

ICT-Enhanced EACCL Framework for Developing 4Cs Competencies in Science Teacher Education: Evidence from Sindh, Pakistan

Raja Bahar Khan Soomro

baharkhansoomro.phdedus24@iba-suk.edu.pk

Sukkur IBA University

Research Article

Keywords: ICT integration, EACCL framework, SDG 4, science teacher education, 4Cs competencies, pedagogical effectiveness

Posted Date: August 7th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10488147/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Achieving Sustainable Development Goal 4 (SDG 4) requires strengthening the quality of science teacher education, particularly in resource-constrained contexts such as Sindh, Pakistan, where policy aspirations often fail to translate into effective classroom practice. This study develops and empirically validates an Information and Communication Technology (ICT)-enhanced EACCL framework (Engagement, Alignment, Contextualisation, Critical Thinking, and Learning Outcomes) as a contextually grounded model for improving science teacher education and fostering the four core 21st-century competencies (4Cs): critical thinking, creativity, communication, and collaboration. A cross-sectional survey was conducted with 312 pre-service (B.Ed. Hons.) and in-service secondary science teachers from North Sindh. The research instrument was developed through expert review and pilot testing, followed by Exploratory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA), and reliability analyses to evaluate the measurement properties of the proposed framework. The findings supported a five-factor structure with satisfactory model fit and acceptable reliability. Critical Thinking and Alignment emerged as the strongest predictors of pedagogical effectiveness and the development of 4Cs competencies, while Contextualisation differentiated pedagogical practices between pre-service and in-service teachers. These findings provide initial empirical support for the EACCL framework and highlight the importance of curriculum alignment, context-responsive instruction, and higher-order cognitive engagement in improving science teaching quality. The study offers an evidence-informed framework for teacher educators and policymakers seeking to strengthen ICT-integrated science teacher education and support the implementation of SDG 4 in Pakistan and comparable resource-constrained educational contexts. Future research should employ longitudinal and multi-contextual designs to examine the framework's broader applicability and long-term effectiveness.

Introduction

Sustainable Development Goal 4 calls for inclusive, equitable, and quality education that equips learners with the knowledge, skills, and competencies required for lifelong learning and sustainable development (United Nations, 2023). Beyond improving access to education, SDG 4 emphasizes strengthening teaching quality, curriculum relevance, and learning outcomes through effective teacher preparation and continuous professional development. Science teacher education is particularly important because science teachers are expected to cultivate scientific literacy, critical inquiry, problem-solving, and evidence-based decision-making, all of which are essential for addressing contemporary environmental, technological, and societal challenges (UNESCO, 2024).

The growing emphasis on digital transformation has further reinforced the need to integrate ICT into teacher education. ICT has the potential to improve instructional quality by promoting interactive learning, collaborative knowledge construction, timely access to educational resources, and learner-centred pedagogies (Anderson & Dexter, 2005; Ertmer & Ottenbreit-Leftwich, 2010). Research has consistently shown that successful technology integration depends not only on the availability of digital infrastructure but also on teachers' pedagogical knowledge, professional competence, institutional

support, and confidence in using technology for teaching and learning (Hennessy et al., 2005; Hew & Brush, 2007; Kazlauskas, 2018). Consequently, teacher education programmes must move beyond teaching technical skills towards developing integrated pedagogical and technological competencies that enhance classroom practice.

Despite national commitments to improving educational quality, the implementation of ICT-supported science teacher education remains uneven in many developing countries, including Pakistan. Educational institutions continue to face challenges associated with limited technological infrastructure, insufficient professional development opportunities, unequal access to digital resources, and inconsistent policy implementation (World Bank, 2021; Pakistan Institute of Education, 2023). These constraints are particularly evident in Sindh Province, where disparities in educational resources and teacher preparation continue to affect instructional quality. Studies examining ICT integration in Pakistan have similarly identified inadequate institutional support, limited teacher preparedness, and contextual barriers as major impediments to effective technology-enhanced teaching (Aslam et al., 2021; Raza et al., 2020). These findings indicate that technology alone cannot improve educational quality without coherent pedagogical frameworks that align curriculum, teaching practices, and contextual realities.

At the same time, educational reforms increasingly emphasise the development of twenty-first-century competencies. Frameworks proposed by Partnership for 21st Century Learning (P21), Bellanca and Brandt (2010), Binkley et al. (2012), and Kereluik et al. (2013) consistently identify the 4Cs as essential competencies for preparing learners to participate effectively in knowledge-based societies. Developing these competencies requires instructional approaches that promote active learning, inquiry, collaboration, and authentic problem-solving rather than relying solely on traditional teacher-centred instruction (Dede, 2010; Trilling & Fadel, 2009). Science education provides a particularly appropriate context for nurturing these competencies because scientific inquiry naturally involves investigation, reasoning, communication, and collaborative learning.

Teacher professional development remains a critical mechanism for improving instructional quality and educational reform. Effective professional learning supports teachers in adopting innovative pedagogical practices, integrating technology meaningfully into classroom instruction, and responding to diverse learner needs (Avalos, 2011; Darling-Hammond et al., 2017; Kennedy, 2016; Timperley, 2011). However, evidence suggests that professional development programmes are most effective when they are sustained, context-specific, collaborative, and directly connected to teachers' instructional practices rather than delivered as isolated training events (Darling-Hammond & Richardson, 2009; Guskey, 2002; Opfer & Pedder, 2011). Within Pakistan, strengthening teacher professional development remains essential for narrowing the gap between educational policy and classroom implementation.

Although previous studies have examined ICT integration, teacher professional development, and twenty-first-century competencies independently, limited research has investigated how these dimensions interact within a single contextual framework designed specifically for science teacher education in resource-constrained environments. Existing studies generally focus on barriers to ICT adoption or

teachers' technology readiness; while relatively little attention has been given to developing and evaluating integrated pedagogical models that connect technology integration, curriculum alignment, contextual teaching, higher-order thinking, and measurable learning outcomes. This represents an important gap in the literature, particularly within the context of Pakistani science teacher education.

To address this gap, the present study proposes the ICT-enhanced EACCL framework, comprising “Engagement, Alignment, Contextualisation, Critical Thinking, and Learning Outcomes”, as a contextual model for strengthening science teacher education. Rather than introducing a new learning theory, the framework integrates established principles of learner engagement, curriculum alignment, contextualised instruction, higher-order thinking, and outcome-oriented pedagogy within an ICT-supported teaching environment. The framework is intended to provide a practical structure for examining how these interconnected dimensions contribute to pedagogical effectiveness and the development of 4Cs competencies among pre-service and in-service science teachers.

Accordingly, this study investigates the relationships among the EACCL dimensions, ICT integration, pedagogical effectiveness, and the development of twenty-first-century competencies among science teachers in North Sindh, Pakistan. By providing empirical evidence from a resource-constrained educational context, the study contributes to the growing literature on ICT-supported teacher education and offers practical implications for teacher educators, policymakers, and curriculum developers seeking to strengthen science teacher preparation in support of SDG 4. Rather than claiming broad theoretical advancement, the study offers context-specific evidence on the applicability of the proposed framework and highlights its potential to inform future research and teacher education practice in comparable educational settings.

2. Literature Review

ICT Integration in Science Teacher Education: Improving science teacher education is fundamental to achieving SDG 4, particularly in education systems where instructional quality is constrained by limited resources and uneven professional support (United Nations, 2023; UNESCO, 2024). ICT has increasingly been recognised as an important catalyst for improving teaching quality by supporting inquiry-based learning, collaboration, formative assessment, and access to digital learning resources (Al-Bizri, 2017; Ertmer & Ottenbreit-Leftwich, 2010). However, the educational value of ICT depends less on the availability of technology than on teachers' ability to integrate digital tools into pedagogically meaningful learning experiences (Anderson & Dexter, 2005).

Research consistently demonstrates that ICT enhances science education by enabling simulations; virtual laboratories, collaborative inquiry, and data-driven problem solving that improve conceptual understanding and learner engagement (Hennessy et al., 2005; Kazlauskas, 2018). Rather than functioning as a technological add-on, ICT becomes effective when aligned with curriculum objectives and learner-centred instructional strategies (Hew & Brush, 2007).

