Sustainable Futures 12 (2026) 101965

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

# Quantum literacy for sustainable futures: An evidence-based competency framework for equitable secondary education

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ARTICLE INFO

*Keywords:*
Sustainable development goals
Quantum literacy
Educational equity
Technology divide
SDG 4 quality education
Climate technology education
Innovation capacity building
Global south STEM
Quantum technologies

ABSTRACT

Quantum technologies are rapidly transitioning from laboratory research into transformational tools for addressing sustainability challenges, yet 85% of secondary students in developing nations lack access to foundational quantum education, risking a new "quantum divide" that threatens equitable development. This study develops an evidence-based competency framework for integrating quantum literacy into secondary education as infrastructure for achieving the UN Sustainable Development Goals (SDGs). Through a systematic Scopus AI-powered synthesis of quantum education literature spanning 15 countries and 75 targeted queries across 12 thematic categories, we constructed an eight-domain competency framework mapping quantum principles to quantified sustainability impacts. The framework proposes three adaptable implementation pathways – infusion, modular, and integrated – supported by teacher professional development models requiring 40–120 training hours. Case studies from the Philippines, South Africa, and Brazil demonstrate the feasibility of each pathway across diverse resource contexts, with documented outcomes including 73% improvement in conceptual understanding and 89% programme completion rates. Empirical evidence from quantum informatics instruction in Ukrainian secondary schools further validates the framework's pedagogical foundations. The study contributes to educational theory by reconceptualising quantum literacy as sustainable development infrastructure, and to policy by providing an equity-focused roadmap that prioritises South-South cooperation and open-source resources. These findings have implications for curriculum reform, teacher education policy, and international development strategies targeting SDG 4 (Quality Education) and SDG 9 (Innovation and Infrastructure).

## 1. Introduction

Quantum technologies are transitioning from experimental physics into transformational infrastructure with the potential to address humanity's most complex sustainable development challenges [1,2]. Unlike the steady, multi-decade evolution of classical digital computing, the current technological trajectory of quantum technologies is characterised by unprecedented speed and scale [3,4]. Quantum computing can solve optimisation problems with $10^{100}$ possible configurations – problems that would take classical computers millennia to solve – in hours or days [5,6]. This computational leap translates directly into sustainability outcomes: quantum-optimised renewable energy grids demonstrate 30%–40% efficiency improvements, directly supporting SDG 7 (Affordable and Clean Energy) through enhanced integration of sustainable energy sources [7,8]; quantum-enhanced drug discovery reduces development timelines from 15 years to 5–7 years with 60% lower resource consumption, and quantum climate models achieve

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https://doi.org/10.1016/j.sftr.2026.101965
Received 12 December 2025; Received in revised form 14 April 2026; Accepted 4 June 2026
Available online 12 June 2026
2666-1888/

**Table 1**
Quantum technologies for sustainable development: Evidence-based applications and impacts.

| SDG domain | Specific quantum application | Quantified sustainability impact | Development stage | Educational implications | Evidence |
|---|---|---|---|---|---|
| **SDG 3** Health | Quantum machine learning for drug-target interaction | 94.21% accuracy in predictions; 60% reduction in discovery time | QTRL 5–6 (2025–2027 deployment) | Quantum algorithms, molecular modelling, data analysis | [9,12] |
| **SDG 6** Clean Water | Quantum sensors for water pollutant detection | Parts-per-trillion detection; 100x sensitivity improvement | QTRL 7–8 (deployed in pilots) | Quantum sensing principles, environmental chemistry | [14,15] |
| **SDG 7** Clean Energy | Quantum optimisation for smart grid management | 30%–40% efficiency gains; 50% reduction in outages | QTRL 6–7 (commercial pilots) | Optimisation algorithms, energy systems | [7,8] |
| **SDG 9** Innovation | Quantum cryptography for secure infrastructure | Unconditional security; deployed in 20+ countries | QTRL 8–9 (operational) | Cryptographic principles, network security | [18,19] |
| **SDG 11** Cities | Quantum computing for traffic optimisation | 25% reduction in congestion; 15% lower emissions | QTRL 5–6 (pilot testing) | Urban systems modelling, algorithms | [17,20] |
| **SDG 13** Climate | Quantum-enhanced climate modelling | 40% accuracy improvement; 2x longer prediction window | QTRL 5–6 (research deployment) | Climate science, computational methods | [10,11] |
| **SDG 14** Oceans | Quantum sensors for ocean monitoring | Real-time pH and temperature at depth; autonomous operation | QTRL 6–7 (field testing) | Marine science, sensor technology | [15,21] |
| **SDG 15** Land | Quantum computing for biodiversity modelling | 10x faster species interaction modelling; improved conservation planning | QTRL 4–5 (research phase) | Ecological modelling, data science | [5,10] |

unprecedented accuracy in extreme weather prediction with lead times extended from 7 to 14 days [7,9,10]. For example, recent advances demonstrate quantum computing's capacity to accelerate climate modelling by up to 40% in accuracy while reducing computational time from months to days, enabling more precise predictions of extreme weather events and optimised mitigation strategies [10,11]. In drug discovery, quantum machine learning algorithms have achieved 94.21% accuracy in drug-target interaction predictions, potentially reducing the timeline for sustainable pharmaceutical development from decades to years while minimising resource consumption [9,12,13].

These applications represent more than incremental technological improvements; they offer pathways to transformative solutions for sustainable development. Quantum sensors with unprecedented precision enable detection of pollutants at parts-per-trillion levels, supporting SDG 6 (Clean Water) and SDG 15 (Life on Land) through enhanced environmental monitoring [14,15]. Quantum-enhanced climate models are improving disaster preparedness and resource allocation, with direct implications for SDG 13 (Climate Action) and SDG 11 (Sustainable Cities) [5,10]. The integration of quantum computing with artificial intelligence and blockchain technologies creates synergistic effects, enabling secure, scalable solutions for smart cities and sustainable supply chains [16,17]. Table 1 presents evidence-based quantum technology applications mapped to specific Sustainable Development Goals, with quantified impacts, development stages, and educational requirements derived from Scopus AI synthesis of recent literature. Critically, these technologies address interconnected sustainability challenges rather than isolated problems. Quantum-enhanced climate models feed into quantum-optimised disaster response systems, which inform quantum-secured emergency communications networks. This systemic impact amplifies the importance of quantum literacy – understanding one application domain requires comprehension of the broader quantum ecosystem. The integration of quantum computing with artificial intelligence and blockchain technologies further extends this impact, creating quantum–classical hybrid systems that leverage the strengths of both paradigms for maximum sustainability benefit [16,17].

Unlike the gradual evolution of digital computing over decades, quantum technologies are advancing from laboratory to application at unprecedented speed, with global investment exceeding $25 billion annually and projected to reach $125 billion by 2030 [22,23]. However, the current maturity of these technologies varies significantly, requiring careful differentiation between deployed systems and developmental technologies. Using the Quantum Technology Readiness Level (QTRL) framework, we can categorise applications from QTRL 1 (basic principles observed) to QTRL 9 (operational deployment) [24]. Post-quantum cryptography has reached QTRL 8-9 with NIST standardisation complete and implementation underway globally. Quantum sensing for gravitational wave detection operates at QTRL 9 in facilities like LIGO. Quantum optimisation for logistics and finance functions at QTRL 6-7, with commercial pilots by IBM, Google, and D-Wave demonstrating practical advantages. Drug discovery applications using quantum simulation remain at QTRL 4-5, requiring 5–10 more years for clinical deployment [12,18,25].

Understanding these rapid developments requires situating them within broader theories of technological evolution. Research on technological trajectories demonstrates that quantum technologies follow characteristic S-shaped growth patterns, with the field currently in an acceleration phase driven by converging innovations in computing, sensing, and communication [3,4]. Patent analysis reveals pathbreaking directions in quantum computing technology that signal imminent transition from research to industrial deployment [26], while the convergence of artificial intelligence and quantum technologies produces accelerated growth effects that amplify both fields' developmental trajectories [27]. Studies of quantum technology research field variability show that newer subfields such as quantum sensing exhibit greater topical diversity, suggesting broader evolutionary pathways and expanded application potential [28]. The emergence of disruptive innovations in quantum technologies is already generating measurable economic and social change [2], with evolutionary analysis indicating that quantum technologies have entered a phase characterised by rapid diversification and increasing industrial relevance [1]. These dynamics of technological evolution underscore that educational systems must respond proactively rather than reactively to quantum advances, as the window for preparation narrows with each technological milestone.

The relationship between technological literacy and sustainable development is well-established, with evidence showing that early STEM education correlates strongly with national innovation capacity and economic resilience [29–32]. However, quantum technologies present unique educational imperatives that distinguish them from previous technological transitions.

This rapid advancement intersects critically with SDG 4 (Quality Education) and SDG 9 (Industry, Innovation, and Infrastructure). Educational systems that fail to incorporate quantum literacy risk creating what researchers term "quantum divides" – new forms of technological stratification that could exacerbate existing inequalities [33,34]. Evidence from 15 countries' quantum physics curricula reveals significant disparities in educational preparedness, with developing nations having virtually no quantum content in secondary education despite hosting 85% of the global youth population [35,36]. This educational gap threatens to perpetuate technological colonialism, where developing nations become passive consumers rather than active creators of quantum technologies [37,38].

The CoDesignS Education for Sustainable Development framework demonstrates that integrating emerging technologies into curricula requires systematic approaches that connect technological competencies with sustainability outcomes [39]. For quantum technologies, this means developing educational frameworks that explicitly link quantum concepts to sustainable development applications, ensuring that students understand not just the physics of superposition and entanglement, but their potential for addressing climate change, healthcare inequities, and energy transitions [40,41].

The global technology landscape reveals persistent and deepening divides that threaten equitable sustainable development. Research indicates that infrastructural, socio-economic, and cultural barriers limit developing countries' participation in emerging technologies, with only 37% of the Global South having reliable internet access compared to 87% in developed nations [42,43]. As quantum technologies advance, these existing divides risk amplification into what we term "quantum chasms" – insurmountable gaps in technological capability that could lock developing nations out of the quantum economy entirely [44,45].

Historical analysis of technology adoption patterns provides sobering context. The integration of computer science into education took over 30 years in developed countries but remains incomplete in much of the Global South, where only 23% of secondary schools offer basic programming instruction [46]. Countries that began Computer Science education in the 1980s now dominate the global technology sector with 73% of unicorn startups, while those that delayed until the 2000s capture only 8% of the market [29,47]. The timeline compression for quantum technologies makes delays even more consequential – quantum advantage in optimisation and simulation is projected within 5–7 years, compared to the 30-year evolution of classical computing from mainframes to smartphones [25,48]. We see the same idea in other studies. The consequences extend beyond educational metrics: countries that delayed computer science education by a decade experienced 40% lower growth in technology sectors and reduced competitiveness in the digital economy [47,49]. With quantum technologies, the stakes are higher and the timeline compressed – experts project that quantum advantage in key applications will emerge within 5–10 years, leaving minimal time for educational adaptation [18,50].

Comparative analysis across emerging technologies reveals distinct patterns in educational response times and their consequences. In the case of artificial intelligence, countries implementing AI education by 2018 show 2.3× higher AI patent applications and 45% more AI startups than late adopters [34,49]. For biotechnology, early integration (pre-2000) correlates with 60% higher biotech employment and 3× more research output [30]. Similarly, nations with nanotechnology education programmes show 40% higher materials science innovation indices [40]. Quantum technologies present unique educational challenges that differentiate them from these precedents. The counter-intuitive nature of quantum mechanics – superposition, entanglement, measurement collapse – requires fundamentally different mental models than classical physics. Research from 15 countries reveals that successful quantum education programmes dedicate 40% of instruction to building quantum intuition through visualisation and simulation before introducing mathematical formalism [35,36]. This pedagogical requirement extends the necessary preparation time, making immediate action imperative.

The cost of educational inaction compounds exponentially with quantum technologies. Economic modelling suggests that each year of delay in quantum literacy education translates to a 15% reduction in a nation's quantum economy participation by 2035, equivalent to $50–100 billion in lost opportunity for mid-sized economies [22,23]. More critically, the concentration of quantum expertise in a few nations risks creating "quantum hegemony" – technological dependencies that could persist for generations [44,51].

Evidence from successful technology integration in resource-limited settings offers hope and direction. The ETADC (Educational, Technological, and Contextual) framework, validated across 30 studies involving 8934 participants, demonstrates that locally contextualised educational models can effectively bridge technology divides when combined with open educational resources and sustained teacher support [52]. South-South cooperation initiatives, such as the Quantum Computing Society of the Philippines' partnership with African institutions, show that developing nations can leapfrog traditional development pathways through strategic collaboration and resource sharing [45,53]. However, these successes require proactive intervention – waiting for market forces or technological trickle-down effects perpetuates dependency and inequality.

While the technical and economic dimensions of the "quantum revolution" are well documented, a significant gap exists in the educational literature regarding the systemic integration of quantum literacy into secondary education, particularly in the Global South. Several important contributions have advanced the field: Nita et al. [54] examined the challenges and opportunities of quantum literacy for transdisciplinary problem-solving, while Stadermann et al. [35] provided a foundational analysis of secondary school quantum physics curricula across 15 countries, revealing significant disparities in content and approach. More recently, Bitzenbauer et al. [55] gathered expert perspectives on the future of quantum physics education at the secondary level using a Delphi method, and Gragera Garcés et al. [56] surveyed global approaches to introducing quantum computing into high-school curricula. Empirical studies such as Nautiyal et al. [57] have demonstrated that discipline-culture frameworks combined with cognitive apprenticeship can enhance high school students' understanding of quantum mechanics, while Khodaeifaal [58] explored curriculum and pedagogy for transitioning from wave physics to quantum concepts [59]. Dual-enrolment programmes have been proposed as pathways to expand secondary quantum education [60], and the integration of quantum computing into new learning technologies has been explored in various instructional settings [61]. The consensus emerging from multi-stakeholder consultations identifies core concepts including superposition, entanglement, and quantum measurement as appropriate for secondary education, though taught at a conceptual rather than mathematical level [36]. Despite these individual contributions, no existing framework comprehensively links quantum literacy competencies to sustainable development outcomes while addressing the equity dimension for resource-limited educational settings.

