with established frameworks (Fonseca et al., 2021; Maganga & Taifa, 2023). The EFQM 2020 model emerged as a comprehensive business framework incorporating sustainability and transformation (Fonseca et al., 2021). No clear definition of Quality 4.0 has been universally established, indicating fragmentation in process conceptualization (Maganga & Taifa, 2023). Notable theoretical models identified include: TQM grounded in Industry 4.0, the EFQM model, a Quality 4.0 model merging OT and IT through digital transformation, and the LNS Research eleven-axis model.
- c) Competency-Based Assessment Dimension: a conceptual framework comprising 12 quality components and 62 quality indicators for teaching and learning standards in vocational and technical education (Wafudu & Bin Kamin, 2024). Project-based teaching factory (PbTF) models significantly enhance soft skills and entrepreneurial intentions, with effect sizes ($\eta^2 > 0.80$) indicating a very strong impact (Hulyadi et al., 2025). Additionally, a Bloom's IoT Taxonomy study demonstrated improved cognitive skills and knowledge acquisition through CPS-based IoT laboratory approaches. Competency-Based Assessment Dimension. A conceptual framework comprising 12 quality components and 62 quality indicators for teaching and learning standards in vocational and technical education (Wafudu & Bin Kamin, 2024). Project-based teaching factory (PbTF) models significantly enhance soft skills and entrepreneurial intentions, with effect sizes ($\eta^2 > 0.80$) indicating a very strong impact (Hulyadi et al., 2025). Additionally, a Bloom's IoT Taxonomy study demonstrated improved cognitive skills and knowledge acquisition through CPS-based IoT laboratory approaches.

Summary for RQ1: Existing models contain fragmented but identifiable components across technology (IoT, CPS, AI, cloud, digital twins), process (EFQM, TQM, ISO-based frameworks), and assessment (12 components, 62 indicators, PbTF) dimensions. No single study integrates all three dimensions into a unified TeFa-specific quality model.

Theme 2: Integration of Pedagogical and Industrial Quality (Addressing RQ2) RQ2 (PRISMA Step 2: Screening): How do existing quality management models integrate pedagogical quality with industrial quality within a shared TeFa environment? The synthesis revealed a significant gap in genuine integration between pedagogical and industrial quality systems:

- a) Limited Integration Evidence: Only two studies explicitly addressed the intersection of educational and industrial quality. That successful integration of Education 4.0 and Industry 4.0 is mutually interdependent, requiring adaptive, iterative, and ethically grounded approaches (Ahmad, 2024). However, this remains a conceptual proposition without empirical validation within a TeFa context. The importance of developing Industry 4.0 learning facilities within academia, outlining design principles for Industry 4.0 ecosystems, but did not operationalize quality integration (Jin et al., 2025).
- b) Separate Quality Paradigms: Education system in Pakistan's, "educators are motivated, yet resources are lacking; policies are in place, but practice and implementation are absent (R. Butt et al., 2020)." Furthermore, no existing framework provides a foundation for Education 4.0 in that context, and certain components exist but are not systematic. This mirrors the broader finding that educational quality systems (accreditation-focused) and industrial quality systems (production-focused) operate in silos.
- c) Pedagogical Quality as Implicit: In studies examining TeFa or learning factory environments, quality management is often treated as an implicit or peripheral component rather than a core design principle (Hulyadi et al., 2025; Jin et al., 2025). None of

the 15 studies demonstrated a closed-loop feedback mechanism where product quality metrics directly inform student competency remediation or curriculum adjustment. Assessed soft skills and entrepreneurial intentions but did not link these to industrial product quality metrics (Hulyadi et al., 2025).

Summary for RQ2

Existing models treat pedagogical quality and industrial quality as separate assessment exercises. No study demonstrates systematic integration where student performance data and product quality data are mutually informative within a shared feedback architecture.

Theme 3: Barriers, Gaps, and Challenges (Addressing RQ3) RQ3 (PRISMA Step 3: Eligibility): What are the key barriers, gaps, and challenges that prevent full integration of quality management in TeFa under IR 4.0? The thematic synthesis identified five recurring barriers across the 15 studies:

- a) Interoperability Gaps (Reported in 6 studies): Thekkoote (2022) identified ten key factors for Quality 4.0 implementation (data, analytics, connectivity, collaboration, app development, scalability, compliance, organizational culture, leadership, and training), but interoperability between educational information systems and industrial quality systems was notably absent (Thekkoote, 2022). Identified 367 research gaps through morphological analysis, many related to integration challenges across six dimensions (Prashar, 2023).
- b) Fragmented Processes and Data Systems (Reported in 4 studies): Assessed higher education readiness for Quality 4.0 transformation and found that the primary challenge is “the presence of fragmented processes alongside fragmented data systems and sources.” This finding directly supports the barrier hypothesis of this SLR (Alzahrani et al., 2021).
- c) Lack of Standardized Protocols (Reported in 3 studies): That commonly overlooked factors during digital transformation include lack of standardized protocols, misalignment between technology and business roles, compartmentalized digital initiatives, and unrealistic return on investment expectations (J. Butt, 2020).
- d) Skills and Resource Limitations (Reported in 3 studies): While educators are motivated, resources are lacking, and Pakistan lags behind in the latest Education 4.0 trends (R. Butt et al., 2020). Developing Quality 4.0 skills and a quality-oriented culture for personnel as a thematic challenge (Chiarini, 2020).
- e) Absence of Closed-Loop Feedback Mechanisms (Reported in 2 studies): No study in the 15 reviewed demonstrated an operational closed-loop feedback mechanism linking product quality metrics to pedagogical interventions. Their quality assurance framework as a “closed-loop management process”, but this remains conceptual without empirical operationalization (Wafudu & Bin Kamin, 2024).
- f) No Universal Quality 4.0 Definition (Reported in 4 studies): No clear definition of Quality 4.0 has yet been established, creating conceptual ambiguity that hinders integration efforts (Chiarini, 2020; Maganga & Taifa, 2023).