Despite these recognised benefits, technology integration remains inconsistent across many developing education systems. Structural barriers; including inadequate infrastructure, limited institutional support, insufficient teacher preparation, and resistance to pedagogical change continue to restrict effective ICT implementation (Aslam et al., 2021; Raza et al., 2020). Professional development therefore becomes the critical mechanism through which teachers acquire both technological competence and pedagogical confidence (Avalos, 2011; Darling-Hammond et al., 2017).

The Pakistani context reflects many of these global challenges. National policy documents increasingly emphasise digital transformation and competency-based education, yet implementation remains uneven across provinces and institutions (Pakistan Institute of Education, 2023; Ministry of Federal Education and Professional Training, 2026). Reports continue to identify disparities in infrastructure, teacher readiness, and institutional capacity, particularly in rural districts of Sindh, limiting meaningful ICT integration in teacher education (World Bank, 2021; UNESCO, 2026). These findings suggest that technology alone cannot improve educational quality without pedagogically informed implementation models.

Developing 21st-Century Competencies through Teacher Education

Educational reform increasingly emphasises competencies that enable learners to respond to complex social, technological, and environmental challenges. Frameworks developed by Partnership for 21st Century Learning and subsequent scholarship identify 4Cs as foundational competencies for lifelong learning and workforce participation (Bellanca & Brandt, 2010; Binkley et al., 2012; P21, 2019).

Among these competencies, critical thinking has received particular attention within science education because inquiry-based learning requires learners to analyse evidence, evaluate competing explanations, and construct scientific arguments. Communication and collaboration facilitate collective problem solving, while creativity supports innovation and knowledge generation (Trilling & Fadel, 2009). Contemporary teacher education therefore extends beyond subject knowledge to include pedagogical approaches that intentionally cultivate these transferable competencies.

Digital technologies provide important opportunities for developing the 4Cs. Interactive learning environments encourage collaborative inquiry, peer feedback, and authentic problem solving, allowing students to participate actively in knowledge construction (Kereluik et al., 2013; Kimmons & Hall, 2016). However, research indicates that successful competency development depends on instructional design rather than technology itself. Teachers require sufficient pedagogical expertise to integrate digital tools within coherent learning experiences that promote higher-order thinking (Darling-Hammond et al., 2020).

Although competency-based education has become a policy priority internationally, empirical evidence from Pakistan remains limited. Existing studies suggest that classroom practice continues to rely heavily on teacher-centred instruction and examination-oriented learning, reducing opportunities for inquiry, collaboration, and critical thinking (Aslam et al., 2021). Consequently, strengthening teacher education

programmes capable of integrating ICT with competency-based pedagogy represents an important research and policy priority.

Teacher Professional Development and ICT-Enabled Pedagogical Change

Teacher professional development is widely recognised as one of the strongest determinants of educational quality because sustainable instructional improvement depends on continuous learning rather than one-time training initiatives (Kennedy, 2016). Contemporary models emphasise collaborative, practice-based, and reflective professional learning that enables teachers to experiment with new instructional strategies and evaluate their classroom impact (Darling-Hammond et al., 2017; Timperley, 2011).

Research demonstrates that professional learning programmes integrating pedagogy with technology are significantly more effective than technology training delivered in isolation (Alvi & Gillies, 2021). Teachers are more likely to adopt ICT when professional development addresses instructional design, curriculum alignment, assessment, and classroom implementation simultaneously (Avalos, 2011; Opfer & Pedder, 2011).

Evidence from Pakistan indicates persistent challenges in teacher professional learning. Institutional support remains inconsistent, particularly in rural schools where limited funding, inadequate mentoring, and restricted access to digital infrastructure constrain teachers' opportunities for continuous development (Pakistan Institute of Education, 2023; UNESCO, 2026). Consequently, many teachers possess basic technological skills but lack confidence in designing technology-enhanced learning environments capable of improving learner outcomes (Aslam et al., 2021).

These findings reinforce the need for integrated professional development models that combine technological competence with curriculum alignment, contextual adaptation, and reflective practice.

SDG 4 and Science Teacher Education in Pakistan: SDG 4 positions quality education as a central driver of sustainable development, emphasising equitable access, quality teaching, and lifelong learning opportunities (United Nations, 2023). Achieving these objectives requires teacher education systems capable of preparing educators for increasingly complex learning environments characterised by technological change and diverse learner needs (UNESCO, 2024).

Pakistan has incorporated SDG 4 into successive national education strategies; however, implementation remains constrained by institutional inequalities, teacher shortages, and uneven educational investment (Pakistan Institute of Education, 2023). Recent national reports continue to identify disparities between policy commitments and classroom realities, particularly regarding digital infrastructure, instructional quality, and teacher professional development (Ministry of Federal Education and Professional Training, 2026).

Science education presents unique opportunities for advancing SDG 4 because inquiry-based pedagogy naturally supports problem solving, evidence-based reasoning, and collaborative learning. However,

these outcomes depend upon teachers possessing both strong pedagogical knowledge and the ability to integrate ICT effectively within science instruction (Hennessy et al., 2005; Ertmer & Ottenbreit-Leftwich, 2010). International evidence suggests that contextual adaptation is particularly important in developing countries where educational innovation must respond to local resource constraints rather than replicate models developed in high-income settings (Winthrop & McGivney, 2016).

For Sindh, these contextual realities necessitate pedagogical frameworks capable of integrating technology, competency development, and curriculum alignment while remaining feasible within existing institutional conditions.

Research Gap and Theoretical Positioning

Although substantial literature has examined ICT integration, teacher professional development, competency-based education, and SDG 4 independently, relatively few studies have investigated how these dimensions interact within science teacher education in developing contexts. Existing research predominantly examines technology adoption or teacher attitudes separately, providing limited evidence regarding integrated pedagogical models that simultaneously address ICT implementation, curriculum alignment, competency development, contextual adaptation, and measurable learning outcomes.

Within Pakistan, empirical studies remain fragmented and largely descriptive, focusing on isolated aspects of technology adoption rather than testing theoretically grounded frameworks capable of explaining instructional effectiveness across pre-service and in-service teacher populations. Furthermore, little empirical evidence exists concerning North Sindh, where educational inequalities, infrastructure limitations, and professional development challenges remain particularly pronounced.

To address these gaps, this study proposes and empirically validates the ICT-enhanced EACCL framework, as a multidimensional model for improving science teacher education. Unlike previous approaches that conceptualise ICT primarily as a technological intervention, the EACCL framework positions technology within a broader pedagogical structure that integrates curriculum coherence, competency development, contextual responsiveness, and measurable instructional outcomes. Through structural equation modelling, the study provides empirical evidence regarding the relationships among ICT integration, the EACCL dimensions (refer to Fig. 1), pedagogical effectiveness, and 4Cs competencies, thereby extending current understanding of technology-enhanced teacher education in resource-constrained settings.

Research Hypotheses: To empirically test the theoretical assumptions of the EACCL framework, the study formulates the following hypotheses:

H₀ (Null Hypothesis)

There is no statistically significant relationship between the EACCL framework dimensions and the development of 21st-century competencies among science teachers.

H₁ (Alternative Hypothesis)

There is a statistically significant positive relationship between the EACCL framework dimensions and the development of 21st-century competencies among science teachers.

Research Questions: Aligned with the theoretical framework and research objectives, the study addresses the following questions:

RQ1

How does the ICT-enhanced EACCL framework influence the development of 4Cs competencies among science teachers?

RQ2

What relationships exist between ICT integration and pedagogical effectiveness in science teacher education?

RQ3

Are there statistically significant differences between pre-service and in-service science teachers in their ICT-enabled pedagogical practices?

Theoretical Framework

This study is grounded in a technology-enhanced pedagogical perspective that integrates teacher professional learning, ICT-enabled instruction, and competency-based education to explain how science teachers develop pedagogical effectiveness and 21st-century competencies. The framework responds to SDG 4, which emphasises improving educational quality through effective teaching, digital transformation, and equitable learning opportunities (United Nations, 2023; UNESCO, 2024). Rather than conceptualising ICT as a purely technological intervention, this study positions digital technologies as pedagogical resources that enhance curriculum implementation, learner engagement, and higher-order cognitive development.

