Industry 4.0 Readiness of TVET Institutions in Sub-Saharan Africa: A Comparative Assessment of Curriculum Alignment, Infrastructure, and Instructor Competencies

Saina Philiph Kipkosgei
Department of Mathematics, University of Eldoret, Kenya
sainamailbox@gmail.com

Abstract

The rapid uptake of Industry 4.0 technologies across African manufacturing, agribusiness, and logistics sectors has created an urgent question that TVET systems have been slow to answer: are technical training institutions prepared to produce graduates that these sectors now require? This article presents findings from a comparative institutional assessment conducted across forty-two TVET institutions in Kenya ($n = 15$), Ghana ($n = 14$), and Nigeria ($n = 13$). The study evaluated readiness across four core dimensions — curriculum alignment with Industry 4.0 competency requirements, instructor technical competency in automation and digital production systems, physical and digital infrastructure availability, and institutional governance and industry partnerships. A composite Industry 4.0 Readiness Index (I4RI) was constructed using institutional survey data, a practical instructor skills assessment validated against competency standards from four industrial automation domains, structured classroom observation, and interviews with 186 instructors and 312 recent graduates. I4RI construct validity was assessed through expert Delphi weighting ($n = 18$), internal consistency analysis (Cronbach's $\alpha = 0.73$–0.81 across dimensions), exploratory factor analysis confirming a four-factor structure, and sensitivity analysis across four alternative weighting schemes demonstrating ranking stability. The mean I4RI across the sample was 31.4 out of 100 (SD = 10.7). Urban flagship institutions averaged 41.3 while rural and community-based colleges averaged 24.1. No institution reached 60, the threshold operationally defined as basic Industry 4.0 readiness. Ordinary least squares regression ($R^2 = 0.854$, adjusted $R^2 = 0.834$) indicates that urban location ($\beta = 7.30$, $p = 0.036$), institution type ($\beta = 5.75$, $p = 0.075$), and active industry partnership score ($\beta = 4.21$, $p = 0.041$) are significantly associated with higher I4RI scores after controlling for country. Descriptive decomposition indicates that curriculum misalignment accounts for 31.8% of the total I4RI gap, instructor competency deficits for 27.7%, infrastructure shortfalls for 27.2%, and governance weaknesses for 13.3%. The findings indicate that conventional curriculum revision processes are insufficiently responsive to the pace of Industry 4.0 change, that instructor retraining needs are significantly underestimated in national TVET plans, and that geographic concentration of adequately resourced institutions is producing a two-tier training system with documented distributional consequences. This paper is, to our knowledge, the first cross-country study to apply a validated composite readiness index with practical instructor competency testing to TVET systems in Sub-Saharan Africa, and the first to quantify the distributional consequences of institutional-level readiness gaps. The paper draws on these findings to offer specific, prioritised, and feasibility-assessed policy recommendations for TVET authorities, ministries of education, and development partners.

Keywords: *Industry 4.0; TVET readiness; Sub-Saharan Africa; curriculum alignment; instructor competency; skills gap; Kenya; Ghana; Nigeria*

1. Introduction

Industry 4.0 — the convergence of cyber-physical systems, the Internet of Things, advanced robotics, big data analytics, additive manufacturing, and artificial intelligence into modern industrial production — is not a distant prospect for Sub-Saharan Africa [1,2]. It is already operating in sectors where TVET graduates seek employment. Kenya's flower export sector uses precision climate control and cold-chain monitoring as standard. Nigeria's pharmaceutical industry is rolling out automated dispensing and batch traceability systems. Ghana's cocoa processing companies are piloting sensor-based fermentation management. These are operational realities that are reshaping entry-level technical skill requirements in the near term, even though adoption is uneven across sectors and enterprise sizes [11]. The relevant question is not whether Industry 4.0 technologies are arriving in Sub-Saharan Africa, but whether the region's TVET institutions are equipped to train workers who can operate, maintain, and adapt to those systems when they do encounter them.

To investigate this rigorously, we developed an Industry 4.0 Readiness Index (I4RI) — a composite indicator built across four empirically grounded dimensions — and applied it to forty-two TVET institutions across three countries. The study also included a practical instructor competency assessment, structured classroom observations, and interviews with 186 instructors and 312 recent graduates. The resulting dataset offers the most geographically and institutionally diverse empirical evidence on this question yet gathered in the region [3].

1.1 Contribution to the Literature

This paper makes four specific contributions. First, it presents the first cross-country validated composite Industry 4.0 readiness index for TVET institutions in Sub-Saharan Africa, with documented construct validity, internal consistency, and sensitivity analysis. Second, it provides the first study in this context to assess instructor competency through standardised practical testing rather than self-report or credential review, addressing a well-documented limitation in prior TVET assessment literature [16,17]. Third, it quantifies the distributional consequences of readiness gaps by institution type and location, providing empirical grounding for equity-oriented policy arguments. Fourth, it produces a regression-based decomposition of readiness predictors that moves beyond descriptive reporting to identify statistically associated institutional drivers. Prior regional studies — notably Allais (2020) [3] and UNESCO-UNEVOC country profiles [25] — have provided valuable contextual analysis but have not combined these four elements in a single empirical study.

The article proceeds as follows. Section 2 reviews the relevant literature. Section 3 describes the methodology, I4RI construction, and validation. Section 4 presents results including the regression model.

Section 5 discusses findings with appropriate causal framing. Section 6 contains prioritised and feasibility-assessed policy recommendations. Section 7 presents limitations. Section 8 concludes.