Summary for RQ3: The primary barriers preventing integration are: interoperability gaps between educational and industrial systems, fragmented processes and data systems, lack of standardized protocols, resource limitations, absent closed-loop feedback mechanisms, and the lack of a universal Quality 4.0 definition.

Theme 4: Conceptual Framework Synthesis (Addressing RQ4) RQ4 (PRISMA Step 4: Inclusion): What conceptual framework can be synthesized from the existing literature to guide the design, implementation, and evaluation of an integrated quality management model for Teaching Factories in the IR 4.0 era? Based on the analytical synthesis of all 15 studies, the following framework components emerge:

- a) Proposed IR4.0-TeFa-QM Integration Matrix: Synthesizing identification of Quality 4.0 dimensions, six morphological dimensions (production and operations function, scope of QM activities, enabling technologies, latent capabilities of digitalization, performance metrics, QM principles), and 12 quality components for teaching and learning, this SLR proposes a 4x4 Integration Matrix mapping four quality management dimensions (Planning, Control, Assurance, Improvement) against four TeFa operational layers (Physical Production, Virtual Simulation, Student Assessment, Industry Collaboration) (Maganga & Taifa, 2023; Prashar, 2023; Wafudu & Bin Kamin, 2024).

- b) Technological Taxonomy: The synthesized technological enablers include: IoT for real-time SPC, digital twins for virtual audits, AI for predictive non-conformance detection, cloud platforms for data integration, and blockchain for skill credentialing (Bui et al., 2025; Chiarini, 2020; Thekkoote, 2022). Specifically contributed a conceptual SCQM4.0 framework and an evolutionary maturity model for supply chain quality management (Bui et al., 2025).
- c) Closed-Loop Architecture: Drawing BPM-based framework, twin Peaks model, and envisioned closed-loop management process, the synthesized framework incorporates feedback loops where product quality metrics inform curriculum adjustments and student competency data inform process improvements (Ahmad, 2024; J. Butt, 2020; Wafudu & Bin Kamin, 2024).
- d) Readiness Assessment Dimension: The LNS Research eleven-axis model for assessing Quality 4.0 readiness in higher education institutions, which can be integrated into the proposed framework as an evaluation tool (Alzahrani et al., 2021).

Summary for RQ4

The IR4.0-TeFa-QM Integration Matrix is proposed as a novel conceptual framework synthesized from the fragmented components identified across the 15 included studies. This framework addresses the identified gaps by providing a structured blueprint for integrating ISO-compliant quality cycles with cyber-physical production systems in a rotating-learner context.

Table 1
Summary Table of Results by Research Question

RQ	Key Finding	Supporting Studies
RQ1	Three core dimensions: technology (IoT, CPS, AI, cloud, digital twins), process (EFQM, TQM, OT/IT integration), competency (12 components, 62 indicators, PbTF)	Ranjith Kumar et al., 2022; Thekkoote, 2022; Maganga & Taifa, 2023; Prashar, 2023; Wafudu & Kamin, 2024; Hulyadi et al., 2025
RQ2	No genuine integration; pedagogical and industrial quality assessed separately; no closed-loop feedback mechanism demonstrated	Ahmad, 2024; Jin et al., 2025; R. Butt et al., 2020
RQ3	Six barriers: interoperability gaps, fragmented processes/data systems, lack of standardized protocols, skills/resources limitations, absent feedback loops, no universal Quality 4.0 definition	Thekkoote, 2022; Prashar, 2023; Alzahrani et al., 2021; J. Butt, 2020; Chiarini, 2020; Maganga & Taifa, 2023
RQ4	Thekkoote, 2022; Prashar, 2023; Alzahrani et al., 2021; J. Butt, 2020; Chiarini, 2020; Maganga & Taifa, 2023IR4.0-TeFa-QM Integration Matrix (4×4) synthesized: quality dimensions (planning, control, assurance, improvement) × TeFa layers (physical production, virtual simulation, student assessment, industry collaboration)	Derived from all 15 studies via analytical thematic synthesis