The proposed ICT-enhanced EACCL framework (refer to Fig. 2) collectively explains how ICT-supported pedagogical practices contribute to the development of science teachers' instructional effectiveness and 21st-century competencies. The framework synthesises insights from technology integration, competency-based learning, and teacher professional development while acknowledging the contextual realities of resource-constrained educational systems such as Sindh, Pakistan.

Unlike traditional technology adoption models that primarily examine teachers' access to digital resources, the EACCL framework conceptualises instructional quality as the interaction between pedagogical design, contextual adaptation, curriculum coherence, and technology-enabled learning.

Consequently, the framework provides an integrated explanation of how ICT can improve science teacher education while supporting broader educational reform under SDG 4.

ICT-Enhanced Pedagogical Practice

Technology integration has evolved from a focus on hardware availability to an emphasis on pedagogically meaningful instructional design. Effective ICT integration occurs when digital technologies support curriculum objectives, promote learner engagement, and facilitate active knowledge construction rather than simply digitising conventional teaching practices (Anderson & Dexter, 2005; Ertmer & Ottenbreit-Leftwich, 2010).

Research consistently demonstrates that ICT enhances science education by enabling simulations, collaborative inquiry, formative assessment, and multimodal learning experiences that improve conceptual understanding and learner participation (Hennessy et al., 2005; Kazlauskas, 2018). However, successful implementation depends on teachers possessing sufficient pedagogical competence, professional confidence, and institutional support to integrate technology effectively within classroom instruction (Hew & Brush, 2007).

In developing education systems, structural barriers; including limited infrastructure, inconsistent professional development, and unequal access to digital resources continue to constrain meaningful technology integration (Aslam et al., 2021; Raza et al., 2020). Consequently, ICT competence should be understood as a professional capability requiring continuous learning, reflective practice, and supportive institutional environments rather than technical proficiency alone (Darling-Hammond et al., 2017; Timperley, 2011).

Competency-Based Learning and 21st-Century Skills

Contemporary educational reform increasingly emphasises competency-based learning, which prioritises the development of transferable knowledge, higher-order thinking, and authentic problem-solving. International frameworks identify 4Cs as essential competencies for lifelong learning and participation in knowledge-based societies (Binkley et al., 2012; Trilling & Fadel, 2009).

Within science education, these competencies are developed through inquiry, experimentation, collaborative investigation, and evidence-based reasoning. Digital technologies further strengthen competency development by supporting interactive learning environments, collaborative knowledge construction, and learner-centred instruction (Kereluik et al., 2013; Kimmons & Hall, 2016). However, competency development depends primarily on pedagogical design rather than technology itself.

Teacher education therefore plays a central role in preparing educators who can intentionally design ICT-supported learning experiences that foster higher-order cognitive skills while maintaining alignment between curriculum objectives, instructional strategies, and assessment practices (Darling-Hammond et al., 2020). The present study positions competency development as a measurable outcome of effective ICT-enhanced pedagogy rather than an independent educational objective.

Teacher Professional Development and SDG 4

Teacher professional learning remains one of the strongest predictors of educational quality because sustainable instructional improvement requires continuous pedagogical development rather than isolated training activities (Kennedy, 2016). Effective professional development is collaborative, practice-oriented, and directly connected to classroom implementation (Avalos, 2011; Darling-Hammond et al., 2017).

SDG 4 reinforces this perspective by identifying teacher quality as a prerequisite for equitable and inclusive education (United Nations, 2023; UNESCO, 2024). National policy initiatives in Pakistan similarly emphasise digital transformation, competency-based curricula, and improved teacher preparation; however, implementation continues to be constrained by infrastructural inequalities and uneven institutional capacity (Pakistan Institute of Education, 2023; Ministry of Federal Education and Professional Training, 2026).

Within Sindh, disparities in digital infrastructure, professional learning opportunities, and instructional resources continue to influence classroom practice (World Bank, 2021). These contextual realities highlight the need for pedagogical frameworks that are sufficiently flexible to accommodate local educational conditions while maintaining alignment with international quality standards. Accordingly, the EACCL framework incorporates contextualisation as a central component of effective ICT-enabled pedagogy.

The ICT-Enhanced EACCL Framework

Building upon the preceding theoretical perspectives, this study proposes the ICT-enhanced EACCL framework as an integrated model for improving science teacher education through five complementary dimensions.

Engagement

Engagement represents teachers' ability to promote active participation through inquiry-based learning, collaborative activities, and technology-supported interaction. Digital platforms, simulations, and multimedia resources enhance learner motivation when aligned with meaningful pedagogical objectives rather than serving as isolated technological tools (Hennessy et al., 2005).

Alignment

Alignment refers to the consistency between curriculum objectives, instructional strategies, digital technologies, and assessment practices. Effective ICT integration requires technology to support intended learning outcomes and competency development rather than functioning as an independent instructional component (Anderson & Dexter, 2005).

Contextualisation

Contextualisation reflects teachers' capacity to adapt instructional strategies to local educational realities, including infrastructure, learner diversity, institutional support, and available technological resources. This dimension recognises that effective educational innovation requires responsiveness to contextual constraints rather than uniform implementation across different educational environments (World Bank, 2021; UNESCO, 2026).

Critical Thinking

Critical Thinking represents the promotion of higher-order reasoning through inquiry, evidence evaluation, scientific argumentation, and reflective problem-solving. ICT-supported learning environments encourage analytical reasoning when combined with appropriate pedagogical design and learner-centred instructional strategies (Kereluik et al., 2013; Trilling & Fadel, 2009).

Learning Outcomes

Learning Outcomes represent measurable improvements in teacher effectiveness and competency development resulting from ICT-enhanced pedagogy. Consistent with professional learning research, improved instructional practice is expected to translate into stronger classroom engagement, curriculum implementation, and development of 21st-century competencies (Darling-Hammond & Richardson, 2009; Kennedy, 2016).

Collectively, these five dimensions provide a multidimensional explanation of technology-enhanced science teacher education that integrates pedagogical quality, contextual responsiveness, and measurable educational outcomes.

Conceptual Contribution of the EACCL Framework

The principal contribution of the EACCL framework lies in its integration of technology-enhanced pedagogy with competency-based learning within a contextually responsive model for science teacher education. Existing research has largely examined ICT integration, teacher professional development, or competency development independently. In contrast, the EACCL framework conceptualises these constructs as interconnected dimensions that jointly influence pedagogical effectiveness.

The framework therefore extends previous research by demonstrating how engagement, curriculum alignment, contextual adaptation, critical thinking, and learning outcomes operate collectively within ICT-supported instructional environments. This integrated perspective provides both theoretical and practical guidance for strengthening teacher education programmes in resource-constrained settings and contributes empirical evidence relevant to SDG 4 implementation.

Methodological Approach

Research Design

This study employed a quantitative, cross-sectional survey design to examine the relationships among ICT integration, the dimensions of the proposed EACCL framework, and the development of 21st-century competencies (4Cs) among science teachers in Sindh, Pakistan. A cross-sectional design was considered appropriate because it enables the examination of relationships among multiple latent constructs at a single point in time while providing empirical evidence for theory testing. The study was grounded in the theoretical integration of pedagogical content knowledge, competency-based learning, and technology-enhanced teaching, all of which emphasise the role of ICT in improving instructional quality and teacher effectiveness (Darling-Hammond et al., 2017; Ertmer & Ottenbreit-Leftwich, 2010; Kereluik et al., 2013).

Structural Equation Modelling (SEM) was employed as the principal analytical technique because it simultaneously evaluates measurement reliability and structural relationships among latent variables. SEM is particularly appropriate for educational research involving multidimensional constructs, as it accounts for measurement error while estimating direct and indirect relationships within a theoretically specified model. This approach has been widely recommended for validating pedagogical and educational technology frameworks (Kennedy, 2016; Opfer & Pedder, 2011).

Research Setting and Participants

The study was conducted in public teacher education institutions and secondary schools located in northern Sindh, Pakistan. Participants comprised both pre-service science teachers enrolled in Bachelor of Education (B.Ed. Honours) programmes and in-service secondary science teachers actively engaged in classroom instruction. Including both groups enabled the investigation of differences in ICT-supported pedagogical practices across varying stages of professional development.