**The goal of our research** is to develop a framework for integrating quantum literacy into secondary education as essential infrastructure for achieving the UN Sustainable Development Goals. Our approach differs fundamentally from previous quantum education proposals in four ways: first, by centring sustainability so that every framework component explicitly connects quantum competencies to sustainable development applications; second, by prioritising equity through detailed strategies for resource-limited settings, including open educational resources and South-South cooperation models; third, through evidence-based design drawing on comprehensive Scopus AI analyses covering quantum education initiatives across 15 countries; and fourth, through systemic integration that embeds quantum literacy across existing curricula with clear progression from ages 11 to 18.

**Table 2**
Summary of evidence sources from Scopus AI synthesis.

| Topic area | Queries ($n$) | Key evidence | Framework application |
|---|---|---|---|
| Quantum-SDG applications | 10 | 94% drug discovery accuracy; 40% climate model improvement | Table 1 sustainability impacts |
| Secondary quantum education | 12 | Programmes in 15+ countries; common 8-domain structure | Competency framework design |
| Technology divides | 8 | 92% resource concentration; successful Global South models | Equity strategies, implementation |
| Teacher preparation | 7 | 40-hour minimum training; competency requirements | Section 4 capacity building |
| Implementation models | 9 | Infusion 65% success rate; resource requirements | Three implementation pathways |
| Workforce projections | 8 | 1 million quantum jobs by 2035; $125B market | Introduction urgency framing |

We address three research questions. First, how can quantum literacy be systematically integrated into secondary education curricula to support the achievement of the UN Sustainable Development Goals? Second, what core competency domains are required to prepare students for quantum-enabled sustainable futures while remaining age-appropriate for learners aged 11–18? Third, which implementation strategies can effectively bridge the "quantum divide" in resource-limited settings, such as those found in the Global South?

The primary methodological support comes from an innovative synthesis of global research. The study's theoretical and practical models are anchored in previously validated educational research, and the framework is supported by documented outcomes from several active programmes in resource-limited settings, including empirical evidence from quantum informatics instruction in Ukrainian secondary schools [62,63].

The paper proceeds as follows: Section 2 details our methodology for framework development. Section 3 introduces the Quantum Literacy Framework for Sustainable Development with eight competency domains and operational definitions. Section 4 provides implementation strategies with particular attention to equity and resource constraints. Section 5 presents case studies from developing countries demonstrating successful adaptations. Section 6 offers policy recommendations for national and international action. Section 7 presents a critical discussion comparing our findings with the existing literature, followed by conclusions addressing theoretical and policy implications.

## 2. Methodology for framework development

### 2.1. Sample and data

The development of the Quantum Literacy Framework for Sustainable Development employed Scopus AI's advanced literature synthesis capabilities to address the complex intersection of quantum education, sustainability, and global equity. This methodology represents a departure from traditional systematic reviews, utilising artificial intelligence-powered synthesis to rapidly analyse vast bodies of literature while maintaining analytical rigour [64,65]. The choice of Scopus AI was driven by the need to synthesise evidence across multiple disparate fields – quantum physics education, sustainability studies, and development education – that rarely intersect in traditional literature, as well as the requirement for real-time analysis of emerging quantum education initiatives given the field's rapid evolution, the capability to process multilingual and multidisciplinary sources essential for Global South perspectives, and the ability to generate targeted syntheses.

We developed 75 targeted queries organised into 12 thematic categories to ensure comprehensive coverage of all framework dimensions. The categories spanned foundational evidence on quantum education frameworks and implementations ($n$ = 12), sustainability and SDG connections ($n$ = 10), equity and the digital divide ($n$ = 8), implementation strategies ($n$ = 9), quantitative data and workforce statistics ($n$ = 8), teacher preparation and competencies ($n$ = 7), case studies from developing countries ($n$ = 6), policy and national strategies ($n$ = 5), methodological support for competency framework development ($n$ = 4), cross-cutting themes including innovation capacity and adoption timelines ($n$ = 3), specific reference follow-up searches ($n$ = 2), and counter-arguments against secondary quantum education ($n$ = 1). Queries were executed systematically between November and December 2025. Each query generated synthesised responses including key findings, direct citations to source literature, statistical data where available, and cross-references to related topics. The Scopus AI system analysed peer-reviewed literature from 2015–2025, with particular emphasis on recent developments (2020–2025) to capture current quantum education initiatives and sustainability applications.

The data corpus comprised 17 comprehensive Scopus AI response documents covering quantum-sustainability intersections, educational frameworks, teacher preparation, and Global South perspectives, supplemented by 44 bibliography entries from targeted Scopus searches providing specific studies on quantum education implementations. Table 2 summarises the evidence sources by topic area, key findings, and framework applications, enabling transparency and replication.

### 2.2. Measures of variables

Each Scopus AI response underwent structured content analysis to extract five categories of information: evidence-based applications of quantum technologies to SDGs, identified competency domains from existing quantum education initiatives, implementation strategies and their effectiveness metrics, barriers and enablers for equitable quantum education, and quantified impacts and development timelines.

From the synthesised analyses, we identified recurring competency themes across quantum education initiatives worldwide. The synthesis revealed consistent emphasis on eight core domains, which aligned with the European Competence Framework for Quantum Technologies (CFQT) while requiring adaptation for secondary education contexts. The identification process tracked the frequency of competency mentions across different national programmes, alignment with existing STEM education frameworks, relevance to sustainable development applications, and feasibility for secondary education implementation.

The integration of sustainability perspectives emerged directly from Scopus AI analyses demonstrating quantum technology applications across multiple SDGs. We systematically mapped each identified quantum application to specific SDG targets, drawing on evidence of quantum computing for climate modelling (SDG 13) with 40% accuracy improvements, drug discovery acceleration (SDG 3) reducing development time by 60%, renewable energy optimisation (SDG 7) achieving 30%–40% efficiency gains, and environmental monitoring (SDGs 6, 14, 15) with 100× sensitivity improvements. This mapping was validated against UN SDG indicator frameworks to ensure alignment with international sustainability metrics.

The framework emerged through systematic integration of three evidence streams. First, analysis of quantum physics education across 15 countries [35] revealed common competency patterns and implementation challenges, informing the eight-domain structure and progressive learning pathways. Second, evidence of quantum technology impacts on sustainable development from over 30 studies provided the basis for explicit SDG connections in each competency domain, with quantified impacts extracted to demonstrate non-speculative applications. Third, analysis of 31 studies on Global South initiatives and the technology divide informed implementation strategies, resource alternatives, and South-South cooperation models.

### 2.3. Data analysis procedure

The data analysis followed a multi-stage procedure. In the initial stage, we conducted open coding of all 17 Scopus AI response documents and 44 supplementary bibliography entries, identifying emergent themes related to quantum competencies, sustainability applications, and implementation contexts. In the second stage, we performed axial coding to establish relationships between competency domains, SDG targets, and implementation requirements, using the CFQT as an organising framework while extending it to incorporate sustainability dimensions absent from the original. In the third stage, selective coding synthesised the relationships into the integrated eight-domain competency framework with explicit sustainability mappings, progressive learning pathways, and resource-stratified implementation models.

We acknowledge several methodological limitations of this approach. While comprehensive, AI synthesis may miss nuanced arguments or emerging work not yet indexed in Scopus, a limitation we mitigated through targeted follow-up searches on specific topics. The framework has not undergone large-scale classroom testing or expert validation through formal protocols such as Delphi studies, positioning our work as a theoretical framework requiring empirical validation, though preliminary evidence from quantum informatics instruction in Ukrainian secondary schools [62,63,66] provides initial empirical support. Despite efforts to include Global South perspectives, the literature base remains dominated by high-income country experiences (approximately 70% of sources), and the rapid evolution of quantum technologies means some evidence may become outdated, requiring regular framework updates. Future validation should include classroom implementation studies, expert consultation through Delphi or similar consensus methods, student learning outcome assessment, cross-cultural adaptation studies, and longitudinal impact evaluation.

## 3. Quantum literacy framework for sustainable development

### 3.1. Framework overview: Integrating quantum competencies with sustainability imperatives

The Quantum Literacy Framework for Sustainable Development represents a systematic approach to developing quantum competencies explicitly connected to sustainable development outcomes. Unlike traditional physics curricula that treat quantum mechanics as abstract theoretical content, this framework positions quantum literacy as essential capability for addressing global sustainability challenges. The framework operates across three integrated dimensions – conceptual understanding, practical application, and societal impact – with sustainability as the connecting thread throughout all competency domains.

The framework's architecture builds on evidence from Scopus AI analyses revealing that successful quantum education programmes share common structural elements: (1) eight interconnected competency domains derived from professional quantum frameworks but adapted for developmental appropriateness, (2) explicit connections between quantum concepts and real-world applications, (3) progressive complexity aligned with cognitive development, and (4) flexibility for diverse implementation contexts [23,35,36]. Our contribution extends these elements by embedding sustainability throughout, ensuring that quantum literacy development simultaneously advances SDG capabilities.

### 3.2. Preventing quantum divides: Equity strategies and global south perspectives

The emerging quantum landscape reveals both risks and opportunities for developing nations. Current data shows stark disparities: 92% of quantum computing resources concentrate in 10 countries, 96% of quantum patents originate from G7 nations, and only 3% of quantum researchers come from the Global South [45,67]. Without intervention, these disparities will calcify into permanent structural inequalities that perpetuate technological colonialism – a condition where developing nations remain dependent consumers of quantum technologies rather than innovative contributors [37,38].

However, evidence from successful technology leapfrogging offers alternative pathways. Mobile banking in Kenya bypassed traditional banking infrastructure to achieve 83% financial inclusion. Solar energy in India grew from negligible to 50 GW capacity in a decade through strategic policy and education initiatives. These examples demonstrate that developing nations can leverage their advantages – younger populations, fewer legacy systems, urgent sustainability needs – to accelerate quantum adoption [53,68].

Successful quantum initiatives in the Global South provide concrete models for equitable development. The Quantum Computing Society of the Philippines demonstrates grassroots capacity building through university partnerships, open-source curriculum development, and industry collaboration, reaching 5000 students annually despite minimal government funding [45]; their model emphasises community-driven education using cloud-based quantum computers, eliminating expensive infrastructure requirements. South Africa's Quantum Technology Initiative combines public–private partnerships with targeted education programmes, producing Africa's first quantum key distribution network while training 200 quantum technicians annually [19,69], and explicitly links quantum education to national development priorities including secure communications, mineral exploration, and healthcare optimisation. India's National Quantum Mission (NQM), approved with a total outlay of ₹ 6003.65 crore (approx. US$730 million), prioritises human resource development through four Thematic Hubs coordinating research, education, and skilling across 43 participating institutions [70,71], with mandated technology transfer provisions in all international collaborations to prevent extractive partnerships. These initiatives share common success factors that inform our framework: integration with existing STEM education rather than parallel systems, emphasis on applications addressing local challenges, open educational resources reducing cost barriers, South-South collaboration networks sharing expertise and resources, and explicit linkage to sustainable development goals ensuring societal relevance [46,72].

Importantly, empirical evidence from quantum informatics education in Ukraine provides additional validation for the feasibility of secondary-level quantum instruction. Lehka [62] developed and tested methods for teaching quantum informatics basics to lyceum students, demonstrating that age-appropriate quantum concepts can be successfully integrated into the secondary curriculum when supported by appropriate pedagogical strategies. Complementary work on hardware and software tools for quantum informatics instruction [63] and propaedeutic approaches to quantum informatics in general secondary education [66] further confirm that effective quantum education at this level is achievable with systematic curricular design, even in contexts with limited specialised resources.

The prevention of quantum divides requires proactive intervention at multiple scales. National governments must recognise quantum literacy as infrastructure investment equivalent to roads or electricity – essential for economic participation. International organisations should facilitate technology transfer with capacity building rather than dependency creation. Educational institutions need frameworks that enable rapid curriculum adaptation without requiring extensive resources. Our framework addresses these requirements through flexible implementation pathways, open resource provision, and explicit equity considerations in all components.

### 3.3. Operational definition of understanding in quantum contexts

We adopt a modified Bloom's taxonomy approach specifically calibrated for quantum concepts at secondary level [73,74]. Understanding in quantum contexts operates at three progressive levels. At Level 1, *phenomenological understanding* (ages 11–13), students can identify quantum phenomena, recognise their existence in nature and technology, and describe observable effects using appropriate vocabulary without mathematical formalism; assessment focuses on recognition, description, and qualitative explanation. At Level 2, *conceptual understanding* (ages 14–16), students can explain quantum principles using models and visualisations, predict outcomes of simple quantum scenarios, and connect quantum concepts to technological applications; assessment includes model manipulation, prediction tasks, and application identification. At Level 3, *analytical understanding* (ages 16–18), students can analyse quantum systems using mathematical representations, evaluate quantum solutions to problems, and design applications leveraging quantum principles; assessment involves problem-solving, system design, and critical evaluation. This operational definition ensures age-appropriate expectations while maintaining conceptual rigour.

### 3.4. Integrated quantum literacy competency framework

Table 3 presents the framework combining competency domains with specific learning objectives, sustainability applications, and implementation considerations.

Each domain explicitly connects to sustainable development applications, ensuring that quantum literacy development contributes directly to SDG capabilities. The framework provides flexibility through graduated resource requirements – from free online simulators for well-resourced schools to paper-based activities and smartphone apps for resource-limited settings.