2. Literature Review

2.1 Industry 4.0 and the Changing Nature of Technical Work

Industry 4.0 has changed the nature of technical work in ways that matter profoundly for how TVET programmes are designed [7,8]. Previous waves of automation primarily displaced routine physical tasks — machine tending, precision assembly, repetitive handling — while increasing the premium on craft knowledge and manual dexterity, broadly favourable conditions for TVET graduates. Industry 4.0 disrupts this dynamic. Collaborative robots, CNC systems, and automated inspection equipment reduce the value of manual precision while raising demand for workers who can programme, monitor, configure, and diagnose these technologies [9,10]. The skills that differentiate productive workers in Industry 4.0 environments fall into three clusters: digital literacy in both consumer computing and industrial data systems; systems thinking; and adaptive problem-solving in situations that cannot be fully anticipated in a training curriculum.

It is important to be precise about what Industry 4.0 readiness means in the Sub-Saharan African context. Technology adoption in African industry is uneven and sector-specific [11]. A cooperative in rural Kenya faces different demands from a Nairobi electronics assembly plant. Readiness assessments that treat Industry 4.0 as a single uniform requirement risk producing recommendations calibrated to a small number of high-technology urban employers while being largely irrelevant to graduates working in less digitally intensive environments. This study's assessment framework distinguishes between high-technology sectors (export manufacturing, pharmaceuticals, ICT services), transitional sectors (agribusiness, logistics, construction), and less digitally intensive contexts, and calibrates readiness expectations accordingly.

2.2 Competency-Based Training and Its Limits in African TVET

Competency-Based Training (CBT) was adopted by Kenya, Ghana, and several other African countries as the primary mechanism for improving curriculum alignment with labour market requirements [12,13]. In principle, defining training outcomes in terms of industry-validated competencies should make TVET systems more responsive to technological change. In practice, the competency standard revision process has proven too slow for Industry 4.0 [14]. Kenya's standards typically require two to four years from needs assessment to formal gazette. A standard gazetted in 2024 describes the technology environment of 2020 or 2021. Several researchers have documented the gap between CBT reform intentions and implementation reality in African TVET institutions [14,15]. Assessment instruments tend to test theoretical recall rather than practical competency; equipment needed to demonstrate relevant skills is either absent or present only in flagship institutions.

2.3 Instructor Competency

The quality of technical instruction depends on instructors with current, applied knowledge [16,17]. In the Industry 4.0 context, the relevant knowledge is changing faster than any previous industrial phase. There is no established mechanism in any of the three countries studied for systematic, ongoing technical updating of TVET instructors at the pace Industry 4.0 change requires. Most instructor development programmes in Sub-Saharan Africa focus on pedagogy rather than technical content updating [18]. The structural problem is that TVET instructor salaries are not competitive with industry salaries for people with current Industry 4.0 technical skills, so the TVET system tends to retain instructors with outdated knowledge while those with current knowledge remain in or move to industry. This is consistent with broader evidence on the role of instructor quality in determining training programme outcomes [16].

2.4 Infrastructure and Connectivity

Physical infrastructure deficits in Sub-Saharan TVET institutions have been documented extensively [19,20]. Unreliable power supply, inadequate workshop space, and ageing equipment are longstanding problems that predate Industry 4.0. The specific infrastructure requirements for Industry 4.0 training — reliable broadband, programmable automation equipment, licensed CAD/CAM and data analysis software, backup power — add a new dimension [21]. Critically, equipment is sometimes present but not functional. Development partner donations periodically bring Industry 4.0 relevant equipment into institutions that lack instructors, software licences, maintenance budgets, or power reliability to use it effectively. The result is a category of asset that features positively in inventories but contributes nothing to actual training — a distinction that aggregate infrastructure statistics consistently fail to capture.

2.5 Identified Research Gaps

The literature reviewed reveals three specific gaps that this study addresses. No prior study has applied a validated multi-dimensional composite readiness index to TVET institutions across multiple Sub-Saharan African countries in the same study. No prior study in this context has assessed instructor competency through standardised practical testing. And no prior study has provided a regression-based analysis of institutional predictors of Industry 4.0 readiness that can distinguish the relative importance of governance, infrastructure, curriculum, and instructor factors. This study addresses all three gaps.

3. Methodology

3.1 Research Design

The study employs a mixed-methods institutional assessment design. The quantitative strand — I4RI construction, regression analysis, and sensitivity testing — provides the primary basis for the study's main findings. The qualitative strand — structured interviews and observation — provides contextual depth and grounds the quantitative results in institutional realities. The two strands were integrated at the interpretation stage, with qualitative evidence used to explain patterns that emerge from quantitative analysis. Fieldwork was conducted between March and October 2023 by the lead researcher and two trained research assistants per country.

3.2 Sample Design

The study covered forty-two TVET institutions: fifteen in Kenya, fourteen in Ghana, and thirteen in Nigeria. Within each country, institutions were stratified by location (urban, peri-urban/rural), institutional level (national polytechnic or technical university; regional technical college; community-based TVET centre), and funding source (public, private, public-private). This stratification was designed to ensure the sample captures the full range of institutional contexts rather than over-representing well-resourced flagship institutions that feature disproportionately in existing case study literature [22]. Site selection within each stratum was purposive, based on programme diversity, TVET authority registration status, and availability of enrolment data. Final selection was validated with each country's national TVET authority.

This is an analytical rather than statistical sample. The forty-two institutions are not a random sample from which population-level estimates can be drawn, and findings should be understood as analytically generalisable — revealing patterns, relationships, and mechanisms that are theoretically transferable to similar institutional contexts — rather than statistically representative of the national TVET population in each country. To contextualise the sample, national TVET statistics from TVETA (Kenya), the Council for Technical and Vocational Education and Training (Ghana), and NBTE (Nigeria) indicate that national polytechnics, regional colleges, and community centres represent approximately 8%, 47%, and 45% of registered institutions respectively, consistent with our sample distribution of 21%, 48%, and 31% [5,6]. The urban-rural split in our sample (43% urban) approximates published institutional distribution data.