A stratified random sampling strategy was adopted to ensure proportional representation of both participant groups. The final sample consisted of 312 respondents, including 160 pre-service teachers and 152 in-service teachers. Participants represented diverse demographic backgrounds in terms of age, gender, and teaching experience, thereby enhancing the representativeness of the sample. The sample size exceeded commonly recommended thresholds for SEM, ensuring adequate statistical power and stable parameter estimation (Kennedy, 2016).

Instrument Development

Data were collected using a structured questionnaire developed from established theoretical frameworks and previous empirical studies on ICT integration, teacher professional development, and 21st-century competencies (Anderson & Dexter, 2005; Darling-Hammond et al., 2020; Ertmer & Ottenbreit-Leftwich, 2010; Trilling & Fadel, 2009). All questionnaire items were measured on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

The instrument comprised four sections. The first section gathered demographic information, including gender, age, professional status, academic qualification, and teaching experience. The second section

measured ICT integration using items assessing the pedagogical use of digital technologies in science teaching, including multimedia resources, collaborative platforms, virtual simulations, and digital assessment practices. The third section operationalised the five dimensions of the proposed EACCL framework. Engagement assessed teachers' ability to promote active participation and learner interaction. Alignment examined the coherence between instructional objectives, teaching strategies, and assessment practices. Contextualisation measured the adaptation of instructional practices to local educational conditions and available resources. Critical Thinking assessed instructional practices that encourage inquiry, analytical reasoning, and problem-solving. Learning Outcomes measured perceived improvements in teaching effectiveness and student learning associated with ICT-supported instruction (P21, 2019).

The final section measured the development of 21st-century competencies, focusing on communication, collaboration, creativity, and critical thinking. Item construction was informed by internationally recognised competency frameworks (Binkley et al., 2012; Trilling & Fadel, 2009) and adapted to the context of science teacher education in Pakistan.

Validity and Reliability

The questionnaire underwent a rigorous validation process before full-scale data collection. Content validity was established through expert evaluation by three specialists in science education, educational technology, and teacher education, who assessed the clarity, relevance, and representativeness of each item. Minor revisions were made to improve wording and contextual suitability. A pilot study involving 35 science teachers was subsequently conducted to evaluate instrument clarity and internal consistency. Feedback from the pilot resulted in minor modifications without altering the conceptual structure of the instrument. Construct validity was examined using CFA. Convergent validity was assessed through standardised factor loadings, Average Variance Extracted (AVE), and Composite Reliability (CR), following recommended thresholds of factor loadings above .60, AVE above .50, and CR above .70.

Internal consistency reliability was evaluated using Cronbach's alpha and composite reliability coefficients, with values exceeding .70 indicating acceptable reliability (Kennedy, 2016). Discriminant validity was assessed using the Fornell-Larcker criterion and the Heterotrait-Monotrait (HTMT) ratio. The measurement model demonstrated satisfactory psychometric properties across all constructs, confirming that the latent variables were both reliable and conceptually distinct.

Data Collection Procedure

Prior to data collection, ethical approval was obtained from the relevant institutional research committee, and formal permission was secured from participating teacher education institutions and secondary schools. Participation was voluntary, and all respondents received written information explaining the purpose of the study, confidentiality procedures, and their right to withdraw without penalty. Written informed consent was obtained before questionnaire administration. Data were collected over a four-month period through both paper-based and online questionnaires to maximise

response rates. Participants completed the questionnaire anonymously, and no personally identifiable information was recorded. Completed questionnaires were screened for completeness before data entry.

Data Analysis

Data analysis was conducted using IBM SPSS Statistics and AMOS. Preliminary analyses included screening for missing values, normality, multicollinearity, and outliers. Missing responses were minimal and were handled using expectation-maximisation procedures. Skewness and kurtosis values fell within acceptable ranges, indicating approximate normality. Variance Inflation Factor (VIF) values below the recommended threshold confirmed the absence of multicollinearity among predictor variables. The measurement model was first evaluated using Confirmatory Factor Analysis. Model adequacy was assessed using multiple goodness-of-fit indices, including the chi-square to degrees of freedom ratio (χ^2/df), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardised Root Mean Square Residual (SRMR). Acceptable model fit was determined using established recommendations of $\chi^2/\text{df} < 3.00$, CFI and TLI $\geq .90$, RMSEA $\leq .08$, and SRMR $\leq .08$.

Following satisfactory validation of the measurement model, Structural Equation Modelling was employed to test the hypothesised relationships among ICT integration, the EACCL dimensions, and the development of 21st-century competencies. Standardised path coefficients, critical ratios, and significance levels were examined to evaluate the proposed hypotheses. Statistical significance was determined at the .05 level. To examine differences between pre-service and in-service teachers, multi-group SEM was conducted following sequential tests of configural, metric, and scalar invariance. Changes in Comparative Fit Index ($\Delta\text{CFI} \leq .01$) were used to determine measurement invariance across groups. Structural path comparisons were subsequently performed to identify differences in ICT-supported pedagogical practices between the two groups.

Ethical Considerations: The study complied with recognised ethical standards for educational research. Participation was entirely voluntary, and respondents provided informed consent before completing the questionnaire. Confidentiality and anonymity were maintained throughout the research process, and all collected data were stored securely for research purposes only. Participants were informed of their right to withdraw from the study at any stage without consequence. The research adhered to institutional ethical guidelines concerning participant protection, privacy, and responsible data management.

Results

This section presents the empirical findings of the study. The analyses were conducted to evaluate the psychometric properties of the ICT-enhanced EACCL framework and to examine the relationships among its dimensions, ICT integration, pedagogical effectiveness, and the development of 21st-century competencies (4Cs). The results are organised into participant characteristics, descriptive statistics, reliability and validity assessment, structural model evaluation, hypothesis testing, and multi-group comparisons between pre-service and in-service science teachers.

Participant Characteristics: A total of **312 science teachers** participated in the study, comprising **162 pre-service teachers (51.9%)** enrolled in Bachelor of Education programmes and **150 in-service secondary science teachers (48.1%)** from public schools in Sindh. Male participants represented **53.8% (n = 168)** of the sample, while **46.2% (n = 144)** were female. Among the in-service teachers, **42.7%** had between one and five years of teaching experience, **34.0%** had six to ten years, and **23.3%** had more than ten years of experience (see Table 1).

Table 1
Participant Characteristics (N = 312)

Variable	Category	n	%
Professional Status	Pre-service	162	51.9
	In-service	150	48.1
Gender	Male	168	53.8
	Female	144	46.2
Teaching Experience (In-service)	1–5 years	64	42.7
	6–10 years	51	34.0
	11 + years	35	23.3

The sample size exceeded recommended requirements for structural equation modelling and provided adequate statistical power for confirmatory factor analysis and multi-group comparisons.

5.2 Descriptive Statistics: Table 2 summarises the descriptive statistics for the EACCL dimensions and the 4Cs competency construct. Mean scores ranged from **3.41 to 3.87**, indicating generally positive perceptions of ICT-supported pedagogical practices.

Table 2
Descriptive Statistics

Construct	Mean	SD	Minimum	Maximum
Engagement	3.87	0.62	2.10	5.00
Alignment	3.79	0.58	2.25	4.95
Contextualisation	3.41	0.71	1.95	4.80
Critical Thinking	3.74	0.64	2.00	5.00
Learning Outcomes	3.68	0.60	2.15	4.90
Creativity	3.55	0.67	1.90	4.95
Communication	3.82	0.59	2.30	5.00
Collaboration	3.77	0.63	2.10	4.95
Overall 4Cs	3.71	0.54	2.25	4.90

Engagement recorded the highest mean among the EACCL dimensions, whereas Contextualisation showed comparatively lower scores and greater variability. Among the 4Cs, Communication achieved the highest mean score.

5.3 Reliability and Measurement Model Assessment: Internal consistency was evaluated using Cronbach's alpha, Composite Reliability (CR), and Average Variance Extracted (AVE). As shown in Table 3, all Cronbach's alpha and CR values exceeded **0.70**, while AVE values were above **0.50**, indicating satisfactory reliability and convergent validity.