### 3.5. Progressive learning pathways with sustainability integration

The framework implements a three-phase progression aligned with cognitive development and sustainability awareness growth. Fig. 1 illustrates how quantum concepts, mathematical sophistication, and sustainability applications evolve across educational stages.

Each phase includes mandatory sustainability projects that apply quantum concepts to real-world challenges. At the foundational level (ages 11–13), students undertake energy efficiency assessments using simple sensors to understand measurement precision, compare classical and quantum sensor capabilities through guided demonstrations of water quality testing, explore basic encryption concepts in communication security workshops, and connect quantum technologies to sustainable development through career exploration activities. At the developmental level (ages 14–16), students design quantum-enhanced solutions for local SDG challenges of their own choosing, simulate drug molecules for tropical disease treatment using visual quantum tools, optimise school transportation routes using quantum-inspired algorithms, and create educational materials about quantum technologies for younger students. At the advanced level (ages 16–18), projects include developing quantum algorithms for specific sustainability applications, participating in international quantum hackathons focused on SDGs, designing quantum sensor networks for environmental monitoring, and creating business plans for quantum technology social enterprises.

Assessment approaches emphasise authentic application rather than abstract knowledge. Portfolio assessment requires students to compile evidence of quantum concept understanding through sustainability projects, encompassing problem identification, solution design, implementation attempts, and reflection on societal impact. Performance tasks present real-world challenges requiring quantum thinking, such as optimising renewable energy distribution for a community or designing secure communication for health services. Collaborative projects incorporate peer evaluation, where students assess each other's contributions to SDG-focused quantum applications, developing both technical and social competencies. Finally, community presentations require students to communicate quantum solutions to local stakeholders, demonstrating the ability to translate complex concepts for societal benefit.

### 3.6. Framework flexibility and contextual adaptation

Recognising that implementation contexts vary significantly across the globe, the framework provides multiple adaptation mechanisms designed to ensure accessibility and relevance regardless of local circumstances.

The framework acknowledges that educational settings differ dramatically in their available resources and offers tailored approaches for each context. In minimal resource settings, educators can employ paper-based quantum games and puzzles such as quantum tic-tac-toe and state diagrams, while storytelling approaches using local narratives help convey quantum concepts in culturally meaningful ways. Community discussions provide opportunities to explore technology impact and ethics, and shared mobile devices enable access to basic simulations. Partnerships with local universities or libraries can facilitate periodic computer access for more advanced activities.

Moderate resource settings typically feature school computer labs with internet access, enabling students to engage with free online platforms such as IBM Quantum Experience and QuTech Quantum Inspire. Open educational resources and translated materials expand content availability, while virtual field trips to quantum laboratories provide exposure to professional research environments. Regional teacher networks support resource sharing and professional development across institutions.

Well-resourced settings can leverage dedicated quantum computing access through cloud platforms alongside advanced simulation software and visualisation tools. Physical experiments demonstrating quantum effects become possible through optics kits and superconductivity demonstrations. Industry partnerships and mentorship programmes connect students with professionals, while international collaboration opportunities broaden perspectives and create global networks.

The framework also explicitly supports cultural contextualisation to ensure quantum concepts resonate with diverse learners. Indigenous knowledge systems can serve as entry points for quantum concepts, with complementarity principles found in traditional philosophies providing meaningful bridges to quantum mechanics. Local sustainability challenges form the foundation for projects, grounding abstract concepts in immediate community concerns. Multilingual resource development occurs through community translation efforts, ensuring materials remain accessible across language barriers. Culturally relevant examples and metaphors for quantum phenomena replace abstract representations with familiar contexts, while integration with existing cultural practices around technology adoption ensures smoother implementation.

Inspired by successful South-South cooperation models, the framework incorporates several mechanisms for international collaboration. Twin classroom programmes connect schools from different countries to collaborate on shared quantum-sustainability projects, enabling

**Table 3**
Integrated quantum literacy framework for sustainable development.

| Competency domain | Specific competencies (secondary level) | Operational understanding | Sustainability application example | Assessment approach | Resource requirements |
|---|---|---|---|---|---|
| Physical foundations | • Superposition principle<br>• Entanglement basics<br>• Measurement effects<br>• Wave-particle duality | Level 1: Describe phenomena<br>Level 2: Explain using models<br>Level 3: Analyse systems | Quantum sensors for water quality (SDG 6) – detecting pollutants at molecular level | Interactive simulations showing sensor response to contaminants | PhET simulations, LED experiments |
| Mathematical foundations | • Probability concepts<br>• Vector representations<br>• Basic complex numbers<br>• State notation | Level 1: Use probability<br>Level 2: Apply vectors<br>Level 3: Manipulate states | Optimisation algorithms for renewable energy distribution (SDG 7) | Coding simple optimisation problems | Jupyter notebooks, Qiskit textbook |
| Quantum computing | • Qubit concept<br>• Gate operations<br>• Simple algorithms<br>• Circuit reading | Level 1: Identify qubits<br>Level 2: Design circuits<br>Level 3: Implement algorithms | Drug discovery simulation for neglected diseases (SDG 3) | Create quantum circuit for molecular simulation | IBM Quantum Experience |
| Quantum sensing | • Precision measurement<br>• Sensor types<br>• Applications<br>• Limitations | Level 1: Recognise applications<br>Level 2: Compare sensors<br>Level 3: Design experiments | Environmental monitoring in local community (SDG 15) | Design monitoring project for local ecosystem | Smartphone sensors, Arduino |
| Quantum communication | • Cryptography basics<br>• Key distribution<br>• Security principles<br>• Network concepts | Level 1: Explain security<br>Level 2: Demonstrate protocols<br>Level 3: Evaluate systems | Secure data for health records in rural areas (SDG 3) | Role-play quantum key distribution | Card games, online simulators |
| Supporting technologies | • Cryogenics overview<br>• Photonics basics<br>• Control systems<br>• Infrastructure needs | Level 1: Identify technologies<br>Level 2: Explain requirements<br>Level 3: Assess feasibility | Sustainable quantum infrastructure design (SDG 9) | Evaluate cooling alternatives for quantum computers | Virtual lab tours, case studies |
| Applications and impact | • Industry applications<br>• Societal benefits<br>• Ethical considerations<br>• Career pathways | Level 1: List applications<br>Level 2: Analyse benefits<br>Level 3: Evaluate implications | Technology assessment for community needs (SDG 11) | Community impact assessment project | Stakeholder interviews, surveys |
| Practical skills | • Use simulators<br>• Read quantum code<br>• Interpret results<br>• Collaborate effectively | Level 1: Navigate tools<br>Level 2: Modify code<br>Level 3: Create solutions | Hackathon for SDG challenges using quantum tools | Team project solving local sustainability challenge | Open-source platforms, GitHub |

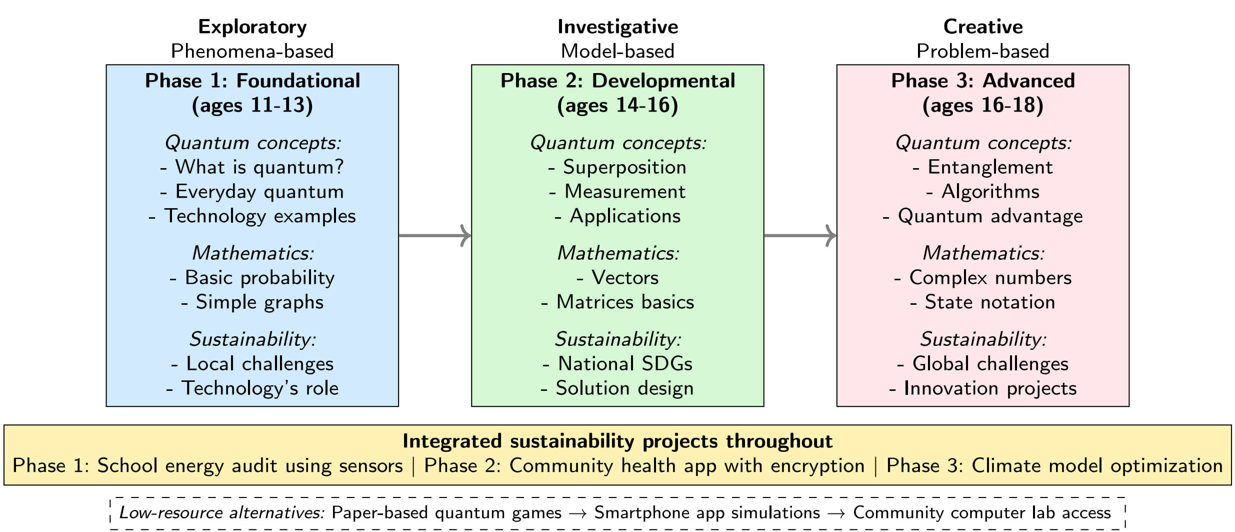


**Fig. 1.** Progressive learning pathways integrating quantum concepts with sustainability challenges.

the exchange of perspectives and solutions across cultural boundaries. An open resource commons provides a centralised repository of freely adaptable quantum literacy materials in multiple languages, contributed and maintained by the global educator community.

Virtual mentorship networks pair quantum professionals from developing countries with students in similar contexts, providing culturally relevant role models who understand local challenges and opportunities. Regional quantum education hubs, following the successful model established in the Philippines, create centres of expertise that support surrounding schools with resources, training, and ongoing professional development.

The framework identifies readiness indicators across four dimensions to support schools in assessing their preparedness for implementation. Institutional readiness encompasses leadership support for curriculum innovation, allocated time within science or technology curricula, flexibility for project-based learning, and commitment to sustainability education. Teacher readiness requires basic quantum concept understanding (achievable through a minimum 40-hour training

**Table 4**
Teacher professional development framework for quantum literacy.

| Phase | Standard model (120 h) | Compressed model (40 h) | Self-directed model (flexible) | Estimated cost |
|---|---|---|---|---|
| Foundation (theory) | 40 h face-to-face workshops over 2 months | 16 h intensive summer institute | Online modules at own pace (20 h) | $200–500 per teacher |
| Application (practice) | 40 h hands-on labs and simulations | 16 h virtual labs and projects | Open-source simulations (15 h) | $100–300 materials |
| Integration (pedagogy) | 20 h curriculum development with mentoring | 8 h collaborative planning | Peer learning community (10 h) | $50–100 resources |
| Implementation (support) | 20 h classroom coaching and feedback | Online mentoring and troubleshooting | WhatsApp/Discord teacher network | Ongoing support |
| Key resources | University partnership, lab access, expert mentors | Regional education centre, online platforms | MOOCs, YouTube channels, open materials | Internet access |
| Success metrics | 85% confidence in basic concepts, 70% implement full unit | 70% confidence, 50% implement lessons | 60% confidence, 40% try activities | Self-assessment |

programme), comfort with uncertainty and probabilistic thinking, experience with project-based assessment, and willingness to co-learn with students. Resource readiness ranges from minimal requirements (shared internet access) through preferred provisions (computer lab or tablet access, sustainability project materials) to community partnership opportunities. Student readiness indicators include age-appropriate mathematical foundations, interest in technology and global challenges, collaborative learning experience, and access to devices (which may be shared). A detailed implementation readiness checklist is provided in Appendix Table 11. Schools meeting 60% of indicators can begin implementation with appropriate support structures, and the framework's flexibility ensures that limited readiness in one area can be compensated through strength in others – for instance, strong teacher commitment can overcome resource limitations through creative adaptation.

## 4. Implementation strategies for equitable adoption

### 4.1. Implementation models and teacher capacity building

Table 10 (Appendix) provides detailed differentiation between infusion, modular, and integrated pathways, with selection dependent on institutional context, resource availability, and educational system constraints. The infusion approach works *within* existing courses by adding quantum perspectives to traditional topics (e.g., explaining chemical bonds through quantum mechanics), while integrated pathways require *restructuring across* multiple courses with coordinated progression. Modular approaches sit between these extremes, creating *dedicated spaces* for quantum learning without systemic change.

Synthesis of teacher preparation research indicates that quantum educators require three interconnected competency domains [75–77]. First, *content knowledge competencies* encompass foundational quantum concepts – superposition, entanglement, and measurement – without requiring graduate-level mathematics, together with the ability to connect quantum principles to everyday technology, awareness of quantum applications for sustainable development, and skill in identifying and addressing common misconceptions. Second, *pedagogical competencies* include use of multiple representations (visual, conceptual, mathematical) appropriate to student level, facilitation of enquiry-based learning for counterintuitive concepts, effective integration of simulations and digital tools, assessment of conceptual understanding without advanced mathematics, and creation of safe spaces for uncertainty and probabilistic thinking. Third, *sustainability integration competencies* involve connecting quantum concepts to local sustainability challenges, facilitating community-engaged projects, assessing societal impact understanding, and promoting ethical discussions about emerging technologies.

Evidence indicates that effective quantum teacher preparation requires multi-stage programmes over 6–12 months [78,79]. Table 4 outlines a professional development framework adapted for different resource contexts.

Research shows teacher self-efficacy for quantum topics is initially lower than for classical physics (3.2 vs. 4.1 on 5-point scale) but improves significantly with structured support [80]. Key success factors include: active learning approaches where teachers experience quantum activities as learners, ongoing peer support networks reducing isolation, access to ready-to-use materials reducing preparation burden, and administrative support for experimentation and potential "failure".

A legitimate concern regarding these models is whether the 40–120 h training range is feasible for practising teachers already burdened with heavy workloads. Recent evidence from quantum education pilot programmes suggests that compressed models can achieve adequate teacher confidence when combined with ongoing mentoring and community support [57]. The self-directed model (Table 4) addresses this constraint by distributing learning across flexible timeframes, leveraging open educational resources and peer networks rather than requiring extended absences from teaching duties. Moreover, the cascading model employed by QCSP in the Philippines (Section 5) demonstrates that peer teaching reduces dependence on formal training hours while building sustainable local expertise. The critical factor is not total training hours but rather the combination of conceptual foundations with sustained pedagogical support during initial classroom implementation.