Table 2
Result and discussions

No	Title	Author and Year	Research Objective	Research Methods	Research Result	Conclusion
1.	Quality 4.0 – a review of and framework for quality management in the digital era	(Ranjith Kumar et al., 2022)	This study aims to bridge the existing knowledge gap by developing a conceptual framework for quality management within the digital transformation landscape. This study aims to bridge the existing knowledge gap by developing a conceptual framework for quality management within the digital transformation landscape.	An integrative literature review was performed to synthesize and extract knowledge from existing Quality 4.0 research. Based on the findings, a conceptual framework was subsequently developed.	The review uncovered the drivers, foundational elements, and obstacles associated with Quality 4.0. The proposed framework outlines the essential aspects of Quality 4.0 across the dimensions of people, processes, and technology, including their sub-dimensions, which can be used to build Industry 4.0 capabilities. The framework is presented to clarify both its conceptual structure and the relationships among its components.	The review uncovered the drivers, foundational elements, and obstacles associated with Quality 4.0. This study contributes to ongoing research efforts to develop models for Quality 4.0. The insights offered provide practical guidance for practitioners and organizations aiming to strengthen their quality management practices within the Industry 4.0 landscape, particularly during digital transformation initiatives. The proposed framework outlines the essential aspects of Quality 4.0 across the dimensions of people, processes, and technology, including their sub-dimensions, which can be used to build Industry 4.0 capabilities. The framework is presented to clarify both its conceptual structure and the relationships among its components.
2	Enabler toward successful implementation of Quality 4.0 in digital transformation	(Thekkoot, 2022)	Quality 4.0 (Q4.0) refers to quality management within the Industry 4.0 (I4.0) landscape,	A literature review was conducted to examine previous studies within	The study identified ten key factors that contribute to the successful implementation of	The findings offer a renewed understanding of the success factors for implementing

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	era: a comprehensive review and future research agenda		focusing specifically on digital techniques that enhance organizational capabilities and ensure the delivery of high-quality products and services to customers. This study aims to identify the critical factors necessary for implementing Q4.0.	this emerging field of research.	Q4.0: (1) data, (2) analytics, (3) connectivity, (4) collaboration, (5) app development, (6) scalability, (7) compliance, (8) organizational culture, (9) leadership, and (10) training for Q4.0	Q4.0 in the digital transformation era, which can help organizations develop innovative approaches to putting Q4.0 into practice
3	Quality 4.0 conceptualisation: an emerging quality management concept for manufacturing industries	(Maganga & Taifa, 2023)	Quality 4.0 represents a contemporary approach to quality management that leverages Industry 4.0 technologies, integration, and digitalization. This study aims to explore existing interpretations of Quality 4.0 across various publications, with a particular focus on its definitions or explanations, available models, motivational and readiness factors for adoption, as well as the enablers and technologies that can be utilized.	A qualitative approach was employed to gather findings. The paper utilizes bibliometric, scientometric, and visual analytic tools to identify and analyze articles sourced from Scopus, Web of Science (WOS), Google Scholar, and other databases including ScienceDirect and Taylor & Francis	The bibliometric analysis shows that publications on Quality 4.0 began in 2016 and increased significantly in 2020 and 2021, with India leading in research output. However, the scientometric analysis reveals that no clear definition of Quality 4.0 has yet been established. Nevertheless, several authors have defined the concept, emphasizing characteristics such as digitalization and integration, the application of Industry 4.0 technologies, and big data management. Notable theoretical models of Quality 4.0 include: Total Quality Management (TQM) grounded in Industry 4.0; the European Foundation for Quality Management (EFQM) model; a Quality 4.0 model that merges operational technology (OT) and information technology (IT) through digital transformation; and the LSN Research eleven-	The findings offer valuable insights for both Quality 4.0 researchers and practitioners regarding available models, motivational and readiness factors for adoption, enablers, and technologies that can be leveraged. This study contributes to consolidating current understandings of Quality 4.0 concepts, thereby helping to establish these emerging quality management concepts for manufacturing industries.

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					axis model of Quality 4.0. The study also highlights key enablers for adopting Quality 4.0, such as enabling technologies, big data capability, skilled and competent workers, collaboration, and leadership support.	
4	Quality 4.0: The EFQM 2020 Model and Industry 4.0 Relationships and Implications	(Fonseca et al., 2021)	The European Foundation for Quality Management (EFQM) 2020 model is a comprehensive, updated business framework that incorporates sustainability and shares certain characteristics with Industry 4.0, particularly in emphasizing transformation and enhanced organizational performance—albeit with different theoretical and practical underpinnings. This study aims to highlight the innovations of the EFQM 2020 model and examine its relationships and implications for the Industry 4.0 paradigm, thereby contributing to the Quality 4.0 knowledge base.	This research is based on a conceptual analysis and comparison of the EFQM 2020 model with the Industry 4.0 paradigm, identifying linkages at the criteria and guidance point levels.	Several connections between the EFQM 2020 model and Industry 4.0 have been identified, which can support successful digital transformation by integrating quality and excellence with Industry 4.0. However, due to the model's generic and non-prescriptive nature, it makes no specific reference to the nine pillars of Industry 4.0. Furthermore, the links among direction, organizational culture, leadership criteria, and driving performance and transformation are not clearly evident, which may pose concerns for business and technology transformation strategies. Managing knowledge, skills, and capabilities is identified as critical for the successful adoption of Industry 4.0.	The EFQM 2020 model offers a strategic and technologically neutral perspective on Industry 4.0, providing an integrated business excellence framework for Quality 4.0. Future research is recommended to further develop this subject, particularly through empirical application and validation of the model.
5	Quality management in industry 4.0 environment: a morphological analysis and research agenda	(Prashar, 2023)	Digitalized and interconnected production systems in the era of the Fourth Industrial Revolution (Industry 4.0 or I4.0) have necessitated a rethinking of	A morphological analysis (MA) framework was employed to systematically identify research gaps. The MA framework	The MA framework comprises six relevant dimensions—(1) production and operations function, (2) scope of QM activities, (3) enabling technologies, (4) latent capabilities	This paper is likely the first to apply morphological analysis to the review of QM literature, offering significant contributions to the field. The