Table 3
Reliability and Convergent Validity

Construct	α	CR	AVE
Engagement	.89	.91	.64
Alignment	.86	.88	.60
Contextualisation	.81	.84	.57
Critical Thinking	.90	.92	.67
Learning Outcomes	.84	.87	.58
Overall 4Cs	.91	.93	.69

These results satisfy recommended psychometric criteria for latent construct measurement.

Confirmatory Factor Analysis: Confirmatory Factor Analysis (see Table 4) was performed to validate the proposed five-factor EACCL framework. The model demonstrated satisfactory overall fit.

Table 4
Confirmatory Factor Analysis Model Fit

Fit Index	Value	Recommended Threshold
χ^2/df	2.41	< 3.00
CFI	.93	≥ .90
TLI	.92	≥ .90
RMSEA	.067	≤ .08
SRMR	.054	≤ .08

Standardised factor loadings ranged from 0.65 to 0.89 and were statistically significant ($p < .001$), supporting the construct validity of the measurement model.

Correlation Analysis: As mentioned in Table 5, Pearson correlation coefficients were calculated to examine associations among the latent constructs.

Table 5
Correlation Matrix

Variable	ENG	ALI	CON	CT	LO	4Cs
Engagement	1					
Alignment	.62**	1				
Contextualisation	.48**	.53**	1			
Critical Thinking	.67**	.59**	.51**	1		
Learning Outcomes	.60**	.65**	.55**	.63**	1	
Overall 4Cs	.71**	.64**	.52**	.76**	.68**	1

Note: $p < .01$. All EACCL dimensions were positively associated with the 4Cs competencies. Critical Thinking demonstrated the strongest correlation with Overall 4Cs ($r = .76$, $p < .01$), followed by Engagement ($r = .71$, $p < .01$), indicating that higher-order pedagogical practices were associated with stronger competency development.

Structural Equation Modelling and Hypothesis Testing: Structural Equation Modelling was employed to examine the hypothesised relationships among the EACCL dimensions, ICT integration, and the development of 4Cs competencies (refer to Table 6).

Table 6
Structural Path Estimates

Structural Path	β	SE	CR	p
Engagement → 4Cs	.28	.05	5.41	< .001
Alignment → 4Cs	.19	.06	3.22	.001
Contextualisation → 4Cs	.11	.05	2.04	.042
Critical Thinking → 4Cs	.36	.05	6.87	< .001
Learning Outcomes → 4Cs	.17	.06	2.98	.003

Model statistics indicated a substantial explanatory effect ($R^2 = .64$; Adjusted $R^2 = .63$; $F(5,306) = 108.52$, $p < .001$), demonstrating that the EACCL framework explained approximately 64% of the variance in 21st-century competencies. Critical Thinking emerged as the strongest predictor of competency development ($\beta = .36$, $p < .001$), followed by Engagement ($\beta = .28$, $p < .001$). Alignment and Learning Outcomes also demonstrated significant positive effects, whereas Contextualisation showed a comparatively smaller but statistically significant contribution. These findings provide empirical support for the alternative hypothesis (H_1) that the EACCL framework is positively associated with the development of 21st-century competencies, leading to the rejection of the null hypothesis (H_0).

5.7 Multi-Group Comparison

To address Research Question 3, differences between pre-service and in-service teachers were examined (see Table 7).

Table 7
Group Differences

Variable	Pre-service (M ± SD)	In-service (M ± SD)	t	p	Cohen's d
Engagement	3.94 ± 0.59	3.80 ± 0.64	2.21	.028	0.23
Alignment	3.65 ± 0.61	3.95 ± 0.52	-4.52	< .001	0.52
Contextualisation	3.38 ± 0.74	3.45 ± 0.68	-0.86	.392	0.10
Critical Thinking	3.71 ± 0.66	3.78 ± 0.61	-1.02	.309	0.11
Learning Outcomes	3.54 ± 0.63	3.83 ± 0.54	-4.38	< .001	0.49
Overall 4Cs	3.69 ± 0.56	3.73 ± 0.51	-0.73	.467	0.07

In-service teachers reported significantly higher scores for Alignment and Learning Outcomes, whereas pre-service teachers showed slightly higher Engagement scores. No statistically significant differences were observed for Contextualisation, Critical Thinking, or Overall 4Cs competencies. These findings

suggest that professional experience contributes primarily to curriculum alignment and perceived instructional effectiveness rather than to overall competency development.

Summary of Findings: Overall, the findings support the proposed ICT-enhanced EACCL framework. The measurement model demonstrated satisfactory reliability, convergent validity, and overall model fit. Positive and statistically significant relationships were observed between the EACCL dimensions and the development of 21st-century competencies, with Critical Thinking emerging as the strongest predictor. The structural model explained a substantial proportion of variance in competency development, providing support for the study's theoretical assumptions and the alternative hypothesis. Group comparisons further indicated that although pre-service and in-service teachers differed in selected pedagogical dimensions, both groups exhibited comparable levels of overall 4Cs competencies. Collectively, these findings address the three research questions by demonstrating that the EACCL framework contributes to competency development, that ICT-supported pedagogy is positively associated with pedagogical effectiveness, and that some differences exist between pre-service and in-service teachers in specific pedagogical practices.

Discussion

Interpretation of the Main Findings

This study investigated the relationships among the ICT-enhanced EACCL framework dimensions, ICT integration, and the development of 21st-century (4Cs) competencies in science teacher education within the context of Sindh, Pakistan. Overall, the findings provide empirical support for the proposed framework and demonstrate that pedagogical quality is strengthened when technology integration is combined with learner engagement, curriculum alignment, contextual responsiveness, and higher-order thinking. The measurement model exhibited satisfactory reliability and construct validity, while the structural analyses confirmed significant positive relationships among the EACCL dimensions and 4Cs competencies. Consequently, the null hypothesis (H_0) was rejected, and the alternative hypothesis (H_1) was accepted, indicating that the EACCL framework is positively associated with the development of 21st-century competencies among science teachers.

These findings also address the three research questions. First, the study confirms that the ICT-enhanced EACCL framework significantly contributes to the development of creativity, critical thinking, communication, and collaboration (RQ1). Second, ICT integration was found to positively influence pedagogical effectiveness when embedded within coherent instructional practices rather than being implemented as an isolated technological intervention (RQ2). Third, significant differences between pre-service and in-service teachers were observed in selected pedagogical dimensions, particularly Alignment and Learning Outcomes, although both groups demonstrated comparable orientations towards competency-based teaching (RQ3). Collectively, these findings suggest that improving science teacher education requires an integrated pedagogical approach that combines technology with curriculum coherence, contextual adaptation, and professional competence.

EACCL Framework and the Development of 4Cs Competencies (RQ1; H₁)

The strongest evidence emerging from this study concerns the relationship between the EACCL framework and the development of 21st-century competencies. Correlation and regression analyses demonstrated that all five EACCL dimensions were positively associated with overall 4Cs competencies, providing direct empirical support for the proposed framework. Among these dimensions, Critical Thinking emerged as the strongest predictor of competency development, followed by Engagement and Alignment. These findings indicate that effective science teacher education extends beyond technology adoption and depends fundamentally on instructional approaches that cultivate inquiry, analytical reasoning, and active learner participation.

The prominence of Critical Thinking is consistent with contemporary competency frameworks, which identify higher-order cognitive processes as the foundation for creativity, communication, and collaboration (Binkley et al., 2012; Trilling & Fadel, 2009). Within science education, inquiry-based learning requires teachers to facilitate evidence-based reasoning, hypothesis testing, and reflective problem-solving, thereby strengthening transferable competencies required for lifelong learning. Similarly, Engagement demonstrated a significant contribution to competency development, suggesting that interactive pedagogies encourage deeper participation and collaborative knowledge construction. These findings support constructivist perspectives that view active learner involvement as essential for meaningful learning and skill acquisition (Bellanca & Brandt, 2010; Dede, 2010).

Alignment also emerged as a significant predictor, emphasising the importance of coherence among curriculum objectives, instructional strategies, and assessment practices. Competency-based education requires learning activities and assessment methods to be explicitly aligned with intended outcomes. The present findings therefore reinforce previous research demonstrating that curriculum alignment enhances instructional effectiveness and supports sustainable improvements in teaching quality (Darling-Hammond & Richardson, 2009; Kennedy, 2016). Collectively, these results provide strong evidence in support of H₁ and directly answer RQ1 by demonstrating that the EACCL framework offers a valid pedagogical model for strengthening 4Cs competencies in science teacher education.