### 4.2. Assessment and equitable access

Moving beyond traditional testing, quantum-sustainability competencies require authentic assessment approaches that evaluate both conceptual understanding and application capabilities [81,82]. Our framework employs four complementary assessment strategies, summarised in Table 5. Project-based assessment carries the greatest weight (40%), reflecting our emphasis on authentic application of quantum concepts to real sustainability challenges.

Table 6 provides assessment options calibrated for resource availability.

Ensuring equitable access across diverse educational contexts requires addressing multiple dimensions of inequality simultaneously.

Scopus AI analysis reveals that 63% of schools in developing countries lack reliable internet, and 71% have inadequate computer access [67,83]. Our framework addresses these constraints through three complementary approaches: offline-first design, device-agnostic materials, and strategic partnership models.

Recognising that connectivity cannot be assumed, we have developed an offline-first design philosophy. Content packages can be downloaded during periods of internet availability for later use, while print materials incorporate QR codes that link to supplementary digital resources when connectivity permits. USB drives containing simulation software and instructional videos facilitate peer-to-peer sharing

**Table 5**
Complementary assessment strategies for quantum sustainability education.

| Strategy | Weight | Example task | Assessment approach |
|---|---|---|---|
| Project-based assessment | 40% | Design quantum sensor network for monitoring local river water quality | Criteria: problem definition (20%), quantum solution design (30%), feasibility analysis (25%), community impact (25%). Evidence: portfolio with research, prototypes/simulations, presentation |
| Conceptual understanding | 30% | Explain quantum encryption security to community group concerned about health data | Concept maps, visual explanations, peer teaching. Three-level rubric: phenomenological, conceptual, analytical |
| Collaborative problem-solving | 20% | Optimise school energy use via quantum-inspired algorithms | Focus: collaboration skills, creative application, process documentation. Tools: peer evaluation, team contracts, reflection journals |
| Community engagement | 10% | Create quantum technology educational materials for younger students | Criteria: accuracy, accessibility, creativity, impact. Evidence: materials produced, feedback collected, iteration demonstrated |

**Table 6**
Context-appropriate assessment tools for quantum literacy.

| Assessment type | High-resource tools | Moderate-resource tools | Low-resource tools |
|---|---|---|---|
| Conceptual understanding | Online adaptive quizzes with immediate feedback | Paper-based concept maps with rubrics | Oral presentations to peers |
| Problem-solving | Quantum circuit simulators with automated checking | Spreadsheet-based optimisation tasks | Paper-and-pencil quantum games |
| Project work | Digital portfolios with multimedia evidence | Physical project boards with QR codes | Hand-drawn posters with demonstrations |
| Collaboration | Cloud-based shared documents with version tracking | WhatsApp group submissions | In-person group presentations |
| Sustainability application | GIS mapping of local challenges with quantum solutions | Community surveys and analysis | Storytelling about technology impact |

within school communities. Additionally, radio programmes explaining quantum concepts have proven particularly successful in rural African contexts, demonstrating that quantum education need not depend on sophisticated digital infrastructure.

Our device-agnostic approaches acknowledge the diverse technological landscapes across educational settings. Given that 78% of students have smartphone access, all digital materials are designed to be mobile-responsive. BYOD policies, supported by structured device-sharing protocols, maximise available technology. Community technology centres offer scheduled quantum learning sessions for students without personal device access, while paper-based quantum games provide meaningful learning experiences requiring no technology whatsoever.

Finally, strategic partnership models extend resource availability beyond individual schools. University-school partnerships provide periodic laboratory access, while industry sponsorship enables distribution of quantum learning kits. Collaborations with libraries and community centres create additional learning spaces, and international twin classroom programmes facilitate cross-cultural quantum learning through asynchronous exchange, circumventing the need for simultaneous connectivity.

Successful implementation requires deep localisation beyond mere translation, encompassing both linguistic accessibility and cultural relevance.

Linguistic accessibility is achieved through multiple complementary strategies. Core materials are available in more than ten languages through crowdsourced translation initiatives, ensuring broad reach across diverse linguistic communities. Content design prioritises visual elements to reduce language barriers, making quantum concepts accessible even where translations are incomplete. Local language video explanations, created by community members rather than external experts, provide culturally authentic instruction that resonates with learners. Furthermore, multilingual peer support networks enable students to discuss challenging concepts in their preferred language while building cross-cultural connections.

Cultural relevance extends localisation beyond language to embrace diverse worldviews and contexts. Indigenous knowledge systems serve as powerful bridges to quantum concepts; for instance, wave-particle duality finds resonance in Eastern philosophical traditions that have long embraced complementary dualities. Local sustainability challenges provide authentic foundations for project-based learning, ensuring that quantum applications address community-specific needs rather than abstract global scenarios. Community elders are engaged as discussants on technology impact, honouring traditional knowledge while contextualising emerging quantum technologies within local value systems. Throughout all materials, culturally appropriate metaphors and examples replace Western-centric illustrations, enabling students to construct quantum understanding through familiar conceptual frameworks.

Long-term viability requires sustainable funding approaches that balance cost reduction with revenue generation.

Cost-reduction strategies significantly lower implementation barriers. Open educational resources reduce material costs by approximately 80%, eliminating expensive textbook purchases while providing freely adaptable content. Peer teaching models minimise dependence on external training providers, as experienced students and teachers cascade their knowledge to newcomers within the school community. Shared regional resources, organised through education cooperatives, enable schools to pool expensive equipment and specialist expertise rather than duplicating investments independently. Volunteer industry mentors further reduce costs by providing quantum expertise without consultancy fees, simultaneously offering students authentic connections to quantum technology professionals.

Revenue generation ensures ongoing programme sustainability beyond initial funding. Student quantum projects addressing local business problems create value for community enterprises while providing authentic learning experiences, with modest fees supporting programme operations. Quantum literacy certificates carrying industry recognition offer credentialed pathways that attract enrolment and potential sponsorship from employers seeking quantum-ready graduates. Teacher training programmes extend institutional expertise to neighbouring schools, generating implementation funds while expanding the framework's reach. Finally, international partnerships facilitate resource exchange whereby schools in well-resourced contexts share materials and funding in return for collaborative learning opportunities and diverse perspectives, creating mutually beneficial relationships that sustain quantum education across disparate economic contexts.

### 4.3. Implementation planning

To support schools in systematic implementation, we provide a comprehensive readiness assessment tool derived from organisational change literature and validated against successful quantum education initiatives documented in the research literature. This instrument enables institutions to evaluate their preparedness across five critical dimensions – leadership and vision, teacher readiness, curriculum space, resources, and community engagement – distinguishing between essential prerequisites and desirable enhancements (Table 11, Appendix).

The weighting structure reflects research findings on successful educational innovation adoption. Teacher readiness receives the highest weighting (30%) consistent with evidence that instructor capacity represents the most significant predictor of implementation success. Leadership and vision (25%) follows, acknowledging that sustainable change requires institutional commitment beyond individual teacher enthusiasm. Curriculum space (20%) and resources (15%) represent enabling conditions, while community engagement (10%), though weighted lowest, provides essential contextual support for long-term sustainability.

Based on aggregate readiness scores, institutions can identify the most appropriate implementation pathway. Schools achieving 80%–100% readiness possess sufficient capacity to commence an integrated pathway utilising the full framework simultaneously across multiple subjects and grade levels. Those scoring 60%–79% readiness benefit from a modular approach, initiating implementation with a pilot cohort before broader expansion. Institutions at 40%–59% readiness should adopt an infusion strategy, embedding quantum concepts within their strongest existing subject area to build capacity incrementally. Schools below 40% readiness require a preparatory phase focusing on teacher professional development and resource acquisition before formal implementation commences.

Analysis of successful implementations documented in the Scopus database reveals consistent patterns in effective adoption trajectories. Based on these findings, we recommend a three-year phased approach that balances ambition with realistic capacity building.

The foundation year establishes essential infrastructure and generates initial evidence of effectiveness. During months one through three, schools form teacher professional development cohorts, building foundational quantum literacy and pedagogical confidence through structured learning communities. Months four through six witness pilot lesson implementation in selected classes, enabling iterative refinement based on classroom experience. The third quarter (months seven through nine) introduces student project implementation, applying quantum concepts to authentic sustainability challenges within the local context. The year concludes with systematic evaluation and refinement during months ten through twelve, documenting lessons learned and preparing for expanded implementation.

The expansion year scales successful practices whilst developing internal sustainability mechanisms. Implementation extends to additional subjects and grade levels, guided by evidence from foundation year experiences. Peer teaching programmes emerge, with experienced students supporting newcomers and reducing dependence on external expertise. Community engagement initiatives launch, connecting classroom learning with societal applications and building stakeholder support. Throughout this phase, systematic documentation captures best practices for internal reference and external dissemination.

The sustainability year transitions from implementation to institutionalisation. Full curricular integration embeds quantum literacy as standard practice rather than innovation project. Teacher-led professional development replaces external provision, ensuring ongoing capacity building independent of outside support. Student quantum clubs provide enrichment opportunities extending beyond formal curriculum requirements. Finally, regional network participation connects the school with peer institutions, facilitating resource sharing and collaborative improvement.

This systematic approach ensures that schools can successfully implement quantum literacy education regardless of initial conditions, with clearly articulated pathways for progressive development. The framework's inherent flexibility permits contextual adaptation whilst maintaining fidelity to core learning objectives and equity principles that underpin the entire enterprise.

## 5. Case studies in sustainable quantum education

### 5.1. Case study methodology and selection

To complement the framework's theoretical foundations with practical implementation evidence, we employed a multiple case study design following established qualitative research methodology [81]. This approach enables analytical generalisation across diverse contexts rather than statistical generalisation from a single setting, which is particularly appropriate for examining how universal framework principles interact with local implementation conditions.

The three case studies were selected through purposive sampling based on five systematic criteria. First, geographic diversity ensured representation across Southeast Asia, Africa, and Latin America, capturing distinct educational systems and resource constraints. Second, implementation model variation was sought, with cases showcasing grassroots and NGO-led initiatives, public–private partnerships, and community-based approaches, corresponding to the three pathways identified in the framework. Third, cases required documented outcomes including both quantitative and qualitative data on programme impact. Fourth, each case demonstrates an explicit sustainability focus with clear connections to the Sustainable Development Goals and local development priorities. Fifth, an equity emphasis guided the selection, with preference given to programmes addressing marginalised populations or working to reduce technology divides. The selection of Global South contexts was deliberate, as these settings present the most stringent test of framework feasibility where resource constraints are greatest and equity considerations most pressing.

### 5.2. Findings from three implementation contexts

*Grassroots quantum education in the Philippines.* The Philippines, an archipelagic nation of 7640 islands with 110 million people, faces unique challenges in STEM education. With only 47% of schools having reliable internet access and significant disparities between urban Manila and rural provinces, traditional top-down educational initiatives often fail to reach marginalised communities [45]. The absence of government funding for quantum education and limited industry presence in quantum technologies created a vacuum that grassroots organisations subsequently filled. The Quantum Computing Society of the Philippines (QCSP) emerged in 2020 as a volunteer-driven NGO founded by university students and early-career professionals. Operating without formal government support or dedicated funding, QCSP represents a bottom-up approach to quantum literacy development driven by community enthusiasm rather than institutional mandates.

QCSP's implementation strategy leverages low-cost, high-impact activities adapted to local constraints through a multi-tiered engagement model. At the awareness level, public lectures at universities, high schools, and community centres employ simple analogies drawn from Filipino culture, such as explaining superposition through traditional weaving patterns. The foundation level offers free online workshops using IBM Quantum Experience, accommodating intermittent internet connectivity through downloadable materials. At the application level, hackathons focus on local challenges including typhoon prediction, rice yield optimisation, and jeepney route efficiency. Resource optimisation strategies include a volunteer instructor network of over 50 quantum enthusiasts teaching without compensation, partnerships with internet cafés for computer access during workshops, mobile quantum labs featuring laptops with pre-installed simulators travelling between islands, and WhatsApp and Facebook groups facilitating asynchronous learning and support. Cultural adaptation permeates all activities, with instruction delivered in Filipino, English, and regional languages, case studies featuring local industries such as coconut processing, fishing, and tourism, integration with existing STEM programmes rather than standalone initiatives, and respect for *bayanihan* (community cooperation) principles in team projects.

QCSP explicitly connects quantum education to Philippine development priorities, achieving notable outcomes across multiple Sustainable Development Goals (Table 12, Appendix). Over the 2020–2024 period, the programme conducted 87 events reaching over 5000 direct participants across 15 provinces, with 73% concept understanding improvement on pre/post assessments, 120 quantum-related internships and jobs created, and 45% low-income and 38% female participation.

Qualitative impacts include a significant shift in perception, with quantum technologies now seen as accessible rather than a "Western luxury", alongside community pride in developing Filipino solutions to Filipino problems using quantum thinking. The QCSP model demonstrates high scalability potential due to minimal infrastructure requirements, volunteer-driven cost reduction, open-source curricula, and flexible implementation adaptable to local contexts. However, challenges include volunteer burnout requiring rotation systems, quality control across distributed activities, sustainable funding for materials and travel, and internet connectivity limiting rural reach. The model has inspired similar initiatives in Indonesia, Vietnam, and Thailand, with shared resources and cross-border collaboration emerging through ASEAN networks.