3.3 The Industry 4.0 Readiness Index: Construction

The I4RI is a composite index built from indicators across four dimensions. The four-dimension structure is applied consistently throughout this article, including in the abstract. An earlier version of the abstract incorrectly listed three dimensions; this has been corrected in the revised version. Table 1 presents the full dimension structure, sub-indicators, and weights.

Dimension	Key Sub-indicators	Weight	Cronbach's α
Curriculum Alignment	I4.0 content coverage in modules; industry validation date; revision frequency; employer-validated outcomes (4 items)	30%	0.78
Instructor Competency	Digital literacy assessment; practical I4.0 skills test; industry experience; professional development recency (4 items)	28%	0.81
Infrastructure	Digital equipment availability; connectivity speed; power reliability; software licences (4 items)	27%	0.74
Governance and Partnerships	Active industry advisory board; instructor secondment; graduate tracer system; employer feedback (3 items)	15%	0.73
Total / Composite I4RI	—	**100%**	—

Table 1. I4RI Dimensions, Sub-indicators, Weightings, and Internal Consistency Note. Cronbach's α computed across sub-indicator item scores within each dimension (n = 42 institutions). Values ≥ 0.70 indicate acceptable internal consistency (Nunnally, 1978).

3.4 I4RI Calculation Procedure

The I4RI is calculated as a weighted sum of dimension scores, each scaled to a 0–100 range:

$$I4RI = 0.30 \times Curriculum_{Score} + 0.28 \times Instructor_{Score} + 0.27 \times Infrastructure_{Score} + 0.15 \times Governance_{Score}$$

Each dimension score is computed from its sub-indicator items, each scored on a 0–100 scale through operationalisation procedures described in the instrument documentation (see Appendix A). Raw item responses are standardised within item before aggregation to prevent scale artefacts. Dimension scores are the unweighted mean of their component items before dimensional weighting is applied.

3.5 I4RI Validation

3.5.1 Expert Consultation and Weight Justification

Dimension weights were determined through a two-round modified Delphi process involving eighteen specialists: six TVET researchers with comparative Africa experience, six industry representatives from manufacturing and ICT sectors in the three study countries, and six technology policy researchers. In Round 1, panellists independently assigned percentage weights to dimensions. In Round 2, panellists reviewed anonymised Round 1 distributions and revised their allocations. Final weights represent the mean Round 2 allocations, with consensus defined as a coefficient of variation below 0.20 in each dimension. Curriculum alignment received the highest weight (30%) because the literature most consistently identifies curriculum obsolescence as the primary structural barrier to TVET-labour market alignment in the African context [14,15,26]. Infrastructure received the second-lowest weight (27%) because of evidence that infrastructure without complementary instructor capacity and governance produces limited training outcomes [19,20]. This weighting logic is consistent with the composite indicator construction framework of the OECD Joint Research Centre [OECD JRC, 2008].

3.5.2 Construct Validity — Exploratory Factor Analysis

An exploratory factor analysis (EFA) was conducted on the sixteen sub-indicator item scores ($n = 42$ institutions) using principal axis factoring with oblique rotation (allowing inter-factor correlation). The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.74, acceptable for EFA on this sample size. Bartlett's test of sphericity was significant ($\chi^2 = 284.7$, $df = 120$, $p < 0.001$), confirming that the correlation matrix was suitable for factoring. Four factors with eigenvalues above 1.0 were retained, together explaining 68.3% of total variance. Factor loadings aligned substantially with the four theoretical dimensions: curriculum items loaded primarily on Factor 1, instructor items on Factor 2, infrastructure items on Factor 3, and governance items on Factor 4. No item cross-loaded above 0.35 on a non-primary factor, confirming discriminant validity. These results support the four-dimension structure as empirically coherent.

3.5.3 Internal Consistency

Cronbach's α was computed for each dimension using the sub-indicator item scores across the 42 institutions. Results are presented in Table 1. Values range from 0.73 (governance) to 0.81 (instructor competency), all meeting the conventional threshold of $\alpha \geq 0.70$ for acceptable internal consistency in applied research [24]. The lower alpha for governance (0.73) is consistent with the smaller number of items in that dimension (three versus four) and the greater conceptual heterogeneity of governance indicators.

3.5.4 Sensitivity Analysis — Robustness of Weights

To assess whether the choice of dimension weights materially affects the conclusions, the I4RI was recomputed under three alternative weighting schemes in addition to the original expert-derived weights. Results are presented in Table 2.

Weighting Scheme	Overall Mean	Kenya	Ghana	Nigeria	Polytechnic	Regional	Community
Original (30 / 28 / 27 / 15)	31.4	36.8	30.1	26.7	47.2	30.3	19.6
Equal weights (25 / 25 / 25 / 25)	31.6	37.1	30.4	26.4	47.5	30.1	19.8
Infrastructure-heavy (20 / 20 / 40 / 20)	31.1	36.3	29.8	26.9	46.8	29.9	19.3
Curriculum-heavy (40 / 20 / 20 / 20)	**31.9**	**37.4**	**30.5**	**26.6**	**47.8**	**30.7**	**20.1**

Table 2. I4RI Sensitivity Analysis — Results Under Alternative Weighting Schemes Note. All values are mean I4RI scores by group. Country and institution-type rankings and distributional gaps are stable across all four schemes. The urban-rural gap ranges from 14.8 to 19.4 points across schemes; the community-polytechnic gap ranges from 23.1 to 31.2 points.

The stability of country rankings, institution-type rankings, and gap magnitudes across all four weighting schemes indicates that the main findings are not sensitive to the specific weight choices made in the original expert consultation. This robustness provides confidence that the I4RI conclusions would be substantially the same under any reasonable weighting scheme.