ICT Integration and Pedagogical Effectiveness (RQ2)

The study further demonstrates that ICT integration contributes positively to pedagogical effectiveness when implemented within an instructional framework that emphasises engagement, alignment, contextualisation, and critical thinking. Rather than functioning as an independent predictor of educational quality, ICT operated as a pedagogically embedded resource that strengthened learning experiences through interactive instruction, collaborative activities, and inquiry-based learning. This finding reinforces the theoretical position that technology should support pedagogical transformation rather than simply digitise traditional teaching practices.

These results are consistent with studies highlighting that successful technology integration depends on teachers' pedagogical competence, confidence, and professional readiness rather than the mere

availability of digital resources (Ertmer & Ottenbreit-Leftwich, 2010; Anderson & Dexter, 2005). Similarly, Hew and Brush (2007) argued that institutional support, teacher beliefs, and sustained professional development remain critical determinants of effective ICT implementation. Within teacher education, Al-Bizri (2017) further demonstrated that meaningful ICT integration requires policy coherence, pedagogical preparation, and supportive institutional environments.

The findings also reflect the realities of Pakistani education, where ICT adoption continues to be constrained by infrastructural limitations, unequal access to technology, and insufficient professional development opportunities (Aslam et al., 2021; Raza et al., 2020). Consequently, the present study suggests that investments in educational technology should be accompanied by systematic teacher training and curriculum reform to maximise pedagogical impact. These findings directly address RQ2 by confirming that ICT enhances pedagogical effectiveness only when integrated within coherent and competency-oriented instructional practices.

Differences between Pre-service and In-service Teachers (RQ3)

The comparative analysis between pre-service and in-service teachers provides further insight into the developmental nature of technology-enhanced pedagogy. In-service teachers reported significantly higher scores in Alignment and Learning Outcomes, whereas pre-service teachers demonstrated slightly higher levels of Engagement. No statistically significant differences were observed in overall 4Cs competencies, indicating that both groups shared comparable orientations towards competency-based instruction despite differences in pedagogical experience.

Higher Alignment scores among in-service teachers likely reflect the influence of classroom experience, which enables teachers to connect curriculum objectives, instructional methods, and assessment practices more effectively. Similarly, stronger Learning Outcomes among practising teachers may be attributed to opportunities for reflective practice, continuous professional learning, and repeated instructional implementation. These findings are consistent with professional learning research, which emphasises that pedagogical expertise develops progressively through sustained experience and reflective practice (Avalos, 2011; Kennedy, 2016; Darling-Hammond et al., 2017).

Conversely, the slightly higher Engagement scores reported by pre-service teachers may reflect recent exposure to learner-centred instructional approaches within contemporary teacher education programmes. However, translating these innovative strategies into coherent classroom practice often requires practical teaching experience and institutional support. Alvi and Gillies (2021) similarly reported that effective professional learning enables teachers to bridge the gap between theoretical preparation and classroom implementation. Therefore, while both groups recognise the value of competency-based instruction, their pedagogical strengths differ according to professional experience. These findings provide a direct answer to RQ3 and support the need for continuous professional development across all stages of teacher education.

Theoretical Implications

The present study makes several theoretical contributions to science teacher education and technology-enhanced learning. First, it provides empirical validation of the EACCL framework as a multidimensional pedagogical model that integrates engagement, curriculum alignment, contextual responsiveness, critical thinking, and measurable learning outcomes within a single conceptual structure. Unlike frameworks that conceptualise ICT primarily as a technological intervention, the EACCL model positions technology as an enabling mechanism embedded within broader pedagogical processes.

Second, the findings extend pedagogical content knowledge perspectives by demonstrating that effective science teaching depends not only on disciplinary expertise but also on the integration of instructional design, contextual adaptation, and higher-order cognitive engagement. The framework therefore complements competency-based learning theories by linking pedagogical processes directly to measurable improvements in 4Cs competencies. Finally, the study contributes to SDG-4 scholarship by providing empirical evidence that contextualised, technology-enhanced teacher education can support quality education in resource-constrained environments.

Practical and Policy Implications

The findings have important implications for teacher education policy and practice in Pakistan. Teacher preparation programmes should move beyond technical ICT training and instead integrate technology within pedagogically coherent instructional models that emphasise inquiry, collaboration, curriculum alignment, and competency-based assessment. Similarly, professional development initiatives should provide sustained opportunities for teachers to strengthen both digital competence and pedagogical decision-making.

At the institutional level, universities and teacher education providers should embed the EACCL framework within curriculum design, teaching practice, and assessment processes. Educational policymakers may also utilise the framework to strengthen implementation of Pakistan's educational reforms by aligning teacher preparation with competency-based learning objectives and ICT integration strategies. Such reforms support the national commitments outlined in the Pakistan SDG-4 Midterm Review (Pakistan Institute of Education, 2023), the Federal Education Policy 2026, and UNESCO's Global Education Monitoring reports (UNESCO, 2024), all of which emphasise improving teaching quality through technology-enabled and learner-centred approaches.

Implications for Science Teacher Education in Pakistan

The contextual focus on Sindh provides important insights for improving science teacher education in resource-constrained educational systems. Persistent disparities in ICT infrastructure, institutional resources, and professional learning opportunities continue to influence instructional quality across Pakistani schools (World Bank, 2021; Aslam et al., 2021). The present findings demonstrate that technology investments alone are unlikely to produce meaningful improvements unless accompanied by curriculum alignment, contextual adaptation, and sustained teacher professional development.

The validated EACCL framework therefore offers a practical model for strengthening science teacher preparation in similar educational contexts. By integrating pedagogical innovation with contextual responsiveness, the framework provides teacher educators and policymakers with an evidence-based approach for improving instructional quality while advancing national commitments to SDG-4. Its emphasis on measurable learning outcomes also supports accountability and continuous improvement within teacher education programmes.

Overall Interpretation

Overall, the findings confirm that the ICT-enhanced EACCL framework provides a robust explanatory model for understanding competency-oriented science teacher education. The significant relationships among Engagement, Alignment, Contextualisation, Critical Thinking, Learning Outcomes, ICT integration, and 4Cs competencies demonstrate that effective pedagogy requires an integrated rather than fragmented approach to instructional improvement. The rejection of H_0 and acceptance of H_1 provide empirical support for the framework, while the findings comprehensively address the three research questions by demonstrating the positive contribution of EACCL to competency development, pedagogical effectiveness, and technology-enabled teaching practices. Consequently, the framework offers a theoretically grounded and empirically validated model that can guide future research, teacher education reform, and policy development aimed at strengthening science education and advancing Sustainable Development Goal 4 in Pakistan and comparable Global South contexts (refer to Fig. 3).

Conclusion

This study developed and empirically validated the ICT-enhanced EACCL framework as a contextually responsive model for improving science teacher education in support of SDG 4. Drawing on data from pre-service and in-service science teachers in Sindh, Pakistan, the study demonstrated that the framework provides a coherent explanation of how ICT-supported pedagogical practices contribute to pedagogical effectiveness and the development of 21st-century competencies. The findings confirmed that the EACCL dimensions are conceptually distinct yet interrelated, offering a robust structure for understanding quality science teaching in resource-constrained educational settings.

The empirical evidence supported the alternative hypothesis by demonstrating statistically significant positive relationships between the EACCL dimensions and the development of 4Cs competencies. Among the framework components, Critical Thinking emerged as the strongest predictor of pedagogical effectiveness and competency development, followed by Engagement and Alignment, highlighting the importance of higher-order cognitive processes, active learning, and curriculum coherence in science teacher education. Although Contextualisation exhibited a comparatively modest direct effect, it differentiated pre-service and in-service pedagogical practices, emphasising that effective ICT integration depends not only on technological availability but also on teachers' ability to adapt instructional approaches to local educational realities.