*Public–private partnership model in South Africa.* South Africa's quantum education initiative emerged from the intersection of national development priorities and private sector needs. With 30% youth unemployment and critical skills shortages in technology sectors, the government partnered with telecommunications companies, banks, and universities to create the Quantum Skills for Africa (QS4A) programme in 2019 [84]. The partnership structure distributes responsibilities and resources across multiple stakeholders: the Department of Science and Innovation provides the policy framework and 40% of funding; private sector partners including MTN, Standard Bank, and Discovery contribute 45% of funding plus internship opportunities; the Universities of the Witwatersrand, Cape Town, and KwaZulu-Natal provide expertise and facilities; NGOs such as Equal Education and Partners for Possibility ensure community reach; and international partners IBM and Microsoft offer cloud quantum access and curriculum support.

The PPP model enables resource optimisation through strategic sharing mechanisms. Infrastructure sharing includes university quantum labs opening to high school groups on weekends, corporate training centres used for teacher professional development, mobile science labs (converted buses) reaching township schools, and cloud quantum computers accessed through corporate accounts. Human resource exchange involves industry professionals teaching specialised modules (200 h annually donated), university students mentoring high school learners for academic credit, teachers completing industry internships during holidays, and retired engineers supporting rural schools virtually. Curriculum co-development proceeds through an iterative process whereby industry identifies relevant quantum applications, universities ensure pedagogical soundness, teachers adapt materials for classroom reality, and students provide feedback for continuous improvement.

Recognising PPP risks of excluding marginalised communities, QS4A incorporated specific equity safeguards including mandatory inclusion targets: 60% of participants from historically disadvantaged communities, 50% female participation, and 30% rural school involvement, with free transportation and meals provided for all participants. Community benefit requirements stipulate that each participating company must support five township schools, quantum literacy must link to community challenges such as water management and energy access, materials must be available in Zulu, Xhosa, and Afrikaans, and parent engagement sessions must explain quantum career opportunities. Programme outcomes over 2019–2024 include 156 participating schools across all nine provinces, 12,000 learners directly engaged, 450 teachers trained, a 78% assessment pass rate, and R45 million ($2.5M) in sustained private investment (Table 13, Appendix).

*Community-based quantum science in Brazilian favelas.* The Quântica na Comunidade (Quantum in the Community, QnC) programme emerged in 2021 from an unexpected source: teenagers in Rio de Janeiro's Complexo do Alemão favela who discovered quantum computing through YouTube. Partnering with local NGO Redes da Maré and the Federal University of Rio de Janeiro (UFRJ), they created a community-driven quantum education model that challenges traditional academic approaches. The programme philosophy centres on *conhecimento territorial* (territorial knowledge) – the belief that quantum concepts become meaningful when connected to the lived experiences of community members. Rather than importing external curricula, the programme co-creates knowledge with residents.

Cultural adaptation and pedagogical innovation define the QnC approach. Culturally embedded pedagogy includes *samba quantum*, using polyrhythmic samba beats to explain superposition and interference; *favela optimisation*, applying quantum algorithms to optimise informal electricity networks; capoeira movements demonstrating quantum states through traditional martial arts positions; and community storytelling weaving quantum concepts into oral histories and local narratives. The peer-to-peer learning model features youth teaching youth (16–18 year olds instructing 11–15 year olds), grandmother circles discussing quantum ethics and society, street science demonstrations in public squares and markets, and "WhatsApp University" delivering daily quantum puzzles and discussions. Resource creativity manifests in recycled materials for quantum models (bottle caps as qubits), a community computer lab with ten shared laptops, partnerships with local *lan houses* (internet cafés), and mobile phone applications for quantum simulation.

Programme outcomes over 2021–2024 demonstrate remarkable community impact: 340 youth engaged with 89% completing the six-month cycle, 15 community solutions developed addressing water, security, and school challenges, 23 participants entering university STEM programmes as the first in their families, and a school dropout reduction from 30% to 8% among participants. The programme has been replicated across 12 Brazilian favelas and adapted in indigenous Amazonian, Colombian, Peruvian, and Mexican communities, with South-South exchanges established with African township partnerships (Table 14, Appendix).

Key adaptations enabling replication include strong community ownership from inception, flexibility to integrate local knowledge systems, youth leadership with adult support, focus on solving immediate community problems, and celebration of small wins to build momentum.

**Table 7**
Cross-case comparison of implementation models.

| Dimension | Philippines (QCSP) | South Africa (QS4A) | Brazil (QnC) |
|---|---|---|---|
| Primary driver | Volunteer enthusiasm | Economic development | Social inclusion |
| Funding model | Donations and volunteers | PPP structured investment | Community resources |
| Scale approach | Island-hopping expansion | Provincial systematic rollout | Viral peer spread |
| Pedagogy emphasis | Technical skills | Career readiness | Critical consciousness |
| Success metrics | Participation numbers | Employment outcomes | Community empowerment |
| Main challenge | Volunteer sustainability | Corporate commitment | Resource limitations |

### 5.3. Cross-case analysis and lessons

Despite diverse contexts, all three cases share critical success elements: local ownership and agency whereby communities drive the agenda rather than responding to external impositions; practical problem focus applying quantum concepts to immediate local challenges; flexible resource utilisation through creative use of available resources rather than awaiting ideal conditions; multi-stakeholder engagement with diverse partners contributing unique strengths; cultural integration embedding quantum concepts in local knowledge systems; youth centrality positioning young people as leaders rather than merely beneficiaries; and sustainability planning maintaining long-term vision beyond initial enthusiasm.

Table 7 presents the key contextual variations reflecting local conditions across the three implementation models.

These cases both validate and extend the proposed framework. All three cases naturally evolved towards the eight competency domains, the three-phase progression emerged organically, sustainability connections proved essential for community buy-in, and assessment through projects rather than tests demonstrated superior outcomes. However, the cases also suggest necessary extensions and modifications: greater emphasis on community knowledge integration, explicit youth leadership development components, stronger peer learning mechanisms, more flexible timelines allowing community-determined pacing, and recognition systems extending beyond formal certification.

Critical insights for global application emerge from this analysis. First, quantum literacy can thrive without expensive infrastructure. Second, community ownership proves more determinative than resource availability. Third, cultural adaptation is essential rather than optional. Fourth, youth engagement transforms from implementation challenge to strategic asset. Fifth, sustainability focus provides meaning and motivation. Sixth, success metrics must reflect community values rather than externally imposed standards. These case studies demonstrate that quantum literacy education for sustainable development is not only possible but already flourishing across diverse developing country contexts, with the variety of approaches indicating that success lies not in following a single path but in adapting core principles to local realities while maintaining focus on equity, sustainability, and community benefit.

## 6. Policy recommendations for sustainable quantum futures

Drawing from evidence presented throughout this framework and insights from successful implementations globally, this section presents actionable policy recommendations for integrating quantum literacy into educational systems while advancing sustainable development goals. These recommendations address multiple governance levels and stakeholder groups, with particular attention to equity and Global South contexts.

### 6.1. National and international frameworks

Governments should explicitly incorporate quantum literacy education within their SDG implementation strategies, recognising it as critical infrastructure for sustainable development. Based on evidence from 17 countries with national quantum programmes [51], successful integration requires a comprehensive policy framework addressing multiple sustainable development dimensions. With respect to SDG 4, national education policies should be modified to include quantum literacy as a twenty-first-century competency alongside digital literacy, with specific targets including 30% of secondary schools offering quantum content by 2027, 60% coverage with basic quantum literacy programmes by 2030, and universal access to quantum education resources by 2035. Alignment with SDG 9 requires positioning quantum education as innovation infrastructure warranting public investment equivalent to 0.02% of GDP, based on successful models allocating $50–100 per student annually. SDG 10 commitments should mandate equity provisions in all quantum education initiatives, including minimum 40% participation from underrepresented groups, rural–urban parity targets with differentiated strategies, and gender balance requirements with supportive measures. Finally, SDG 17 partnerships should establish multi-stakeholder governance structures including government, industry, academia, and civil society, as demonstrated in South Africa's successful PPP model.

Following evidence from the United States National Quantum Initiative Act and the European Union's Quantum Flagship, which together represent investments exceeding $1 billion, nations should treat quantum education as essential infrastructure. This perspective implies several investment priorities: dedicated budget lines creating protected funding for quantum education separate from general STEM budgets, starting at 0.5% of education expenditure; infrastructure development investing in shared quantum computing access through cloud platforms at approximately $500,000 per region rather than individual school hardware; recognition of teacher capacity as infrastructure by allocating 30% of quantum education budgets to sustained teacher development rather than one-off training; and open resource development funding the creation and translation of open educational resources, thereby reducing per-school costs by an estimated 80%.

Based on case study evidence, effective funding models must address structural inequalities through equity-centred mechanisms. Progressive allocation should ensure that schools serving marginalised communities receive 1.5 times base funding for quantum programmes. Separate capacity-building grants should support schools below the readiness threshold identified in the implementation framework to build necessary prerequisites. Community partnership funds should provide matching funding for community organisations supporting quantum education, following the Brazilian favela model. Innovation challenge funds offering competitive grants of $10,000–50,000 per project should support locally-developed quantum-SDG solutions.

Rather than importing foreign frameworks wholesale, nations should adapt quantum literacy standards to local contexts while maintaining global compatibility. This curriculum development process should proceed through four phases. The first phase, spanning months one through six, involves national consultation through multi-stakeholder workshops identifying local priorities, mapping quantum applications to national challenges, and culturally adapting pedagogical approaches. The second phase, covering months seven through twelve, focuses on framework adaptation by adopting the eight-domain structure with local modifications, integrating indigenous knowledge systems where relevant, and aligning with existing STEM curricula to minimise disruption. Year two constitutes the pilot and refinement phase, testing materials in diverse school contexts across urban and rural settings and varying resource levels, gathering systematic teacher and student feedback, and refining approaches based on evidence of effectiveness. Years three through five involve national rollout through phased implementation with support systems, continuous monitoring and adaptation, and regular review cycles every three years.

Evidence demonstrates that effective quantum teaching requires 40–120 h of professional development [75]. National strategies should ensure systematic capacity building through several mechanisms: establishment of recognised quantum educator certification with career advancement incentives; creation of regional training centres serving 50–100 schools each to reduce travel costs; implementation of cascade training models whereby master trainers support school-level implementation; funding for ongoing professional learning communities providing continuous support; and university partnerships integrating quantum pedagogy into pre-service teacher education. Table 15 (Appendix) summarises these recommendations across five policy domains: SDG integration, infrastructure investment, equity funding, curriculum development, and teacher capacity building.

Building on successful models from the Philippines and Brazil, developing nations should prioritise horizontal collaboration through regional quantum education networks. An ASEAN Quantum Education Initiative could facilitate shared curriculum resources in regional languages, teacher exchange programmes involving two-week immersions, joint hackathons addressing regional challenges, and cost-sharing arrangements for cloud quantum access. An African Quantum Literacy Alliance could develop a pan-African curriculum framework respecting continental diversity, establish mobile quantum labs circulating between countries, create youth ambassador programmes connecting schools across borders, and coordinate shared funding proposals to international donors. A Latin American Quantum Network could promote community-based implementation models, develop indigenous knowledge integration strategies, support social entrepreneurship through quantum applications, and maintain a regional Spanish and Portuguese resource repository.

International cooperation must avoid perpetuating technological dependency by adhering to equitable technology transfer principles. All technology partnerships must include local capacity development representing a minimum of 20% of project value. Publicly funded quantum education resources must carry open licences ensuring broad accessibility. International programmes must allocate funds specifically for locally-developed solutions rather than exclusively importing external innovations. Reciprocal learning should recognise Global South innovations, such as community pedagogy approaches, as valuable contributions to the global knowledge base. All programmes must demonstrate five-year sustainability plans without ongoing external dependency.

International cooperation should focus on shared infrastructure reducing duplication through what might be termed a Global Quantum Education Commons. This commons would include a multi-language repository serving as a centralised platform with resources in over 50 languages through crowdsourced translation, a cloud quantum access pool providing negotiated bulk access to quantum computers for education at a target cost of $10 per student annually, virtual exchange programmes enabling online collaboration between classrooms globally, open assessment tools comprising shared evaluation instruments adapted to local contexts, and a research database serving as a repository of implementation studies and best practices.

International recognition of quantum literacy competencies can enhance mobility and opportunity through global certification mechanisms. A three-tier certification structure would include Foundation level for ages 11–13 covering basic quantum awareness, Practitioner level for ages 14–16 addressing applied quantum thinking, and Advanced level for ages 16–18 focusing on quantum problem-solving. Flexible assessment would provide multiple pathways recognising diverse strengths through project-based evaluation, examination, and portfolio approaches. Industry recognition through partnership with quantum companies would establish internship eligibility criteria, while advanced certification would provide university course equivalency. Equity provisions would ensure fee waivers for low-income students and alternative assessment modalities for students with disabilities.

### *6.2. Monitoring and implementation roadmap*

Monitoring frameworks must connect quantum literacy to sustainable development outcomes through carefully designed indicators. Table 8 presents a comprehensive set of indicators aligned with SDG monitoring systems, establishing measurable targets for 2030.

Beyond participation numbers, equity requires multidimensional assessment across three indicator categories. Access indicators should capture geographic coverage through urban-rural ratios, socioeconomic representation through income quintile distribution, disability inclusion rates, and language accessibility metrics. Quality indicators should assess teacher qualification parity across school types, resource availability indices, learning outcome gaps between demographic groups, and support service adequacy. Outcome indicators should track completion rate differentials, post-programme pathway diversity, long-term career trajectories, and community impact.

Quantum literacy's true value emerges over time, requiring longitudinal tracking through a ten-year impact study framework operating at multiple levels. At the individual level, studies should track cohorts through education and early career, measuring quantum skill application, career progression, and contribution to innovation. Institutional-level assessment should examine school transformation, teacher development, and curriculum evolution. Community-level documentation should capture local problem-solving initiatives, economic development effects, and social cohesion impacts. National-level evaluation should assess contribution to SDG achievement, innovation indices, and economic competitiveness.