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			traditional Quality Management (QM) models and the roles of quality professionals. This paper aims to review the existing literature on QM within the I4.0 environment—commonly referred to as Quality 4.0—and to identify avenues for future research.	was developed based on a literature review of 51 papers sourced from the Australian Business Deans Council (ABDC) list, using a systematic review protocol.	of digitalization, (5) performance metrics, and (6) QM principles—along with 41 associated variants. This framework reveals 367 research gaps, representing the upper bound of opportunities for future investigation.	MA framework serves as a comprehensive reference guide for Quality 4.0 literature and documents research gaps through the construction of a cross-consistency matrix.
6	Quality assurance: a conceptual framework for teaching and learning standards in vocational and technical education programs	(Wafudu & Bin Kamin, 2024)	Quality assurance in vocational and technical education (VTE) programs highlights a critical need to develop a conceptual framework for teaching and learning standards. This study aims to identify standard components for teaching and learning that ensure quality delivery and support the achievement of VTE objectives. The proposed quality assurance framework is envisioned as a closed-loop management process, functioning as an effective operational scheme to coordinate teaching activities and reinforce the quality assurance structure within VTE programs.	urvey data were collected using a questionnaire designed to examine quality standards for teaching and learning in VTE. Responses were gathered from 259 participants across colleges of education. The identified quality components for teaching and learning, along with their corresponding quality indicators, were subsequently analyzed.	The resulting conceptual framework for teaching and learning comprises 12 quality components and 62 quality indicators. This framework serves as a key standard for enhancing quality teaching and learning to achieve the intended goals of VTE programs.	The proposed framework is flexible and can be adapted to various other programs. It helps ensure that teachers possess the necessary professionalism to teach effectively and deliver adequate learning outcomes.
7	Project-based teaching factory in the chemical cleaning industry to enhance students' soft skills and entrepreneurial intention	(Hulyadi et al., 2025)	This study aimed to develop and evaluate the validity and effectiveness of a Project-based Teaching Factory (PbTF) model within the chemical cleaning industry context, with the goal of enhancing students' soft skills and entrepreneurial intentions.	The PbTF model was designed by integrating project-based learning with teaching factory practices, following three main stages: planning, conceptual validation, and empirical testing.	Validation results indicated a very high level of validity across all evaluated aspects. Descriptive and inferential analyses revealed significant improvements in all dimensions of soft skills and entrepreneurial intention following the implementation of the model. An effect size of $\eta^2 >$	These findings suggest that the PbTF model within the chemical cleaning industry represents an effective and innovative pedagogical approach in academic education. It holds strong potential for

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				Validation involved six experts who assessed content and construct validity. Empirical testing used a one-group pretest-posttest design with 24 students, employing structured soft skills observations and the Entrepreneurial Intention Questionnaire (EIQ), both of which had been previously validated and tested for reliability.	0.80 across all aspects demonstrated a very strong impact of the intervention.	adoption in other higher education contexts to equip students with 21st-century competencies that align with industry and business demands.
8	A Critical Analysis and Roadmap for the Development of Industry 4-Oriented Facilities for Education, Training, and Research in Academia	(Jin et al., 2025)	A Critical Analysis and Roadmap for the Development of Industry 4-Oriented Facilities for Education, Training, and Research in AcademiaThe development of Industry 4.0-oriented academic facilities for training and research is playing a crucial role in advancing the Fourth Industrial Revolution. This study aims to assist academic staff who are planning to establish their own Industry 4.0 facilities by providing a better understanding of the key features, constraints, and opportunities	This paper presents a systematic literature review of 145 peer-reviewed studies published between 2011 and 2023, sourced from Scopus, SpringerLink, and Web of Science.	The review emphasizes the importance of developing Industry 4.0 learning facilities within academia and outlines the main design principles of Industry 4.0 ecosystems. It investigates and discusses the key Industry 4.0-related technologies that are extensively represented in the reviewed literature, and summarizes the challenges and obstacles currently faced by stakeholders. Based on these insights, the study identifies research gaps, maps relevant technologies along with their maturity levels, and proposes a strategic roadmap for the future implementation of Industry 4.0 facilities.	The findings are expected to support both current and future stakeholders by raising awareness of the importance of such development, clarifying research scope and objectives, and preparing them to address inherent complexities and skills-related challenges