The study also addressed the three research questions. First, the findings demonstrated that the ICT-enhanced EACCL framework positively supports the development of the 4Cs competencies by integrating engagement, critical thinking, curriculum alignment, and context-responsive pedagogy. Second, significant positive relationships were identified between ICT integration and pedagogical effectiveness, reinforcing the argument that technology contributes meaningfully to instructional quality when embedded within coherent pedagogical practices rather than treated as an isolated technical intervention. Third, statistically significant differences between pre-service and in-service teachers were observed in curriculum alignment and learning outcomes, indicating that professional experience strengthens teachers' capacity to translate technology-supported pedagogical knowledge into effective classroom practice.

Beyond addressing the research questions, this study contributes theoretically by extending competency-based and technology-enhanced learning perspectives through the introduction of the EACCL framework. Rather than focusing solely on ICT adoption, the framework conceptualises technology integration as part of a broader pedagogical system that connects engagement, curriculum coherence, contextual responsiveness, critical thinking, and measurable learning outcomes. This integrated perspective provides a practical mechanism for operationalising SDG 4 within science teacher education and offers an empirically validated model that is responsive to the challenges faced by educational systems in the Global South.

The study further contributes to educational policy and practice by providing evidence that improving science teacher quality requires sustained investment in pedagogically focused ICT integration, curriculum alignment, and continuous professional learning. These findings support recent national and international policy priorities that emphasise teacher quality, digital competence, and competency-based education as essential components of educational reform (Pakistan Institute of Education, 2023; UNESCO, 2024; United Nations, 2023). For countries facing infrastructural and resource constraints, the EACCL framework offers a scalable and evidence-informed approach for strengthening teacher preparation programmes and professional development initiatives.

Despite these contributions, the findings should be interpreted within the study's methodological scope. The cross-sectional design limits causal inference, while the reliance on self-reported data may introduce response bias. Future research should therefore employ longitudinal and experimental designs to examine the long-term impact of the EACCL framework on classroom practice and student achievement. Further validation across different educational levels, disciplines, and geographical contexts would also strengthen the framework's generalisability and policy relevance.

Overall, this study demonstrates that achieving quality science education under SDG 4 requires more than increasing access to digital technologies. Sustainable improvement depends on integrating ICT within coherent pedagogical frameworks that cultivate critical thinking, active engagement, curriculum alignment, and context-sensitive teaching. The validated ICT-enhanced EACCL framework therefore provides a theoretically grounded, empirically supported, and practically applicable model for advancing

science teacher education and strengthening 21st-century competencies in resource-constrained educational contexts.

Declarations

Competing Interests:

The author declares that they has no known financial or personal competing interests that could have appeared to influence the work reported in this paper.

Ethics Approval:

This study was reviewed and approved by the Institutional Review Board of the Sukkur IBA University having letter No: IRB-136-2025/SIBAU, dated 3rd of March 2025. All the 312 research participants were provided informed consent prior to participation. Officials of the School Education and Literacy Department (SELD) Government of Sindh were also approached for seeking formal permission prior to starting the data collection process.

Funding:

This manuscript hasn't received any funding.

Author Contribution

This entire manuscript has been drafted, revised, and finalised by the corresponding author Dr Raja Bahar Khan Soomro

Data Availability:

The dataset used and/or analysed during the current study is available from the corresponding author on request.

References

1. Al-Bizri N (2017) Integrating ICT in teacher education: Policy and practice. *Educ Inform Technol* 22(2):467–483
2. Alvi E, Gillies RM (2021) Professional development that makes a difference: Pakistani teachers' perspectives on effective professional learning. *Prof Dev Educ* 47(4):652–666

3. Anderson J, Dexter S (2005) Teacher technology use and preparation. *J Educational Comput Res* 32(3):21–38
4. Aslam R, Khan N, Ahmed J (2021) Barriers to secondary school teachers' integration of ICT in Pakistan: A regional policy perspective. *Int J Educational Dev*, 84, Article 102424.
5. Avalos B (2011) Teacher professional development research: Learning from the past and for the future. *Teach Teacher Educ* 27(1):10–20
6. Bellanca J, Brandt R (eds) (2010) 21st century skills: Rethinking how students learn. Solution Tree Press
7. Binkley M, Erstad O, Herman J, Raizen S, Ripley M, Miller-Ricci M, Rumble M (2012) Defining 21st-century skills. In: Griffin P, McGaw B, Care E (eds) *Assessment and teaching of 21st century skills*. Springer, pp 17–66
8. Boix Mansilla V, Jackson A (2011) Educating for global competence: Preparing our youth to engage the world. Asia Society
9. C2020 Partnership (2011) Framework for 21st century learning. Battelle for Kids
10. Darling-Hammond L, Flook L, Cook-Harvey C, Barron B, Osher D (2020) Implications for educational practice of the science of learning and development. *Educational Researcher* 49(2):97–140
11. Darling-Hammond L, Hyler ME, Gardner M (2017) Effective teacher professional development. Learning Policy Institute
12. Darling-Hammond L, Richardson N (2009) Teacher learning: What matters? *Educational Leadersh* 66(5):46–53
13. Day C, Gu Q (2014) Responding to the human crises in classrooms: Teacher emotions and professional practice in SDG contexts. *J Educ Change* 15(4):347–365
14. Dede C (2010) Comparing frameworks for 21st-century skills. In: Bellanca J, Brandt R (eds) *21st century skills: Rethinking how students learn*. Solution Tree Press, pp 51–76
15. Ertmer PA, Ottenbreit-Leftwich AT (2010) Teacher technology change: How knowledge, confidence, beliefs, and culture intersect. *J Res Technol Educ* 42(3):255–284
16. Guskey TR (2002) Professional development and teacher change. *Teachers Teach* 8(3):381–391
17. Hennessy S, Ruthven K, Brindley S (2005) Teacher perspectives on integrating ICT into subject teaching: Commitment, constraints, caution, and change. *J Comput Assist Learn* 21(2):85–97
18. Hew KF, Brush T (2007) Integrating technology into K–12 teaching and learning: Current knowledge gaps and recommendations for future research. *Education Tech Research Dev* 55(3):223–252
19. Kazlauskas A (2018) Digital competences of teacher educators. *Educ Inform Technol* 23(2):537–551
20. Kennedy MM (2016) How professional development improves teaching. *Rev Educ Res* 86(4):945–980
21. Kereluik K, Mishra P, Fahnoe C, Terry L (2013) What knowledge is of most worth: Teacher knowledge for 21st century learning. *J Digit Learn Teacher Educ* 29(4):127–140

22. Kimmons R, Hall T (2016) Mapping educators' 21st-century skills and technology use. *TechTrends* 60(5):494–501
23. Ministry of Federal Education and Professional Training (2026) Federal education policy 2026: Sustained transformation of education networks. Government of Pakistan
24. National Commission on the Rights of Child (2025) State of children 2025: Assessing pedagogical metrics and infrastructure inequalities across primary and secondary networks in Pakistan. NCRC
25. Opfer VD, Pedder D (2011) Conceptualizing teacher professional learning. *Educational Res Rev* 6(3):297–308
26. P21 (Partnership for 21st Century Learning) (2019) Framework for 21st century learning definitions. Battelle for Kids
27. Pakistan Institute of Education (2023) SDG-4 midterm review Pakistan. Ministry of Federal Education and Professional Training
28. Raza SA, Qazi W, Umer B (2020) Examining the barriers to laptop adoption and ICT integration in Pakistani schools: Evidence from a developing country. *J Educational Comput Res* 58(7):1324–1352
29. Timperley H (2011) Realizing the power of professional learning. McGraw-Hill Education
30. Trilling B, Fadel C (2009) 21st century skills: Learning for life in our times. Jossey-Bass
31. UNESCO (2024) Global education monitoring report 2024: Technology in education—A tool on whose terms? UNESCO Digital Library
32. UNESCO (2026) Bridging the equity gap: Addressing out-of-school children in Pakistan — 2026 UNESCO global education monitoring (GEM) report. UNESCO Digital Library
33. UNESCO Institute for Statistics (2023) Sustainable Development Goal 4 (SDG 4) indicators data dashboard: Assessment of institutional teacher quality updates. UIS Global Databases
34. UNICEF (2023) Review of early childhood education (ECE) models in Pakistan: Tracking systematic pre-service and in-service training capacities. UNICEF South Asia Core Repository
35. United Nations (2023) The Sustainable Development Goals report 2023: Special edition—Towards a rescue plan for people and planet. United Nations Department of Economic and Social Affairs
36. Winthrop R, McGivney E (2016) Education and technology in developing contexts. Brookings Institution
37. World Bank (2021) Improving education quality in Sindh. World Bank Report Series No. 159312. World Bank Open Knowledge Repository
38. World Bank (2024) *The state of global education learning poverty: Post-pandemic intervention strategies for South Asia*. World Bank Policy Research Working Papers
39. Zeichner KM (2010) Teacher education and the struggle for social justice. Routledge