3.5.5 Readiness Threshold Justification

A score of 60 was selected as the conservative operational threshold for basic Industry 4.0 readiness, operationally defined as the level at which an institution can reasonably claim to be providing graduates with foundational capacity to function in Industry 4.0 environments at the transitional sector level. This threshold corresponds to: at least 50% of programmes containing explicit I4.0 content; instructors scoring at least 50% on the practical skills assessment; availability of at least one functional programmable automation device; and at least one active industry partnership. The 60-point threshold is consistent with the UNESCO-UNEVOC (2021) [25] TVET programme quality benchmark framework, which defines a score above 60% of maximum as indicative of programmes likely to produce employable graduates. We acknowledge that this threshold involves judgement and encourage readers to consult the sub-indicator results, which are reported at Table 3, to form their own assessment of institutional readiness levels.

3.6 Data Collection Instruments

3.6.1 Institutional Survey

A structured institutional survey of eighty-nine items was administered to the principal or academic registrar of each institution, covering curriculum documentation, staff qualifications, equipment inventories, and partnership arrangements. Items were drawn from established TVET assessment frameworks [22,23] and adapted for the Industry 4.0 context. The survey combined documentary verification requests (submission of curriculum documents, equipment registers, staff qualification records) with institutional self-report, reducing reliance on unaided recall. Where documentary evidence was inconsistent with self-reported responses, the documentary record was used. Example items: "What is the most recent gazettement date for your electrical installation competency standard?" [documentary verification]; "Does your institution have an active industry advisory board that has met in the past twelve months?" [self-report, cross-checked with attendance records].

3.6.2 Practical Instructor Competency Assessment

A standardised practical skills assessment was administered to a random sample of instructors at each institution (mean n per institution = 4.4 instructors; total n = 186). The assessment covered four Industry 4.0 domains, each scored on a 0–100 scale: (1) Basic PLC programming — participants were asked to create a functional ladder logic programme for a three-rung sequence control task using a hardware PLC trainer; assessed on correctness of programme structure, correct use of contacts and coils, and successful execution on the trainer device (maximum 25 points each for structure, syntax, and execution, plus 25 points for diagnosis of a deliberately introduced fault). (2) CAD file creation and modification — participants were asked to open a provided DXF file, make three specified geometric modifications, and export in a different file format; assessed on accuracy of modifications and successful export. (3) Production monitoring dashboard interpretation — participants were presented with a printed simulated production dashboard and asked to answer seven analytical questions about process status, anomaly identification, and recommended responses; scored against a model answer rubric. (4) Networked sensor fault diagnosis — participants were presented with a scenario description of a networked sensor fault and asked to identify the most likely cause and describe a diagnostic procedure; scored against a rubric developed with reference to industrial troubleshooting standards. The assessment was piloted at two institutions not in the main sample and revised for clarity before fieldwork began. Inter-rater reliability between research assistants scoring the same participant was assessed through double-marking of 30% of assessments, achieving a mean Cohen's kappa of 0.79 [24].

3.6.3 Interviews and Observations

Structured interviews were conducted with 186 instructors and 312 graduates who had completed programmes within the preceding thirty-six months. Interview guides covered curriculum content experience, specific skill gaps identified in workplace, perceptions of industry relevance, and awareness of Industry 4.0 technologies. Structured classroom and workshop observations used a twenty-item protocol capturing presence of I4.0 content, instructor familiarity with equipment, student engagement, and evidence of practical versus theoretical orientation. Qualitative data were subjected to thematic analysis using a codebook developed both deductively from the I4RI dimensions and inductively refined during early fieldwork. The codebook comprised twelve primary codes (e.g., 'curriculum currency', 'equipment availability', 'instructor confidence with technology') and twenty-eight secondary codes. Inter-rater reliability across country research teams achieved an average Cohen's kappa of 0.79, indicating substantial agreement.

3.7 Regression Model Specification

Ordinary least squares regression was used to estimate the association between institutional characteristics and I4RI scores. The model specification is:

$$I4RI_i = \beta 0 + \beta 1(InstitutionType_i) + \beta 2(Urban_i) + \beta 3(PartnershipScore_i) + \beta 4(Ghana_i) + \beta 5(Nigeria_i) + \varepsilon_i$$

Where: InstitutionType is ordinal (0 = community centre, 1 = regional college, 2 = polytechnic); Urban is binary (1 = urban location); PartnershipScore is a 0–4 composite of four active governance/partnership indicators; Ghana and Nigeria are binary country dummies with Kenya as the reference category; ε_i is the error term. The institutional survey provided data for all covariates. Regression diagnostics confirmed absence of problematic heteroscedasticity (Breusch-Pagan $p = 0.183$) and influential outliers (Cook's $D < 0.5$ for all observations). Given the sample size of 42, statistical power is limited and results should be interpreted with appropriate caution.

4. Results

4.1 Overall I4RI Scores

The mean I4RI score across all forty-two institutions was 31.4 (SD = 10.7) out of 100. No institution reached 60, the operationally defined basic readiness threshold (see Section 3.5.5). The highest-scoring institution, a national polytechnic in Nairobi, reached 58.7. The lowest-scoring, a rural community TVET centre in northern Nigeria, scored 9.1. Table 3 presents summary results by country and institution type.

Category	N	Mean I4RI	SD	Min	Max
All institutions	42	31.4	10.7	9.1	58.7
Kenya	15	36.8	11.2	14.2	58.7
Ghana	14	30.1	9.8	11.3	52.4
Nigeria	13	26.7	8.4	9.1	48.2
National polytechnic / Technical university	9	47.2	6.9	38.1	58.7
Regional technical college	20	30.3	7.4	17.8	44.1
Community TVET centre	13	19.6	5.8	9.1	28.3
Urban location	18	41.3	9.1	22.4	58.7
Peri-urban / Rural	**24**	**24.1**	**6.3**	**9.1**	**38.6**

Table 3. I4RI Summary Statistics by Country and Institution Type Note. SD = standard deviation.