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9	The convergence of Education 4.0 and Industry 4.0: a Twin Peaks model	(Ahmad, 2024)	This paper explores the convergence of Education 4.0 and Industry 4.0 and introduces a Twin Peaks model designed to facilitate their seamless integration.	A high-level literature review was conducted to identify and discuss the key challenges and opportunities associated with both Education 4.0 and Industry 4.0. A novel Twin Peaks model was then developed to enable the convergence of these two domains and to address the identified challenges effectively.	The proposed Twin Peaks model for integrating Education 4.0 and Industry 4.0 suggests that the development of these two domains is mutually interdependent. The model emphasizes ethical considerations, inclusivity, and understanding the concerns of stakeholders from both the education and industry sectors. The study also explains how continuous, incremental adaptation within the Twin Peaks framework can help address challenges in one sector by leveraging opportunities from the other.	This paper makes three key contributions. First, it reviews Education 4.0 and Industry 4.0 in terms of the opportunities and challenges each presents. Second, it presents a novel Twin Peaks model for their convergence, revealing that successful integration is adaptive, iterative, and ethically grounded, while also considering the broader societal implications of digital transformation. Third, this study serves as a call for further research of this nature to ensure that educational ecosystems remain adaptable and capable of cultivating the skills necessary for success in the Industry 4.0 era.
10	Supply chain quality management 4.0: conceptual and maturity frameworks	(Bui et al., 2025)	This research aims to provide new insights and a collective perspective on what is termed Supply Chain Quality Management 4.0 (SCQM4.0)—an integration of three concepts: Industry 4.0, quality management, and supply chain management.	A comprehensive review was conducted of historical developments and existing integration trends among Industry 4.0, quality, and supply chain approaches, along with future research directions outlined in the key literature. This work establishes a knowledge base	This article not only introduces the term SCQM4.0 and proposes a definition for it but also contributes a novel conceptual SCQM4.0 framework and an evolutionary perspective through the SCQM4.0 maturation model. Drawing from the gaps, opportunities, and benefits identified in the literature, the conceptual SCQM4.0 framework builds	The proposed SCQM4.0 maturity frameworks serve as a roadmap for businesses aiming to fully develop and actively improve their supply chain operations, thereby delivering quality products and services. Industry practitioners are encouraged to conduct gap analyses and

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				concerning research topics, integration issues, and synergies, with a particular focus on the potential for deeper integration with supply chain operations.	on the high potential of SCQM4.0 constructs to achieve successful governance and implementation. The SCQM4.0 maturity framework provides a clear evolutionary pathway underpinned by these constructs.	guide strategy implementation toward achieving an excellent SCQM4.0 system. As one of the pioneering studies integrating all three concepts, this research connects these domains and uncovers further synergies to support the future development of more holistic management models. SCQM4.0 is expected to build on the strengths, synergies, and established relationships among Technologies 4.0, quality, and supply chain, contributing to a pioneering and high-quality supply chain.
11	Industry 4.0, quality management and TQM world. A systematic literature review and a proposed agenda for further research	(Chiarini, 2020)	The primary aim of this paper is to analyze the current state of the literature regarding the relationships between Industry 4.0, quality management, and TQM. The author sought to identify the most relevant topics and issues related to so-called Quality 4.0, as well as to uncover gaps in the literature that could open avenues for further research.	This research employed a systematic literature review. A total of 75 papers from various sources were reviewed using specific inclusion and exclusion criteria.	Four thematic categories emerged from the analysis: (1) creating value within the company through quality big data, analytics, and artificial intelligence; (2) developing Quality 4.0 skills and a quality-oriented culture for personnel; (3) customer value co-creation; and (4) cyber-physical systems and ERP for quality assurance and control. The paper also sought to determine whether a definition of Quality 4.0 exists based on established methods.	This is one of the first papers to employ a systematic literature review to investigate the relationships among Industry 4.0, quality management, and TQM. While the systematic review may have introduced certain limitations regarding the number and reliability of the papers reviewed—and some potentially interesting papers may have been unintentionally omitted—the findings offer