Effective monitoring requires systematic data infrastructure through an integrated data system. This system should incorporate school-level reporting through an annual quantum education census with standardised indicators, student portfolios providing digital records of quantum learning journeys and projects, teacher tracking maintaining professional development records and classroom implementation data, community feedback through regular surveys of parents, employers, and community leaders, and an open data commitment ensuring anonymised data availability for research and accountability purposes.

Based on synthesis of global experiences, we propose a ten-year roadmap for quantum literacy integration organised across six dimensions: policy, capacity, implementation, resources, partnerships, and investment (Table 16, Appendix). The roadmap progresses through four phases, from an initial $5–10M foundation investment piloting in 50 schools to eventual universal access with $30M sustained annual investment.

The foundation-building phase spanning years one and two should establish a national quantum education task force with diverse representation, conduct comprehensive needs assessment and stakeholder mapping, develop a contextualised framework adapting global best practices, launch pilot programmes in diverse contexts for evidence generation, build initial teacher capacity through intensive training programmes, and establish international partnerships and cooperation agreements.

The system expansion phase covering years three through five should scale successful pilot models with continuous refinement, establish regional training centres and support networks, integrate quantum literacy into national curricula standards, launch public awareness campaigns highlighting SDG connections, develop robust monitoring and evaluation systems, and strengthen industry-education partnerships for long-term sustainability.

The transformation and sustainability phase spanning years six through ten should achieve universal access to quantum literacy resources, establish quantum education as a normalised component of

**Table 8**
Quantum literacy indicators aligned with SDG monitoring.

| SDG target | Quantum literacy indicator | Measurement method | 2030 target |
|---|---|---|---|
| 4.4 Skills | % youth with quantum literacy competencies | National assessment | 60% coverage |
| 4.5 Equity | Gender parity index for quantum programmes | Enrolment data | 0.95–1.05 ratio |
| 4.b Scholarships | Quantum education scholarships for Global South | Programme tracking | 10,000 annually |
| 5.b Technology | Girls in quantum computing programmes | Participation data | 45% minimum |
| 8.6 Employment | Quantum programme graduates in STEM careers | Tracer studies | 40% placement |
| 9.5 R&D | Student quantum projects addressing SDGs | Project database | 1000 annually |
| 10.2 Inclusion | Marginalised groups in quantum education | Disaggregated data | 40% participation |
| 17.6 Cooperation | South-South quantum education partnerships | Partnership registry | 50 active |

**Table 9**
Discussion synthesis: Research questions, findings, and literature positioning.

| Research question | Main finding | Key evidence | Literature comparison |
|---|---|---|---|
| RQ1: How to integrate quantum literacy into secondary curricula for SDG achievement? | Eight-domain framework with three implementation pathways (infusion, modular, integrated) and explicit SDG mapping | Scopus AI synthesis across 15 countries; Table 1; three case studies | Extends Stadermann et al. [35] 15-country survey by adding SDG dimension absent from their analysis; complements Gragera Garcés et al. [56] curricula review with actionable implementation models |
| RQ2: What competency domains for quantum-enabled sustainable futures (ages 11–18)? | Eight interconnected domains spanning conceptual, applied, and societal dimensions within progressive age-appropriate pathways | Framework validated against 75 Scopus queries; alignment with Merzel et al. [36] competency categories | Confirms Bitzenbauer et al. [55] expert-identified priorities while adding sustainability and equity dimensions they did not address |
| RQ3: Which strategies bridge the quantum divide in resource-limited settings? | Context-adapted pathways with offline-first design, peer teaching, community ownership, and South-South cooperation | Philippines, South Africa, Brazil case studies; Ukrainian empirical evidence [62] | Addresses gap identified by Nita et al. [54] who documented challenges but proposed no framework; extends Khodaeifaal [58] beyond Canadian context |

STEM curricula, generate local innovations addressing community challenges, create self-sustaining ecosystems requiring minimal external support, contribute to global quantum workforce development and innovation capacity, and document and share lessons learned for global benefit.

These policy recommendations provide a roadmap for integrating quantum literacy into educational systems while advancing sustainable development. Success requires coordinated action across multiple governance levels, sustained commitment over extended timeframes, and unwavering focus on equity and inclusion. The evidence presented throughout this framework demonstrates that quantum literacy education is not only feasible but essential for ensuring all nations can participate in and benefit from the quantum transformation ahead.

## 7. Discussion

The preceding sections have presented an eight-domain quantum literacy framework, documented its application across three diverse Global South contexts, and proposed policy pathways for equitable implementation. This discussion situates these findings within the broader landscape of quantum education research, explicitly addresses the study's research questions, and critically examines the framework's contributions and limitations in relation to established literature.

Table 9 synthesises the principal findings against each research question, the key evidence supporting them, and how they compare with the existing literature.

Regarding the first research question, the framework demonstrates that systematic integration of quantum literacy into secondary curricula requires simultaneous attention to content structure, pedagogical approach, and institutional context. The three implementation pathways – infusion, modular, and integrated – provide graduated entry points that accommodate the wide variation in school readiness documented across the 15 countries analysed. This finding extends the work of Stadermann et al. [35], whose influential survey of secondary quantum physics curricula across 15 countries established the landscape of existing approaches but did not address sustainability connections or equity considerations. Similarly, while Gragera Garcés et al. [56] provide a valuable recent survey of quantum computing curricula, their analysis focuses on content coverage without offering the implementation models that practitioners require. Our framework fills this gap by connecting curricular content to both SDG outcomes and context-specific delivery strategies.

The second research question is addressed through the eight-domain competency structure, which emerged inductively from the Scopus AI synthesis and was subsequently validated against existing competency frameworks. The domains align closely with the expert perspectives reported by Bitzenbauer et al. [55], who surveyed quantum physics education researchers on priorities for secondary-level instruction. However, our framework extends their findings in two important respects: it adds sustainability and equity dimensions absent from their expert panel's considerations, and it specifies progressive learning pathways appropriate for the full 11–18 age range rather than focusing on upper secondary students alone. The competency structure also resonates with Merzel et al. [36], whose quantum literacy assessment framework identifies similar conceptual categories, though their work targets tertiary rather than secondary education.

For the third research question, the case studies provide compelling evidence that resource constraints, while real, need not preclude meaningful quantum education. The Philippines' grassroots model achieved 73% concept understanding improvement through volunteer networks and mobile quantum labs, while Brazil's community-based approach reduced school dropout from 30% to 8% among participants – outcomes that challenge assumptions about the infrastructure prerequisites for quantum education. These findings directly address the gap identified by Nita et al. [54], whose systematic review of challenges in quantum education catalogued barriers comprehensively but stopped short of proposing solutions. Our framework moves beyond problem identification to evidence-informed strategies. The findings also extend Khodaeifaal [58], whose work on quantum computing education was limited to the Canadian context, by demonstrating implementation across three markedly different Global South settings.

Several findings were expected based on existing literature, while others proved surprising. The convergence of all three case studies towards the eight competency domains was anticipated, given the theoretical grounding in established quantum education research [35,75]. Similarly, the three-phase progression (foundation, application, integration) aligns with well-established developmental learning theory. However, the effectiveness of grassroots and community-based models was unexpected. Prior literature, including Tucker [60] and Mihailescu et al. [61], has emphasised institutional and governmental pathways for quantum education, yet the QCSP (Philippines) and QnC (Brazil) programmes demonstrate that bottom-up approaches can achieve comparable or superior engagement outcomes. Equally unexpected was the identification of volunteer burnout as a critical sustainability threat – a finding with important implications for the long-term viability of low-cost implementation models that has received little attention in the quantum education literature.

The framework's generalisability is supported by its successful adaptation across three diverse contexts differing in economic conditions, educational systems, and cultural traditions. A fourth context strengthens this evidence: Lehka [62] provides empirical validation from Ukrainian secondary education, demonstrating that quantum informatics concepts can be effectively taught to lyceum students through carefully designed pedagogical methods. The associated studies [63,66] document specific hardware and software tools and propaedeutic approaches that proved effective in this Eastern European context, extending the geographic scope of evidence beyond the Global South case studies. Together, these four contexts – spanning Southeast Asia, Sub-Saharan Africa, Latin America, and Eastern Europe – suggest that the framework's core principles are robust across diverse educational ecosystems, while the specific adaptations required in each setting underscore the importance of contextual flexibility.

The study's findings should be interpreted in light of several important limitations. The framework rests on synthesis of existing initiatives rather than controlled experimental studies; while case studies demonstrate feasibility, systematic evaluation of learning outcomes through randomised controlled trials remains a critical future need [85]. The Scopus AI methodology, though innovative and comprehensive, cannot replace systematic review protocols, and approximately 70% of analysed literature originates from high-income countries, potentially missing innovative approaches from diverse linguistic communities. The 40–120 h teacher training requirement [75] presents genuine challenges for overburdened educators, though compressed and self-directed models partially address this barrier [57]. Quantum mechanics' counterintuitive nature poses fundamental pedagogical challenges, with persistent misconceptions documented even after instruction [86], and the tension between mathematics-light accessibility and conceptual rigour remains unresolved. Furthermore, while quantum-SDG connections are substantiated by documented technological impacts, they remain partially prospective given the early stage of quantum technology deployment.

Despite these limitations, the convergence of evidence from technological trajectory analysis [1,4,27,28], established quantum education research [35,36,55], and our multi-context implementation evidence supports the framework's core proposition: that quantum literacy education can and should be integrated into secondary education as infrastructure for sustainable development. The critical insight emerging from cross-case analysis is that success depends less on resource availability than on community ownership, cultural adaptation, and sustained pedagogical support – principles that align with broader educational development scholarship while challenging technology-deterministic assumptions prevalent in quantum education discourse.

## 8. Conclusion

### 8.1. Theoretical implications

This study makes three principal theoretical contributions to the intersection of quantum education and sustainable development scholarship. First, it reconceptualises quantum literacy as development infrastructure rather than enrichment content. By positioning quantum literacy alongside digital literacy as essential capacity for twenty-first-century sustainable development [1,4], the framework shifts the theoretical basis for quantum education from workforce preparation to human development. This reframing has significant implications for how educational systems prioritise emerging technology education, suggesting that quantum literacy belongs within core curricula rather than optional programmes.

Second, the sustainability-integrated competency model offers a novel theoretical architecture in which every competency domain explicitly connects quantum understanding to sustainable development applications. Unlike existing frameworks that treat sustainability as supplementary context [35,56], the present approach embeds SDG relevance within the competency structure itself, creating synergies rather than competition between quantum and sustainability education objectives. The eight-domain structure that emerged from cross-national synthesis and was validated across four implementation contexts provides an empirically grounded theoretical foundation that future researchers can test, refine, and extend.

Third, the equity-first design principle constitutes a deliberate theoretical departure from prevailing approaches in quantum education that assume resource-rich environments and retrofit accessibility measures [54,58]. By centring Global South contexts and marginalised communities from inception, the framework demonstrates that equitable design need not compromise educational rigour, as evidenced by learning outcomes in the Philippines, South Africa, and Brazil comparable to those reported in well-resourced settings [55]. This theoretical stance connects quantum education to broader debates about decolonising STEM curricula and challenges technological determinism in educational planning, aligning with Coccia's analysis of how technological trajectories can either reinforce or disrupt existing inequalities [2,3].

### 8.2. Policy implications

The framework's findings carry direct implications for educational policymakers at national and international levels. The evidence that quantum literacy education is feasible across diverse contexts with appropriate adaptation – documented through case studies spanning four continents and empirical evidence from Ukrainian secondary schools [62] – challenges policy assumptions that quantum education requires extensive prerequisites or infrastructure investments before implementation can begin. Policymakers can leverage the three implementation pathways (infusion, modular, integrated) to match quantum literacy initiatives to existing institutional capacity, with the infusion approach offering a particularly low-barrier entry point requiring minimal curricular disruption.

The policy roadmap presented in Section 6 provides specific, costed recommendations for national governments, including progressive equity funding (1.5 times base allocation for marginalised communities), regional training centre establishment, and phased ten-year implementation timelines. International cooperation frameworks – particularly South-South cooperation models demonstrated by ASEAN network expansion from the Philippine case study – offer mechanisms for resource sharing and knowledge exchange that reduce individual national costs. The monitoring indicators aligned with SDG reporting systems (Table 8) enable integration of quantum literacy tracking into existing accountability frameworks rather than creating parallel monitoring burdens.