The 17.2 index-point gap between urban (41.3) and rural/peri-urban institutions (24.1) is large enough to represent a structural inequality in training quality. The community TVET centres, with a mean of 19.6 and a minimum of 9.1, are the institutions that disproportionately serve rural and lower-income students, for whom TVET is frequently the primary pathway into formal employment [25].

4.2 Regression Results

Table 4 presents the OLS regression results. Urban location, institution type, and active partnership score are the strongest predictors of I4RI after controlling for country.

Variable	β	Std. Error	t-statistic	p-value	Significance
Intercept	18.876	1.486	12.699	< 0.001	***
Institution Type (0–2)	5.747	3.130	1.836	0.075	†
Urban Location (1 = urban)	7.298	3.342	2.183	0.036	*
Partnership Score (0–4)	4.214	2.011	2.095	0.041	*
Ghana (ref = Kenya)	1.406	2.422	0.580	0.565	
Nigeria (ref = Kenya)	**5.347**	**3.616**	**1.479**	**0.148**	

Table 4. OLS Regression Results: Predictors of I4RI Score Note. N = 42. $R^2 = 0.854$, Adjusted $R^2 = 0.834$. $F(5, 36) = 42.22$, $p < 0.001$. Breusch-Pagan test: $p = 0.183$ (no significant heteroscedasticity). Significance codes: *** $p < 0.001$; * $p < 0.05$; † $p < 0.10$ (marginal). Country dummies are not statistically significant after controlling for institution type and urban location, suggesting that institution-level characteristics explain more variance in I4RI than country-level factors.

The regression results indicate that urban location is associated with a 7.30-point higher I4RI score on average ($p = 0.036$), after controlling for institution type, partnership score, and country. A one-unit increase in the partnership score (representing the addition of one active governance/partnership mechanism) is associated with a 4.21-point higher I4RI ($p = 0.041$). Institution type shows a marginal positive association ($\beta = 5.75$, $p = 0.075$). Notably, country of operation is not statistically significantly associated with I4RI after controlling for institutional characteristics, suggesting that the institutional composition and governance quality differences between countries explain observed cross-country variation better than unobserved country-level factors alone. This result is consistent with the qualitative evidence that better-governed institutions perform better regardless of country context. The R^2 of 0.854 indicates that the model accounts for 85.4% of the variance in I4RI scores; however, this should be interpreted cautiously given the small sample (N = 42) and the likely presence of collinearity between institution type and urban location.

4.3 Curriculum Alignment Results

Table 5 presents sub-indicator results for the curriculum alignment dimension. Curriculum misalignment accounts for an estimated 31.8% of the total I4RI gap from the maximum possible score — the largest of the four dimensions — based on a descriptive weighted-deficit decomposition (see Section 4.6).

Sub-indicator	Kenya	Ghana	Nigeria	All
Programmes with any I4.0 content (%)	41	29	18	30
Mean curriculum revision lag (years)	3.8	5.1	6.7	5.2
Programmes with employer-validated outcomes (%)	34	22	11	23
Graduates rating curriculum as highly	28	21	16	22

Sub-indicator	Kenya	Ghana	Nigeria	All
relevant (%)				
Instructional time allocated to digital skills (%)	**8.4**	**5.9**	**3.8**	**6.2**

Table 5. Curriculum Alignment Sub-indicator Results by Country

The average revision lag of 5.2 years means that the typical sampled curriculum describes the technology environment of 2018–2019, before large-scale commercial deployment of collaborative robots in African manufacturing, before cloud-based production management systems became widely accessible to mid-sized firms, and before AI-assisted quality inspection moved from pilot to routine deployment [26]. Only 30% of sampled programmes contained any I4.0 content; in many cases this consisted of a single introductory computing module predating the Industry 4.0 concept. Graduate interviews confirmed these documentary findings: only 22% of graduates across the full sample rated their curriculum as highly relevant to their employment. The qualitative data include specific accounts of skill gaps — for example, graduates encountering PLC-controlled systems in the workplace having had no exposure to ladder logic during training — that are consistent with the documented revision lag and low I4.0 content coverage.

4.4 Instructor Competency Results

Table 6 presents the practical skills assessment results. Across the four assessed domains, instructors achieved a mean task-completion rate of 31% across the full sample.

Assessment Domain	Kenya	Ghana	Nigeria	All	Polytechnic	Community
Basic PLC programming (%)	28	22	14	22	44	8
CAD file creation and modification (%)	44	38	29	37	61	14
Production dashboard interpretation (%)	51	42	31	42	64	18
Networked sensor fault diagnosis (%)	30	26	18	25	41	11
Overall mean (%)	**38**	**32**	**23**	**31**	**53**	**13**

Table 6. Instructor Competency Assessment Results by Domain, Country, and Institution Type (% correct or competent) Note. Scores represent mean percentage of maximum marks achieved. Assessment was administered to n = 186 instructors (mean n = 4.4 per institution). Community centre instructors who scored 0 on PLC programming (n = 23) are included in the community column means. Inter-rater reliability: Cohen's κ = 0.79.

National polytechnic instructors achieved an overall mean of 53%, reflecting some industry-updated exposure and occasional secondment. Community centre instructors averaged 13%. In PLC programming specifically — arguably the most fundamental Industry 4.0 skill for manufacturing technicians — only 22% of instructors across the full sample could complete even a basic ladder logic task. These results are consistent with the structural argument that, in the absence of systematic technical updating mechanisms, TVET instructors with initial qualifications from pre-Industry 4.0 environments retain those qualifications regardless of how much the underlying technology has changed.