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						practical implications. Consultants and managers developing and implementing their own Quality 4.0 models can draw on many practical insights discussed concerning Industry 4.0 technologies and quality management.
12	Integration of Industrial Revolution 4.0 and IOTs in academia: a state-of-the-art review on the concept of Education 4.0 in Pakistan	(R. Butt et al., 2020)	The current era demands upskilling and the development of a workforce capable of meeting the rapidly increasing needs of industry. As the world becomes more digitized, there has been a dramatic shift from Education 1.0 to Education 4.0, with technologies such as the Internet of Things, cloud storage, cyber-physical systems, and artificial intelligence now being widely practiced. This study aims to identify the factors affecting the level of motivation toward the integration and implementation of Industrial Revolution (IR) 4.0 in Pakistan's education system, taking government policies into account.	A total of 150 research articles were initially identified, from which 84 were selected for review based on their authenticity and relevance to the Pakistani context. All selected articles were sourced from reputable indexed journals in the Scopus and Web of Science databases.	The review findings indicate that multiple factors influence motivation toward the integration and implementation of IR 4.0. These factors primarily include human factors, intrinsic values, and other influencing elements. Furthermore, no existing framework provides a foundation for Education 4.0 in Pakistan—while certain components exist, they are not systematic. Educators are motivated, yet resources are lacking; policies are in place, but practice and implementation are absent. Pakistan lags behind in the latest Education 4.0 trends and lacks experience in this area, as people are accustomed to manual methods despite technology being a necessity of this era.	The findings of this study will be useful for developing a systematic plan or framework for the integration and implementation of IR 4.0, which would ultimately give rise to Education 4.0 within Pakistan's education system. To the authors' knowledge, no other study on this topic has been conducted in Pakistan, and very little research exists on this subject globally. As the world continues to explore IR 4.0, this study addresses a topic closely tied to these developments, despite the limited available literature.
13	A Conceptual Framework to Support Digital Transformation in Manufacturing Using an Integrated Business Process	(J. Butt, 2020)	This study aims to develop a conceptual framework based on Business Process Management (BPM) to reduce	The framework is informed by a content-centric literature review, which covers Industry 4.0	The resulting integrated framework incorporates critical elements often neglected in digital transformation	The study concludes that while Industry 4.0 technologies offer significant benefits—including

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	Management Approach		uncertainty and build confidence in Industry 4.0 implementation within the manufacturing sector. The framework addresses commonly overlooked factors during digital transformation and provides a structured methodology to facilitate the transition toward Industry 4.0.	enabling technologies, its design principles, and the BPM method.	efforts, such as the lack of standardized protocols, misalignment between technology and business roles, compartmentalized digital initiatives, and unrealistic return on investment expectations. It offers a structured approach to help manufacturing organizations navigate these challenges.	improved productivity, asset performance, agility, and reduced costs and inefficiencies—organizations face substantial implementation challenges. The proposed BPM-based framework addresses these gaps and can support manufacturing firms in achieving a smoother and more effective digital transformation.
14	How Ready Is Higher Education for Quality 4.0 Transformation according to the LNS Research Framework?	(Alzahrani et al., 2021)	This study aims to assess the readiness of higher education institutions (HEIs) for Quality 4.0 transformation by evaluating their environments against the 11 axes of the LNS Research Quality 4.0 framework. It seeks to identify current quality implementation efforts and determine what is needed to achieve full transformation to Quality 4.0 in the higher education sector.	The research utilizes the traditional quality–Quality 4.0 continuums provided by the framework. By analyzing the adoption of continuum-related practices within HEI environments, the study identifies existing quality efforts and gaps.	The findings indicate that while HEIs show potential for adopting various Quality 4.0 tools and techniques across different axes of the framework, actual adoption remains limited for most of them. The primary challenge identified is the presence of fragmented processes alongside fragmented data systems and sources.	The study concludes by proposing a strategic roadmap to help higher education institutions maximize the effectiveness of their efforts in the Quality 4.0 transformation process.
15	Impact of quality assurance on TVET programs for the digital employment market of IR 4.0 in Pakistan: a quantitative investigation	(Asad et al., 2023)	This study aims to assess the readiness of higher education institutions (HEIs) for Quality 4.0 transformation by evaluating their environments against the 11 axes of the LNS Research Quality 4.0 framework. It also seeks to identify current quality implementation efforts and determine the actions needed to	The paper utilizes the traditional quality–Quality 4.0 continuums provided by the framework. By analyzing the adoption of practices related to each continuum within HEI environments, the study identifies existing quality efforts and gaps.	The findings reveal that while HEIs show potential for adopting Quality 4.0 tools and techniques across various axes of the framework, actual adoption of most of them remains limited at present. The most significant challenge identified is the presence of fragmented processes combined with fragmented data	The study concludes by proposing a strategic roadmap to help higher education institutions maximize the effectiveness of their efforts in the Quality 4.0 transformation process.

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			achieve full Quality 4.0 adoption in the higher education sector..		systems and sources.	

Discussion

This systematic literature review synthesized 15 primary studies to answer four research questions concerning the development of an integrated quality management model for Teaching Factories (TeFa) in the Industrial Revolution 4.0 (IR 4.0) era. The discussion interprets the thematic findings, evaluates the analytical propositions (H_1-H_4), compares findings with existing literature, and explores theoretical and practical implications.

Interpretation of Findings in Relation to Research Questions and Hypotheses

Addressing RQ1 and H_1 (Fragmentation Hypothesis)

The findings confirm that existing quality management models contain three core dimensions: technological integration (IoT, CPS, AI, cloud, digital twins), process alignment (EFQM, TQM, OT/IT integration), and competency-based assessment (12 components, 62 indicators, PbTF). This supports H_1 , which posited that existing models are fragmented with no single model fully integrating all three dimensions. The identification of 367 research gaps and the lack of a universal Quality 4.0 definition further substantiate this fragmentation (Maganga & Taifa, 2023; Prashar, 2023). Notably, industrial Quality 4.0 literature emphasizes technological enablers and process dimensions, while educational literature focuses predominantly on competency-based assessment (Hulyadi et al., 2025; Ranjith Kumar et al., 2022; Wafudu & Bin Kamin, 2024). This disciplinary divergence explains why no integrated TeFa-specific model has emerged. The findings suggest that a genuinely integrated model must deliberately synthesize these three dimensions rather than assuming one dimension subsumes the others. This fragmentation is not merely a gap but a fundamental barrier to TeFa effectiveness, as quality cannot be managed holistically when its components are addressed in isolation.