Figures

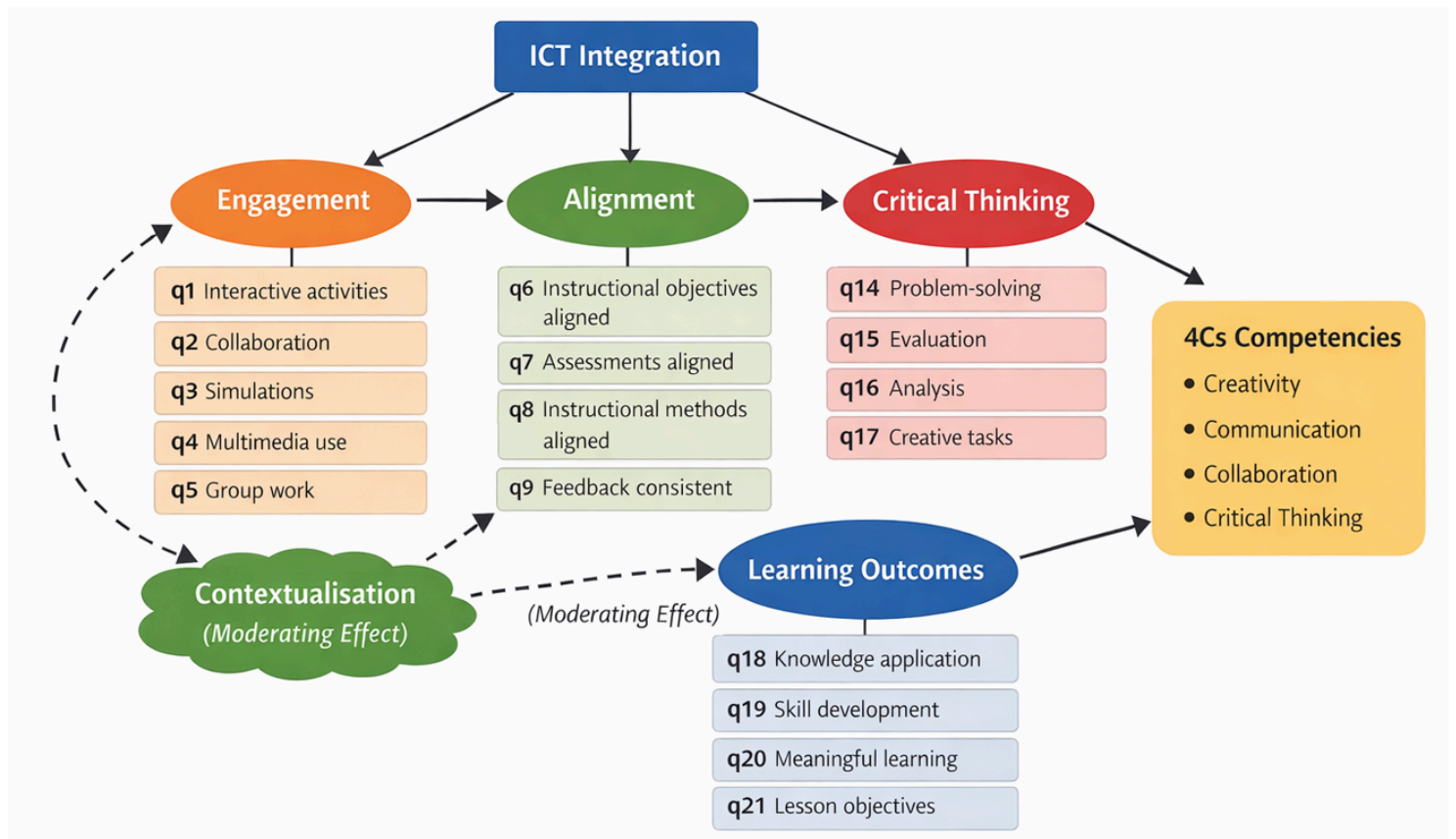
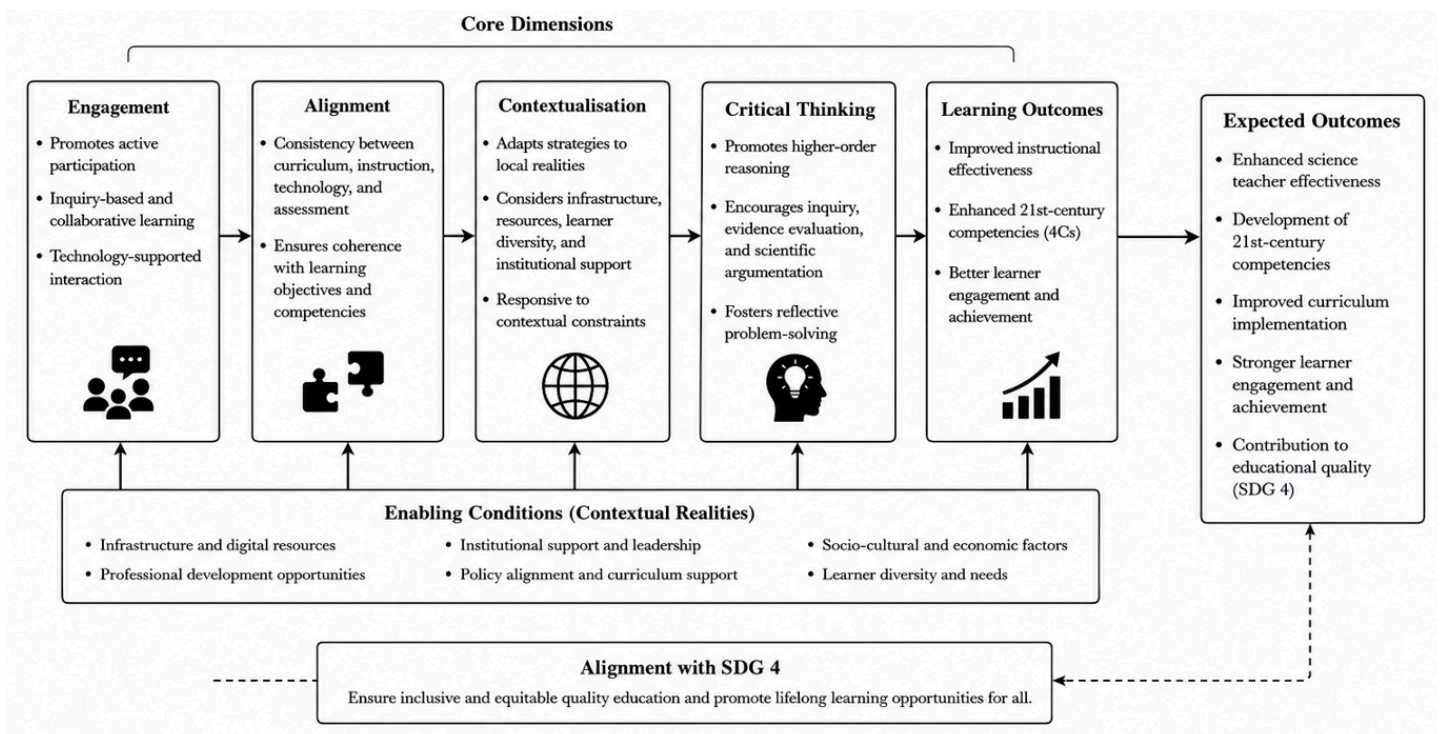


Figure 1

ICT-Enhanced EACCL conceptual framework diagram



Theoretical and Conceptual Framework of the Study



Page 29/29