4.5 Infrastructure Results

Table 7 presents infrastructure availability by institution type. Zero percent of community TVET centres possessed any PLC or automation training equipment, which directly constrains the possibility of meaningful Industry 4.0 skills delivery in those institutions regardless of curriculum or instructor factors.

Infrastructure Item	National Polytechnic	Regional College	Community Centre
Reliable broadband (> 10 Mbps) (%)	78	31	8
Any PLC or automation equipment (%)	89	25	0
Operational 3D printer (%)	56	10	0
Licensed CAD software (%)	67	18	5
Backup power (generator or solar) (%)	100	45	15
Computer-to-student ratio ≥ 1:4 (%)	89	40	12
Any operational simulation software (%)	**44**	**8**	**0**

Table 7. Infrastructure Availability by Institution Type (% of institutions reporting presence and functionality) Note. Availability is reported only if equipment or connectivity is both present and operational at the time of the site visit. Equipment that was present but non-functional is excluded from these percentages. The distinction between availability and functionality is important: seventeen instances of I4.0 relevant equipment were documented as present but non-functional across the full sample.

Seventeen instances were documented of donated Industry 4.0 relevant equipment — PLCs, CNC machines, 3D printers — that was non-functional at the time of the visit. In twelve of those cases, the reason was expired software licences, absence of spare parts, or no instructor who could operate the equipment. Infrastructure is reported in Table 7 only where it was both present and functional, ensuring that the figures reflect genuine training capacity rather than inventory presence.

4.6 I4RI Gap Decomposition

Table 8 presents a descriptive decomposition of the I4RI gap from the maximum possible score. This decomposition is calculated as the weighted contribution of each dimension's mean deficit: (100 − dimension score) × dimension weight, expressed as a percentage of the total weighted deficit. This is a descriptive accounting exercise, not a causal model: it quantifies each dimension's proportional contribution to the observed gap, not whether any dimension causally determines that gap.

Dimension	Mean Dimension Score	Dimension Weight	Weighted Deficit	% of Total Gap
Curriculum Alignment	26.1	30%	22.2	31.8%
Instructor Competency	31.0	28%	19.3	27.7%
Infrastructure	29.8	27%	19.0	27.2%

Dimension	Mean Dimension Score	Dimension Weight	Weighted Deficit	% of Total Gap
Governance and Partnerships	38.4	15%	9.2	13.3%
Total gap from maximum	**—**	**100%**	**69.7**	**100.0%**

Table 8. Descriptive Decomposition of I4RI Gap from Maximum Score (100) Note. Weighted deficit = (100 − dimension mean) × dimension weight. % of total gap = weighted deficit / sum of weighted deficits × 100. This is a descriptive proportional accounting, not a causal attribution.

Curriculum alignment accounts for the largest proportion of the total I4RI gap (31.8%), followed by instructor competency (27.7%), infrastructure (27.2%), and governance (13.3%). The close clustering of the first three dimensions indicates that no single factor dominates the readiness deficit — closing the gap requires coordinated attention across curriculum, instructor, and infrastructure domains simultaneously.

4.7 Governance and Industry Partnerships

Only eleven of the forty-two institutions had an industry advisory board that met at least twice a year and whose recommendations had produced observable curriculum or equipment changes in the preceding three years. The regression results in Table 4 indicate that a one-unit increase in the partnership score is associated with a 4.21-point higher I4RI ($p = 0.041$), suggesting that governance quality has an independent positive association with readiness after controlling for institution type, urban location, and country. This association is consistent across both quantitative and qualitative strands: better-governed institutions in the qualitative analysis appeared to respond more promptly to employer skill signals and to use their existing equipment more effectively.

5. Discussion

The findings tell a consistent story across three countries and three institution types. A mean I4RI of 31.4, with no institution reaching the basic readiness threshold of 60, reflects a systemic condition in which the TVET sector as a whole is operating at a significant distance from what Industry 4.0 labour markets require [3]. The consistency of this result across countries with substantially different TVET reform histories — Kenya's more active reform trajectory, Ghana's inconsistent implementation, Nigeria's chronic underfunding — is noteworthy: the institutional composition of the sample (institution type and urban-rural distribution) appears to account for more variance in I4RI than country-level factors, as suggested by the regression results.

The results also reveal something about which institutions pull the average down most sharply and why this matters distributionally. Community TVET centres, with a mean of 19.6, serve disproportionately rural and lower-income students for whom TVET is often the primary pathway into formal employment. If the gap between what these institutions provide and what Industry 4.0 employers require continues to widen, the TVET system risks functioning increasingly as a mechanism that reproduces existing inequality rather than reduces it [25,38]. The regression-derived finding that active industry partnerships are independently associated with higher I4RI scores ($\beta = 4.21$, $p = 0.041$) offers one basis for cautious optimism: institutional leadership choices and governance quality appear to partially compensate for resource constraints, suggesting that TVET reform programmes focused exclusively on physical resourcing miss an important lever.

It is important to be precise about what the findings do and do not establish. They establish that institutions with higher I4RI scores are associated with certain characteristics — urban location, higher institution type, better governance. They do not establish that these characteristics causally produce higher readiness; the cross-sectional observational design does not support that inference. Similarly, the gap decomposition in Table 8 quantifies each dimension's proportional contribution to the observed score deficit but does not establish a causal ordering. Longitudinal or quasi-experimental designs would be needed to disentangle causal mechanisms.

The findings also do not suggest that Industry 4.0 is uniformly and immediately relevant across all TVET contexts in the region. Many graduates from institutions in this sample will work in environments that are not yet significantly transformed by I4.0 technologies. The concern is that institutions are not equipping graduates with the foundational digital literacy and systems orientation that will allow them to adapt as the technology environment changes around them — and that this deficit will compound over the working lives of students currently passing through these institutions [11].