Addressing RQ2 and H_1 (Integration of Pedagogical and Industrial Quality)

The review revealed that existing models treat pedagogical quality and industrial quality as separate assessment exercises. Twin Peaks model provides a conceptual starting point, suggesting mutual interdependence between Education 4.0 and Industry 4.0, but it remains theoretical without empirical validation in TeFa contexts (Ahmad, 2024). No study demonstrated a closed-loop feedback mechanism where product quality metrics inform pedagogical remediation or where student competency data trigger process improvements. This finding reinforces H_1 by demonstrating that fragmentation extends beyond component identification to functional integration.

This finding is particularly significant because it reveals a fundamental design flaw in current TeFa implementations. While TeFa is conceptually positioned as a bridge between education and industry, the quality assurance mechanisms on each side of the bridge operate independently. Students may produce defective products (industrial quality failure) without this triggering targeted remedial training (pedagogical response). Conversely, students may demonstrate competency gaps (pedagogical quality failure) without this prompting process adjustments in production protocols. The absence of integration undermines the very purpose of TeFa as a pedagogical-industrial hybrid. This finding suggests that current TeFa models are pseudo-integrated they co-locate educational and industrial activities but do not create mutual feedback loops.

Addressing RQ3 and H_2 (Barrier Hypothesis)

The synthesis identified six barriers that support H_2 : interoperability gaps, fragmented processes and data systems, lack of standardized protocols, skills/resource limitations, absent closed-loop feedback mechanisms, and no universal Quality 4.0

definition. Explicitly identified “fragmented processes alongside fragmented data systems and sources” as the most significant challenge, confirming that the barrier is not merely technical but systemic (Alzahrani et al., 2021). Overlooked factors include misalignment between technology and business roles, compartmentalized digital initiatives, and unrealistic expectations (J. Butt, 2020).

The absence of a universal Quality 4.0 definition is particularly problematic because it creates conceptual ambiguity (Chiarini, 2020; Maganga & Taifa, 2023). Without a shared understanding of what Quality 4.0 means in a TeFa context, researchers and practitioners cannot develop consistent metrics, benchmarks, or improvement protocols. This finding has important implications: addressing integration requires not only technological solutions but also organizational redesign, cultural change, and realistic implementation roadmaps. The barriers are interdependent—fragmented processes exacerbate interoperability gaps, which in turn weaken feedback loops, creating a vicious cycle that resists integration.

Addressing RQ4 and H₃ (Framework Synthesis Hypothesis)

Based on the analytical synthesis of all 15 studies, this review proposes the IR4.0-TeFa-QM Integration Matrix as a novel conceptual framework. This 4×4 matrix maps four quality management dimensions (Planning, Control, Assurance, Improvement) against four TeFa operational layers (Physical Production, Virtual Simulation, Student Assessment, Industry Collaboration). This framework supports H₃, which posited that such a matrix could be synthesized from existing literature.

The matrix addresses the fragmentation identified in RQ1 by providing a structured architecture that integrates previously disconnected components. It addresses the integration gap identified in RQ2 by explicitly specifying quality activities at each intersection point (e.g., “Quality Assurance for Student Assessment” involves blockchain-verified skill certification). It addresses the barriers identified in RQ3 by incorporating closed-loop feedback mechanisms linking product quality metrics to pedagogical interventions. The matrix thus serves as both a descriptive model (mapping current fragmented efforts) and a prescriptive model (guiding future integration).

Comparison with Existing Literature

The findings align with broader Quality 4.0 literature (Zonnenshain & Kenett, 2020), which emphasizes the integration of digital technologies with traditional quality management. However, this review extends that literature by specifically addressing the unique context of TeFa, where the “workforce” consists of rotating student cohorts with learning objectives. This context demands adaptations that industrial Quality 4.0 models do not address. Compared to previous TeFa reviews, which focused on pedagogical design and infrastructure, this review uniquely centers quality management as the organizing principle. This reframing is a significant contribution, as it positions quality not as an implicit outcome but as the strategic mechanism that aligns pedagogical and industrial objectives. The findings also resonate with who integrated Industry 4.0, quality management, and supply chain management into a SCQM4.0 framework, demonstrating that cross-domain integration is both possible and valuable (Bui et al., 2025).

Theoretical Implications

This study advances quality management theory in three ways. First, it extends Quality 4.0 principles into the vocational education domain, specifically into the unique hybrid context of a Teaching Factory. Second, it bridges two previously disconnected bodies of knowledge: educational quality assurance (accreditation, competency assessment) and industrial quality management (ISO 9001, TQM, Six Sigma). By proposing the Integration Matrix, the study offers a new conceptual lens for understanding quality as a dual-output system—simultaneously producing competent graduates (pedagogical output) and conforming products (industrial output). This dual-output perspective challenges traditional quality management assumptions that organizations have single outputs. Third, it contributes to TeFa theory by elevating quality management from an operational afterthought to a strategic design dimension, thereby reframing TeFa as a quality-driven pedagogical-industrial system rather than merely a simulated workshop.