**Table 10**
Comparative analysis of quantum literacy implementation models.

| Aspect | Infusion approach | Modular approach | Integrated pathway | Resource requirements | Success rate |
|---|---|---|---|---|---|
| Definition | Quantum concepts embedded within existing physics, chemistry, CS courses without structural changes | Standalone quantum literacy modules added as electives or supplementary units | Complete curricular redesign with quantum as cross-cutting theme across all STEM subjects | | |
| Integration level | Topic-level integration (10%–15% of content) | Course-level integration (full semester/term) | System-level integration (multi-year progression) | Minimal to moderate | 65% [87] |
| Teacher preparation | 20–40 h subject-specific training | 40–80 h comprehensive training | 120+ hours with ongoing support | $500–1000 per teacher | Data from [75] |
| SDG integration | Natural connection through applications | Focused sustainability projects | Systemic sustainability thread | Project materials: $50–200/class | |
| Best for | Schools beginning quantum integration with limited resources | Schools with flexibility for electives and motivated teacher champions | Educational systems ready for comprehensive STEM reform | | |

**Table 11**
Quantum literacy implementation readiness checklist: A diagnostic framework for institutional self-assessment across five weighted dimensions.

| Dimension | Essential indicators (Must have) | Desirable indicators (Should have) | Weight |
|---|---|---|---|
| Leadership and vision | • Administrative support secured<br>• Quantum literacy in school plan<br>• Champion teacher identified | • Board/parent endorsement<br>• Industry partnerships<br>• Dedicated funding allocated | 25% |
| Teacher readiness | • Minimum two interested teachers<br>• Basic STEM competence<br>• Professional development time | • Prior quantum exposure<br>• Innovation mindset<br>• Collaborative disposition | 30% |
| Curriculum space | • 10% instructional time available<br>• Assessment flexibility<br>• SDG connections established | • Dedicated quantum sessions<br>• Cross-subject integration<br>• Extended project time | 20% |
| Resources | • Internet access (even if shared)<br>• Basic computers or tablets<br>• Printing capability | • Simulation software<br>• Maker space access<br>• Laboratory equipment | 15% |
| Community | • Parent communication channels<br>• Local relevance identified<br>• Safety concerns addressed | • Industry connections<br>• University partnership<br>• Media engagement | 10% |

**Table 12**
QCSP programme outcomes and SDG alignments (2020–2024).

| Category | Metric | Outcome |
|---|---|---|
| Reach | Educational events conducted<br>Direct participants<br>Indirect beneficiaries | 87 lectures, workshops, hackathons<br>5000+ across 15 provinces<br>Estimated 20,000 |
| Learning outcomes | Concept understanding improvement<br>Quantum-inspired solutions developed<br>Schools adopting quantum modules | 73% (pre/post assessments)<br>34 for local problems<br>15 institutions |
| SDG 4 (Education)<br>SDG 8 (Employment)<br>SDG 10 (Inequality)<br>SDG 13 (Climate) | Geographic spread<br>Career outcomes<br>Demographic inclusion<br>Environmental projects | 15 provinces reached<br>120 quantum-related internships/jobs<br>45% low-income, 38% women<br>Hackathon climate resilience solutions |
| Capacity building | Teachers trained<br>Career aspiration changes | 89 with cascading impact<br>62% considering STEM careers |

A critical policy insight concerns the relationship between implementation model and sustainability. The grassroots model, while highly effective for initial engagement, faces volunteer burnout risks that threaten long-term viability. The public–private partnership model offers greater financial sustainability but risks equity erosion without deliberate safeguards. Policymakers should consider hybrid approaches that combine community ownership with institutional support structures, as suggested by the cross-case analysis.

### *8.3. Ideas for future research*

The limitations acknowledged in the Discussion point towards several priority research directions. Empirical validation represents the most pressing need: multi-year longitudinal studies tracking student cohorts from initial quantum exposure through university and early career would establish whether the framework's competency domains translate into durable learning outcomes and career readiness. Randomised controlled trials comparing the three implementation pathways across diverse contexts would provide the causal evidence that the current synthesis-based methodology cannot supply [85]. Cross-cultural comparative studies examining how cultural factors – including indigenous knowledge systems, language structures, and philosophical traditions – influence quantum concept understanding would inform localisation strategies currently based primarily on practitioner intuition.

Pedagogical innovation research offers substantial opportunities. The Brazilian favela case study's use of culturally embedded pedagogy (*samba quantum*, capoeira-based demonstrations) suggests promising directions for indigenous knowledge integration that deserve systematic investigation through participatory action research. As extended reality technologies mature, research on immersive quantum education – including virtual reality visualisation of quantum phenomena, gamification, and AI-assisted personalised learning pathways – could address persistent challenges with counterintuitive quantum concepts [86,88]. Development of valid, reliable assessment instruments for quantum literacy that function across mathematical ability levels and cultural contexts remains a critical methodological gap.

Systems-level research is essential for scaling quantum literacy education. Comparative policy analysis examining what factors determine successful national adoption would inform evidence-based policy refinement. Research on optimal teacher professional development models, including minimum effective training duration and the relative effectiveness of face-to-face versus self-directed approaches, would address the feasibility concerns surrounding the 40–120 h training requirement [89]. Investigation of whether quantum education initiatives reduce or exacerbate existing inequalities demands careful longitudinal study with attention to intersectional factors. Finally, deeper investigation of quantum technology's role in sustainability transitions – including lifecycle assessments and potential rebound effects – would strengthen the SDG connections central to the framework while honestly engaging with critiques regarding the directness and certainty of these connections [27,28].

## CRediT authorship contribution statement

**Serhiy O. Semerikov:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Svitlana V. Shokaliuk:** Writing – review & editing, Methodology, Formal analysis. **Olga B. Kanevska:** Writing – review & editing, Writing – original draft, Investigation. **Vita A. Hamaniuk:** Writing – review & editing, Resources, Methodology. **Oleksandr H. Kolgatin:** Writing – review & editing, Investigation, Formal analysis.

## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Claude 4 Opus (Anthropic) in order to enhance readability of the manuscript text, produce research highlights, and enhance keywords for better discoverability. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the published article.

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix. Supplementary tables

See Tables 10–16.

**Table 13**
QS4A programme outcomes and sustainability mechanisms (2019–2024).

| Category | Metric | Outcome |
|---|---|---|
| Scale | Schools participating<br>Learners engaged<br>Teachers trained | 156 across 9 provinces<br>12,000 directly<br>450 in quantum concepts |
| Learning outcomes | Assessment pass rate<br>University progression | 78% quantum literacy<br>230 entering quantum programmes |
| Employment impact | Jobs created<br>Internships provided<br>Private investment | 89 quantum-related positions<br>340 placements<br>R45 million ($2.5M sustained) |
| SDG contributions | SDG 4<br>SDG 8<br>SDG 9<br>SDG 17 | Quality education for excluded populations<br>Decent work through skills development<br>Innovation in telecoms and finance<br>Model partnership architecture |
| Sustainability | Legislative framework<br>Incentive structure<br>Policy integration<br>Continuity mechanism | 5-year minimum commitments<br>Tax benefits for corporate investment<br>National Development Plan 2030<br>Alumni network support |

**Table 14**
QnC programme outcomes and community impact (2021–2024).

| Category | Metric | Outcome |
|---|---|---|
| Participation | Youth engaged<br>Programme completion | 340 participants<br>89% completing 6-month cycle |
| Applied outcomes | Community solutions developed<br>Mathematics improvement<br>University STEM entry<br>Micro-businesses created | 15 (water, security, schools)<br>67% of participants<br>23 (first in families)<br>8 using quantum optimisation |
| SDG contributions | SDG 1 (Poverty)<br>SDG 10 (Inequality)<br>SDG 11 (Cities)<br>SDG 16 (Peace) | Technology skills and jobs<br>Cutting-edge science access<br>Urban challenge solutions<br>Youth engagement, violence reduction |
| Unexpected outcomes | Identity transformation<br>Intergenerational dialogue<br>Dropout reduction<br>External recognition | Community pride and agency<br>Technology and future discussions<br>From 30% to 8% among participants<br>International resources attracted |
| Replication | Brazilian favelas<br>Other contexts<br>South-South exchange | 12 communities adopted model<br>Indigenous Amazonas, Colombia, Peru, Mexico<br>African township partnerships |

**Table 15**
Summary of national policy recommendations for quantum literacy integration.

| Policy domain | Key actions | Resource implications | Timeline |
|---|---|---|---|
| SDG integration | Incorporate quantum literacy into national SDG action plans; establish multi-stakeholder governance | Policy development costs; coordination mechanisms | Years 1–2 |
| Infrastructure investment | Create dedicated budget lines; invest in cloud access; develop open resources | 0.5% education budget; $500K per region for cloud | Years 1–5 |
| Equity funding | Progressive allocation (1.5x for marginalised); capacity-building grants; community partnerships | 40% additional equity allocation | Ongoing |
| Curriculum development | National consultation; framework adaptation; pilot testing; phased rollout | Curriculum development team; pilot school support | Years 1–5 |
| Teacher capacity | Certification programmes; regional centres; cascade training; PLCs; university integration | 30% of quantum education budget | Years 1–10 |

**Table 16**
Ten-year quantum literacy implementation roadmap.

| Dimension | Years 1–2 (Foundation) | Years 3–5 (Expansion) | Years 6–8 (Scaling) | Years 9–10 (Sustainability) |
|---|---|---|---|---|
| Policy | Framework development; stakeholder consultation | Standards adoption; funding allocation | Policy refinement; regional adaptation | Institutionalisation; review cycles |
| Capacity | Master trainer preparation (200) | Teacher rollout (2000) | School-based PLCs (10,000) | Pre-service integration |
| Implementation | Pilot in 50 schools | Expand to 500 schools | Scale to 2500 schools | Universal access |
| Resources | OER development and translation | Platform deployment; lab setup | Maintenance and updates | Community generation |
| Partnerships | Initial PPPs; international links | Regional networks; industry engagement | Ecosystem maturation | Self-sustaining systems |
| Investment | $5–10M initial | $20–30M annually | $50M annually | $30M sustained |

## Data availability

No data was used for the research described in the article.

## References


[1] M. Coccia, S. Roshani, M. Mosleh, Evolution of quantum computing: Theoretical and innovation management implications for emerging quantum industry, IEEE Trans. Eng. Manage. 71 (2024) 2270–2280, http://dx.doi.org/10.1109/TEM.2022.3175633.
[2] M. Coccia, Disruptive innovations in quantum technologies for social change, J. Econ. Bibliogr. 9 (1) (2022) 21–39, URL: https://journals.econsciences.com/index.php/JEB/article/view/2287.
[3] M. Coccia, Technological trajectories in quantum computing to design a quantum ecosystem for industrial change, Technol. Anal. Strat. Manag. 36 (8) (2024) 1733–1748, http://dx.doi.org/10.1080/09537325.2022.2110056.
[4] M. Coccia, S. Roshani, Evolutionary phases in emerging technologies: Theoretical and managerial implications from quantum technologies, IEEE Trans. Eng. Manage. 71 (2024) 8323–8338, http://dx.doi.org/10.1109/TEM.2024.3385116.
[5] G. Munawar, K. Surendro, Utilizing quantum algorithms to achieve carbon neutrality in urban areas: A systematic review, Alex. Eng. J. 108 (2024) 911–936, http://dx.doi.org/10.1016/j.aej.2024.09.043.
[6] B. Szczesny, W. Gryncewicz, Quantum advantage applied - research on probability of success, in: Proceedings - International Conference on Advanced Computer Information Technologies, ACIT, 2023, pp. 468–472, http://dx.doi.org/10.1109/ACIT58437.2023.10275418.
[7] S.K. Sheoran, V. Yadav, R.K. Sheoran, Quantum computing for sustainable energy: Optimising SDG-7 through smart energy management and financial planning, in: Proceedings of International Conference on Modern Sustainable Systems, CMSS 2025, Institute of Electrical and Electronics Engineers Inc, 2025, pp. 1012–1020, http://dx.doi.org/10.1109/CMSS66566.2025.11182548.
[8] P.K. Sinha, M. R, Comparative study of quantum and classical algorithms for renewable energy sources, Results Eng. 27 (2025) 107062, http://dx.doi.org/10.1016/j.rineng.2025.107062.
[9] M.K. Saggi, A.S. Bhatia, S. Kais, Federated quantum machine learning for drug discovery and healthcare, Annu. Rep. Comput. Chem. 20 (2024) 269–322, http://dx.doi.org/10.1016/bs.arcc.2024.10.007.
[10] S. Yadav, Transformative learning with advanced technologies: Harnessing VR and AR for immersive educational experiences, in: J.A. Ruiz-Vanoye, O.D. az Parra (Eds.), Revolutionizing Pedagogy Through Smart Education, IGI Global Scientific Publishing, Hershey, PA, 2025, pp. 139–155, http://dx.doi.org/10.4018/979-8-3693-7793-2.ch008.
[11] K. Deeba, S. Ramya, B. Geetha, K.S. Kumari, Quantum computing AI for climate modeling, in: P. Raj, B. Sundaravadivazhagan, M. Ouaissa, V. Kavitha, K.S. Kumari (Eds.), Quantum Computing and Artificial Intelligence: The Industry Use Cases, Scrivener Publishing LLC, 2025, pp. 247–260, http://dx.doi.org/10.1002/9781394242399.ch9.
[12] K. Suresh, R. Vidhya, S. Poonkodi, S. Hemavathi, V. Kavitha, A. Anoop, Quantum computing in healthcare: exploring applications for drug discovery and precision medicine, in: A. Kumar, A.K. Dubey, V. Piuri, J.J.P.C. Rodrigues (Eds.), Exploring Intelligent Healthcare with Quantum Computing, Institution of Engineering and Technology, 2024, pp. 181–198, http://dx.doi.org/10.1049/PBHE060E_ch10.
[13] P.V. Zahorodko, S.O. Semerikov, V.N. Soloviev, A.M. Striuk, M.I. Striuk, H.M. Shalatska, Comparisons of performance between quantum-enhanced and classical machine learning algorithms on the IBM quantum experience, J. Phys.: Conf. Ser. 1840 (1) (2021) 012021, http://dx.doi.org/10.1088/1742-6596/1840/1/012021.
[14] A. Nayak, A. Tiwari, Biodegradable optical sensors with quantum-assisted signal processing for sustainable and high-precision sensing, in: M.S.V. Kumar, K.S. Raju, K. Rajakumar, S. Saravanakumar (Eds.), A Study on Next-Generation Materials and Devices, CRC Press, London, 2025, pp. 171–176, http://dx.doi.org/10.1201/9781003675259-34.
[15] S. Rosales, O.E. Medina, N. Garzon, K. Zapata, E.A. Taborda, J.C. Ordóñez, F.B. Cortés, C.A. Franco, Systematic review of carbon quantum dots (CQD): Definition, synthesis, applications and perspectives, Renew. Sustain. Energy Rev. 219 (2025) 115854, http://dx.doi.org/10.1016/j.rser.2025.115854.
[16] M. Jammal, L. Sanz-Martín, J. Parra-Domínguez, Quantum innovations: Driving sustainability through AI and quantum technologies, in: P. Novais, P. B. D., I. Satoh, V.J. Inglada, S.R. González, E. Jove Pérez, J. Parra Domínguez, P. Chamoso, R.S. Alonso (Eds.), Ambient Intelligence – Software and Applications

– 15th International Symposium on Ambient Intelligence, in: Lecture Notes in Networks and Systems, vol. 1279, Springer Nature Switzerland, Cham, 2025, pp. 351–359, http://dx.doi.org/10.1007/978-3-031-83117-1_33.