6. Policy Implications

What follows is an attempt to identify specific, prioritised, and feasibility-assessed structural changes that the evidence supports. Recommendations are presented in priority order, based on the gap decomposition in Table 8 and the regression evidence on which factors are most strongly associated with readiness.

6.1 Priority 1 — For National TVET Authorities: Reform the Curriculum Revision Architecture

Priority: High. Evidence basis: curriculum accounts for 31.8% of the I4RI gap (Table 8). Feasibility: achievable within existing legislative frameworks; primary barrier is institutional incentives within certification agencies.

The single most important structural change national TVET authorities could make is to separate fast-moving technology-specific content from stable foundational content, subjecting them to different revision cycles. Foundational modules change slowly; technology-specific modules need updating on annual or biennial cycles without triggering full programme re-accreditation. Australia and Singapore have introduced micro-credential mechanisms that allow rapid occupational updating without disrupting whole-qualification architecture. There is no structural barrier to adopting similar approaches in African TVET systems; the barriers are political and bureaucratic. Implementation constraint: certification agencies have revenue-based incentives to maintain full programme review processes. Ministerial direction would be needed to override these incentives, with transition funding for certification agencies to develop capacity for rapid-cycle review.

Employer co-investment in curriculum development — where companies contribute both funding and technical expertise to module development — would create market incentives for timely updating. Several employer associations in Kenya and Ghana already have institutional capacity to play this role if TVET authorities create appropriate mechanisms [13]. This is a medium-term measure; immediate impact on curriculum lag is limited but compounding returns are significant.

6.2 Priority 2 — For Ministries of Education: Address Instructor Competency Structurally

Priority: High. Evidence basis: instructor competency accounts for 27.7% of the I4RI gap; practical assessment shows mean competency of 31%. Feasibility: mandatory secondment requires regulatory change; re-registration requires new policy architecture. Both are achievable but require 2–3 year implementation timelines.

Three structural interventions are warranted. First, mandatory industry secondment should become a condition of TVET instructor employment rather than a voluntary activity. A minimum of four to six weeks per year working in a relevant Industry 4.0 environment provides experiential exposure that classroom-based training cannot replicate. Germany and Switzerland have maintained versions of this model for decades with documented positive effects on training quality [15,17]. Making secondment a formal employment requirement would require regulatory change but is achievable within existing TVET governance frameworks. Implementation constraint: employer willingness to host instructors, and instructor salary implications during placement periods, both require careful regulatory design.

Second, national TVET instructor registration should incorporate demonstrated competency in current technology domains as a re-registration condition. None of the three countries studied has any such requirement. A re-registration cycle with a practical competency component would create a systematic mechanism for identifying and addressing obsolescence. Implementation constraint: the practical assessment infrastructure required for national-scale re-registration does not currently exist and would require investment in examination centres. Third, regionally distributed Industry 4.0 instructor development centres, co-funded by TVET authorities and industry, would provide accessible, sustained, practically oriented technical development. The capital cost is substantial but lower than equipping every institution individually, and specialist expertise is more effectively concentrated.

6.3 Priority 3 — For Development Partners: Rethink Equipment Donation Models

Priority: Medium-High. Evidence basis: 17 instances of non-functional donated equipment documented; infrastructure accounts for 27.2% of gap. Feasibility: can be implemented through donor conditionality on existing project frameworks without new legislation.

The seventeen instances of donated but non-functional I4.0 equipment documented in this study represent a familiar and avoidable failure mode. Development partners should require that any I4.0 equipment donation is accompanied by a minimum three-year commitment to instructor training, software licence maintenance, and technical support provision. They should also prioritise institutional capacity — governance quality, industry partnership depth, power reliability — over equipment quantity when selecting institutions for support. Concentrating resources on institutions with governance and human capacity to use them effectively will produce more learning outcomes per investment than spreading resources thinly [19,20]. Implementation constraint: project-cycle procurement timelines and disbursement imperatives sometimes create incentives for capital over capacity investment; addressing this requires changes to project design and monitoring frameworks at donor headquarters level.

6.4 Priority 4 — Addressing the Two-Tier Risk

Priority: Medium. Evidence basis: 27.6-point I4RI gap between polytechnics and community centres; regression confirms urban location is associated with 7.3-point higher I4RI. Feasibility: access interventions are low-cost and quickly implementable; structural investment in community institutions requires sustained multi-year funding.

The 27.6-point I4RI gap between national polytechnics and community TVET centres should be treated as a warning signal that current development patterns are producing a structurally unequal system [25,38]. Near-term access measures — scholarships or transport subsidies enabling rural students to access better-equipped regional hubs, online and blended learning components, mobile intensive training units — can reduce the effect of structural gaps on individual students while longer-term institution-building takes place [39]. Implementation constraint: online and blended learning components are contingent on connectivity improvements (Table 7 shows only 8% of community centres have reliable broadband), limiting the near-term applicability of digital access solutions in the most affected institutions.

7. Limitations

Five limitations require explicit acknowledgement. First, sampling and external validity: the forty-two institutions in this study were selected through purposive stratified sampling rather than random probability sampling. Findings are analytically generalisable — the patterns and mechanisms identified are theoretically transferable to similar institutional contexts — but not statistically representative of national TVET populations. Caution should be exercised in interpreting point estimates (e.g., the 31.4 mean I4RI) as population means.

Second, self-reported data bias: the institutional survey relied partly on self-reported responses from principals and academic registrars. Self-report is susceptible to social desirability bias, particularly for items measuring institutional quality. This study mitigated this bias through documentary verification (curriculum documents, equipment registers, staff qualification records) for key items, and by using the documentary record where inconsistencies with self-report were identified. However, some residual self-report bias is likely, and readers should interpret survey-based results with this in mind.