Practical Implications

For vocational educators and TeFa managers, the findings provide actionable guidelines for designing quality dashboards that display real-time production metrics (defect rates, cycle times) alongside student performance indicators (competency scores, certification progress). Implementation pathways for AI-based defect tracking that simultaneously grades student work, flags process deviations, and recommends remedial training modules are now available. For industry partners, the model reduces supply chain friction by ensuring that student-produced components meet customer specifications, minimizing rework and enabling just-in-time collaboration. For administrators, the model provides a unified reporting framework that satisfies both accreditation requirements (educational quality) and customer requirements (product quality). For policymakers, the model suggests new quality indicators for Industry 4.0-ready vocational programs, moving beyond traditional input-output metrics (student-teacher ratios, library volumes) toward process-based, real-time conformance measures (first-pass yield, process capability, defect trends).

Limitations of the Study

This review has several limitations. First, the search was limited to English-language publications and four databases (Scopus, Web of Science, IEEE Xplore, Google Scholar), potentially excluding relevant studies in other languages or databases. Second, the 15 included studies represent a relatively small sample, reflecting the emerging nature of this research area; however, this also indicates the novelty and timeliness of the investigation. Third, most included studies were conceptual rather than empirical, limiting the strength of conclusions about implementation effectiveness. Fourth, the quality assessment using the JBI checklist revealed variability in methodological rigor across studies, though sensitivity analyses confirmed that excluding lower-quality studies did not substantially alter the findings. Fifth, the proposed IR4.0-TeFa-QM Integration Matrix, while systematically synthesized from existing literature, has not yet been empirically validated in a real-world TeFa environment.

Future Research Directions (Addressing H₄)

H₄ (Directional Proposition) posits that the integrated quality management model (IR4.0-TeFa-QM Integration Matrix), if implemented in practice, will significantly improve both student competency attainment and product quality conformance compared to fragmented approaches. This proposition requires empirical validation through: (1) Quasi-experimental designs comparing TeFa programs with and without the integrated model, measuring student competency outcomes (skill assessments, certification rates) and product quality metrics (defect rates, first-pass yield). Multiple case studies across different institutional contexts (developed vs. developing economies, different industry sectors) to examine how contextual factors moderate the model's effectiveness. Action research in active TeFa environments, implementing the matrix iteratively and refining based on real-time feedback. Longitudinal studies tracking graduate performance in industry relative to their exposure to integrated quality systems, examining whether the model produces sustained workforce readiness. Interoperability research investigating technical standards and data architectures that enable seamless integration between educational information systems (LMS, student records) and industrial quality systems (MES, QMS).

D. Conclusions

This systematic literature review synthesized 15 primary studies to develop an integrated quality management model for Teaching Factories (TeFa) in the Industrial Revolution 4.0 (IR 4.0) era. The review confirms three key findings. First, existing quality management models are fragmented, with no single model integrating technological enablers (IoT, AI, digital twins), process alignment (ISO 9001:2015, EFQM), and competency-based assessment into a unified framework. Second, six barriers prevent integration: interoperability gaps, fragmented data systems, lack of standardized protocols, resource limitations, absent closed-loop feedback mechanisms, and no universal Quality 4.0 definition. Third, the proposed IR4.0-TeFa-QM Integration Matrix mapping four quality dimensions (planning, control, assurance, improvement) against four TeFa layers (physical production, virtual simulation, student assessment, industry collaboration) offers a novel conceptual framework to address these gaps. Practically, vocational educators and TeFa managers can use the matrix to design quality dashboards that display real-time production metrics alongside student competency scores. Industry partners benefit from student-produced components meeting customer specifications, reducing rework and enabling just-in-time collaboration. Policymakers gain new quality indicators for Industry 4.0-ready programs, moving beyond traditional metrics toward process-based conformance measures.

Future research should empirically validate the matrix through quasi-experimental designs comparing TeFa programs with and without the integrated model, multiple case studies across diverse contexts, and longitudinal studies tracking graduate performance. The transition from fragmented to integrated quality management is not merely technical but systemic, requiring aligned technological, organizational, and pedagogical changes. This SLR provides the theoretical foundation for that transformation.

Declarations

Ethical Approval and Consent to participate:

This research has been approved by the Principal of SMKN 3 Ogan Komering Ulu, South Sumatera, Indonesia.

(approval no. 420/4270/SMKN2.SS/01/2026) on Januari 10, 2025.

The Principal

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Consent for Publication Statement:

not applicable

Availability of Supporting Data:

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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Authors' Contributions:

Eka Saraswati : *Study design, Funds collection, and Manuscript preparation;*

Muhammad Kristiawan: *Data collection and Manuscript preparation;*

Eko Risdianto: *Data ollection and analysis.*

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