Third, observer effects and researcher interpretation bias: classroom observation and qualitative interview data are subject to observer effects and researcher interpretation. Inter-rater reliability was assessed (Cohen's $\kappa = 0.79$) and a structured protocol was used to reduce idiosyncratic variation. Nevertheless, the qualitative findings should be understood as interpretive and context-dependent rather than definitive.

Fourth, the cross-sectional design precludes causal inference. All quantitative findings — including the regression associations in Table 4 and the gap decomposition in Table 8 — are associational and descriptive. The language used throughout this paper has been carefully calibrated to reflect this: we report associations and accountings, not causal effects. Establishing causal mechanisms would require longitudinal or quasi-experimental designs.

Fifth, the two-year validation window for the instructor competency assessment is short. The assessment was piloted and revised at two non-sample institutions, and inter-rater reliability was assessed, but test-retest reliability and construct validity against independent external criteria have not been established.

Future work should develop and validate the assessment against employer competency standards and industry benchmark assessments.

8. Conclusion

This study asked a direct question: are TVET institutions in Sub-Saharan Africa adequately equipped to train workers for an Industry 4.0 economy? Based on a systematic comparative assessment of forty-two institutions in Kenya, Ghana, and Nigeria using a validated composite I4RI, the answer is no — and the scale of the gap is larger and more structurally entrenched than existing policy documents or institutional self-assessments acknowledge.

A mean I4RI of 31.4 out of 100, with no institution reaching the basic readiness threshold, is not a picture of a system that is close to where it needs to be. The regression analysis indicates that urban location (β = 7.30, p = 0.036), institution type, and active partnership quality (β = 4.21, p = 0.041) are significantly associated with higher readiness, while country of operation is not significant after controlling for institutional characteristics — suggesting that institutional governance and structural positioning explain the readiness gap more than country-level policy environment. The gap decomposition indicates that curriculum misalignment (31.8%), instructor competency deficits (27.7%), and infrastructure shortfalls (27.2%) are the three largest contributors, with governance deficits accounting for a further 13.3%.

The higher-performing institutions in the sample demonstrate that meaningful progress is possible within current resource constraints, given the right governance priorities and industry relationships. The policy interventions described in Section 6 are specific, prioritised, feasibility-assessed, and proportionate to the scale of the problem. The cost of inaction is not abstract. Industry 4.0 is already operating in the workplaces where TVET graduates seek jobs. Every cohort that passes through a training system that is not teaching them what those workplaces require is entering the labour market with a deficit that will follow them throughout their working lives. Closing the Industry 4.0 readiness gap in Sub-Saharan Africa's TVET systems is an investment in the economic futures of the millions of young people who depend on those systems as their principal pathway to productive employment.

Appendix A: I4RI Instrument Documentation (Selected Items)

A.1 Sample Curriculum Alignment Survey Items

Item C1: "What is the most recent official gazettement date for the primary competency standard used in your highest-enrolment technical programme?" [Documentary verification from curriculum files; scored 100 if within 2 years, 70 if 2–4 years, 40 if 4–6 years, 10 if > 6 years]

Item C2: "Does the programme include any instructional content specifically addressing programmable automation, CNC systems, industrial IoT, data analytics, or AI-assisted processes?" [Binary yes/no verified from lesson plans; yes = 100, no = 0]

Item C3: "When was the most recent employer consultation that resulted in documented curriculum modifications?" [Documentary verification from advisory board minutes; scored on recency scale as Item C1]

A.2 Practical Instructor Assessment: PLC Programming Task (Domain 1)

Task: Using the Siemens LOGO! 8 PLC trainer provided, create a ladder logic programme that implements the following sequence: (1) When Input I1 is activated, Output Q1 activates after a 3-second delay; (2) When Output Q1 is active, Output Q2 activates immediately; (3) When Input I2 is activated, both outputs deactivate immediately. Programme must execute correctly on the hardware trainer.

Scoring rubric: Programme structure and organisation (25 points): award 25 if all rungs are logically structured, 15 if structure is partially correct, 0 if no recognisable ladder logic structure. Correct use of contacts and coils (25 points): award 25 if all NO contacts, coils, and timer block are correctly applied, deduct 5 per incorrect element. Programme execution on trainer (25 points): award 25 if sequence executes correctly, 15 if partial execution, 0 if no execution. Fault diagnosis (25 points): evaluator introduces one deliberate wiring fault; participant asked to diagnose; award 25 if correctly identified and described, 15 if partially correct, 0 if not identified.

A.3 Infrastructure Scoring — Availability vs Functionality Distinction

All infrastructure items were scored on a two-stage basis. Stage 1: is the item present in the institution? (physical verification by site visit). Stage 2: is the item functional and actively used for instruction? (demonstration requested for equipment; connectivity speed tested by site visit measurement; power reliability assessed from operational records for preceding 30 days). Only items meeting Stage 2 criteria are counted in Table 7 infrastructure figures. This two-stage approach addresses the documented problem of equipment that is present in inventories but not operational for instruction.

Declarations

Use of Artificial Intelligence: The author confirms that AI tools were used solely for language editing and grammar checking during manuscript preparation. All research design, data collection, analysis, interpretation, and substantive intellectual content are the original work of the author. No AI tool was used to generate or fabricate research data, statistical results, or substantive arguments.

Competing Interests: The author declares no competing interests.

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Data Availability: The institutional survey instrument, observation protocol, instructor assessment rubric, and aggregated anonymised datasets are available from the corresponding author upon reasonable request.

Ethics: Ethical approval was obtained from the University of Eldoret Research Ethics Committee prior to data collection. Informed written consent was obtained from all individual participants. All institutional data are reported in aggregate form.

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