[17] Priyanka, P. Dhuliya, D. Singh Rana, S. Goyal, S. Kukreti, S. Pundir, Quantum computing for sustainable development: A framework for environmental and social impact, in: T. Joshi, S. Semwal (Eds.), 3rd International Conference on Advances in Computing, Communication and Materials, ICACCM 2024, Institute of Electrical and Electronics Engineers Inc, 2024, http://dx.doi.org/10.1109/ICACCM61117.2024.11059008.

[18] R. Dvorak, F. Bahadori, Leveraging open source tools to teach quantum computing foundations: Bridging the future workforce gap in the quantum era, in: 2024 ASEE Annual Conference & Exposition, ASEE Conferences, Portland, Oregon, 2024, http://dx.doi.org/10.18260/1-2–47743.

[19] S.D. Bennett, Accelerated technology transfer: The UK quantum initiative, in: K.L. Lewis, R.C. Hollins (Eds.), Proceedings of SPIE - the International Society for Optical Engineering, Vol. 9992, SPIE, 2016, http://dx.doi.org/10.1117/12.2243371.

[20] L. Li, C.-W. Huang, C. Morgan, K. Luttgen, E. Chow, S. Yang, Empowering rural students through computational thinking and real-world STEM applications: insights from an innovative high school curriculum, Front. Educ. 9 (2024) http://dx.doi.org/10.3389/feduc.2024.1452470.

[21] E. Oh, M.D. Gregoire, A.T. Black, K.J. Hughes, P.D. Kunz, M. Larsen, J. Lautier-Gaud, J. Lee, P.D.D. Schwindt, S.L. Mouradian, F.A. Narducci, C.A. Sackett, Perspective on quantum sensors from basic research to commercial applications, AIAA J. 62 (11) (2024) 4029–4053, http://dx.doi.org/10.2514/1.J062707.

[22] A. Baitulmal, N. Adem, Why should and how can quantum technologies be leveraged at national levels? IET Quantum Commun. 4 (2) (2023) 96–101, http://dx.doi.org/10.1049/qtc2.12057.

[23] F. Greinert, R. Müller, European Competence Framework for Quantum Technologies (CFQT) – Reference Framework for Planning, Mapping and Comparing QT-Related Educational Activities, Personal Qualification and Job Requirements, Publications office of the European Union, Luxembourg, 2024, http://dx.doi.org/10.2759/389764.

[24] A. Purohit, M. Kaur, Z.C. Seskir, M.T. Posner, A. Venegas-Gomez, Building a quantum-ready ecosystem, IET Quantum Commun. 5 (1) (2024) 1–18, http://dx.doi.org/10.1049/qtc2.12072.

[25] S. Wills, Staffing the quantum revolution, Opt. Photonics News 34 (3) (2023) 26–30, http://dx.doi.org/10.1364/opn.34.3.000026.

[26] M. Coccia, S. Roshani, Path-breaking directions in quantum computing technology: A patent analysis with multiple techniques, J. knowl. Econ. 16 (1) (2025) 4991–5024, http://dx.doi.org/10.1007/s13132-024-01977-y.

[27] M. Coccia, Converging artificial intelligence and quantum technologies: Accelerated growth effects in technological evolution, Technologies 12 (5) (2024) 66, http://dx.doi.org/10.3390/technologies12050066.

[28] B. Kargi, M. Coccia, Quantum technology research field variability to explain scientific and technical development in society, Int. J. Technol. Learn. Innov. Dev. 16 (4) (2025) 384–405, http://dx.doi.org/10.1504/IJTLID.2025.149366.

[29] S.M. Jamali, N. Ale Ebrahim, F. Jamali, The role of STEM education in improving the quality of education: a bibliometric study, Int. J. Technol. Des. Educ. 33 (3) (2023) 819–840, http://dx.doi.org/10.1007/s10798-022-09762-1.

[30] N. Chongtham, O. Santosh, M. Bhardwaj, Significance of strengthening STI ecosystems for achieving sustainable development goals, in: K. Singh, N. Chongtham, R. Trikha, M. Bhardwaj, S. Kaur (Eds.), Science, Technology and Innovation Ecosystem: An Indian and Global Perspective, Springer Nature Singapore, Singapore, 2024, pp. 415–435, http://dx.doi.org/10.1007/978-981-97-2815-2_18.

[31] O.V. Barna, O.H. Kuzminska, S.O. Semerikov, Enhancing digital competence through STEM-integrated universal design for learning: a pedagogical framework for computer science education in Ukrainian secondary schools, Discov. Educ. 4 (1) (2025) 357, http://dx.doi.org/10.1007/s44217-025-00821-y.

[32] S.O. Semerikov, P.P. Nechypurenko, T.A. Vakaliuk, I.S. Mintii, Resilience through crisis: an integrated framework for entrepreneurial STEM education in conflict-affected contexts, Discov. Educ. 5 (1) (2026) 24, http://dx.doi.org/10.1007/s44217-025-01041-0.

[33] J.C. Meyer, G. Passante, B. Wilcox, Disparities in access to U.S. quantum information education, Phys. Rev. Phys. Educ. Res. 20 (1) (2024) 010131, http://dx.doi.org/10.1103/PhysRevPhysEducRes.20.010131.

[34] D. Kettani, B. Moulin, L.S. Barbosa, Digital divide (2.0): the shadow of AI technology, Perspect. Glob. Dev. Technol. 24 (3–4) (2025) 484–513, http://dx.doi.org/10.1163/15691497-12341720.

[35] H.K.E. Stadermann, E. Van Den Berg, M.J. Goedhart, Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic, Phys. Rev. Phys. Educ. Res. 15 (1) (2019) 010130, http://dx.doi.org/10.1103/PhysRevPhysEducRes.15.010130.

[36] A. Merzel, P. Bitzenbauer, K. Krijtenburg-Lewerissa, K. Stadermann, E. Andreotti, D. Anttila, M. Bondani, M.L. Chiofalo, S. Faletič, R. Frans, S. Goorney, F. Greinert, L. Jurčić, Z. Koupilová, M. Malgieri, R. Müller, P. Onorato, G. Pospiech, M. Ubben, A. Woitzik, H. Pol, The core of secondary level quantum education: a multi-stakeholder perspective, EPJ Quantum Technol. 11 (1) (2024) 27, http://dx.doi.org/10.1140/epjqt/s40507-024-00237-x.

[37] U. Bhimavarapu, Data colonialism: The silent force behind global inequality, in: K. Wongmahesak, T. Sriyakul, U. Ghosh, I. Wekke (Eds.), Technology, Geopolitics, and the Transformation of International Political Economy, IGI Global Scientific Publishing, Hershey, PA, 2025, pp. 277–301, http://dx.doi.org/10.4018/979-8-3373-1727-4.ch012.

[38] J.S.d.S. Cristóvam, T.P. de Sousa, Technological sovereignty vs. digital coloniality: Smart state and public policies for an AI bethânia [soberania tecnológica vs. colonialidade digital: Estado inteligente e políticas públicas para uma IA Bethânia], Sequencia 45 (98) (2024) 1–33, http://dx.doi.org/10.5007/2177-7055.2024.e103426.

[39] N. Ahmad, M. Toro-Troconis, M. Ibahrine, R. Armour, V. Tait, K. Reedy, R. Malevicius, V. Dale, N. Tasler, Y. Inzolia, Codesigns education for sustainable development: A framework for embedding education for sustainable development in curriculum design, Sustainability 15 (23) (2023) 16460, http://dx.doi.org/10.3390/su152316460.

[40] I.-M. Eichentopf, H.D. Kasperidus, Integrating technology assessment, systems thinking, and system dynamics in sustainability education: The need for an interdisciplinary framework, Int. J. Educ. Res. Open 9 (2025) 100535, http://dx.doi.org/10.1016/j.ijedro.2025.100535.

[41] G. Herrera-Franco, C. Mora-Frank, P. Carrión-Mero, Sustainable development in Latin American higher education institutions, in: W. Leal Filho, F. Frankenberger, U. Tortato (Eds.), Sustainability in Practice: Addressing Challenges and Creating Opportunities in Latin America, in: World Sustainability Series, Springer Nature Switzerland, Cham, 2023, pp. 93–110, http://dx.doi.org/10.1007/978-3-031-34436-7_7.

[42] C. Barclay, E.W. Duggan, Rethinking the digital divide: Towards a path of digital effectiveness, in: Proceedings of the Annual Hawaii International Conference on System Sciences, 2008, http://dx.doi.org/10.1109/HICSS.2008.376.

[43] S. Brooks, P. Donovan, C. Rumble, Developing nations, the digital divide and research databases, Ser. Rev. 31 (4) (2005) 270–278, http://dx.doi.org/10.1016/j.serrev.2005.09.002.

[44] Z.C. Seskir, S. Umbrello, C. Coenen, P.E. Vermaas, Democratization of quantum technologies, Quantum Sci. Technol. 8 (2) (2023) 024005, http://dx.doi.org/10.1088/2058-9565/acb6ae.

[45] D.J.D. Lopez, E. Peramo, J.M. Ayson, A.N.S. Masongsong, L.D.C. Raquel, B.O. Corpus, Quantum computing society of the Philippines: An NGO perspective on promoting quantum information, science, and technology in the Philippines, in: M. Osinski, B. La Cour, L. Yeh (Eds.), Proceedings - IEEE Quantum Week 2024, QCE 2024, Vol. 3, Institute of Electrical and Electronics Engineers Inc, 2024, pp. 89–95, http://dx.doi.org/10.1109/QCE60285.2024.20463.

[46] R. Mudaly, T. Chirikure, STEM education in the global north and global south: competition, conformity, and convenient collaborations, Front. Educ. 8 (2023) http://dx.doi.org/10.3389/feduc.2023.1144399.

[47] P.D.R. Bambi, J.B.B. Pea-Assounga, Unraveling the interplay of research investment, educational attainment, human capital development, and economic advancement in technological innovation: A panel VAR approach, Educ. Inf. Technol. 30 (3) (2025) 3309–3341, http://dx.doi.org/10.1007/s10639-024-12938-y.

[48] S. Devendrababu, S. Ganguly, K. Hemachandran, Mapping quantum industry demands to education: a critical analysis of skills, qualifications, and modalities, EPJ Quantum Technol. 12 (1) (2025) 105, http://dx.doi.org/10.1140/epjqt/s40507-025-00406-6.

[49] E.T. McChesney, Y.-H. Weng, C.E. Winkler, B. Selznick, M.J. Mayhew, The effect of interdisciplinary training on cultivating graduate student innovation capacities, Innov. High. Educ. (2025) http://dx.doi.org/10.1007/s10755-025-09848-3.

[50] U. Genenz, N. Anne, Z. Kiliç, D. Mathews, O. Ok, A. Schmidt, Z.C. Seskir, Why teach quantum on your own time: The values of grassroots organisations involved in quantum technologies education and outreach, in: M. Osinski, B. La Cour, L. Yeh (Eds.), Proceedings - IEEE Quantum Week 2024, QCE 2024, Vol. 3, Institute of Electrical and Electronics Engineers Inc, 2024, pp. 82–88, http://dx.doi.org/10.1109/QCE60285.2024.20462.

[51] A.S. Petrenko, S.S. Petrenko, K.A. Makoveichuk, A.V. Olifirov, H. Krachunov, Security threat model based on analysis of foreign national quantum programs, CEUR Work. Proc. 3057 (2021) 11–25, URL: https://ceur-ws.org/Vol-3057/paper2.pdf.

[52] M. Sabiteka, X. Yu, C. Sun, Toward sustainable education: A contextualized model for educational technology adoption for developing countries, Sustainability 17 (8) (2025) 3592, http://dx.doi.org/10.3390/su17083592.

[53] D.K. Evans, A. Popova, Education in Africa: What Are We Learning? Working Paper 542, Centre for Global Development, 2020, URL: https://www.cgdev.org/sites/default/files/education-africa-what-are-we-learning.pdf.

[54] L. Nita, L. Mazzoli Smith, N. Chancellor, H. Cramman, The challenge and opportunities of quantum literacy for future education and transdisciplinary problem-solving, Res. Sci. Technol. Educ. 41 (2) (2023) 564–580, http://dx.doi.org/10.1080/02635143.2021.1920905.

[55] P. Bitzenbauer, M.S. Ubben, D. Anttila, M. Bondani, M.L. Chiofalo, S. Faletic, S. Goorney, F. Greinert, R. Müller, Z. Koupilová, M. Malgieri, A. Merzel, H.J. Pol, G. Pospiech, H.K.E. Stadermann, E.Y. Weissman, K. Krijtenburg-Lewerissa, Expert perspectives on the future of quantum physics education at the secondary level,

Phys. Rev. Phys. Educ. Res. 21 (2025) 020157, http://dx.doi.org/10.1103/d1yx-kfsz.

[56] M. Gragera Garcés, L. Gómez Orzechowski, J.F. Rodríguez Hernández, Introducing quantum computing to high-school curricula: A global perspective, 2025, arXiv:2505.14809.

[57] V.V. Nautiyal, E.E.P. Salvador, X.R.O. Braña, R. Shastri, V. Singh, A. Tyagi, B. Vidhani, V. Prasad, Enhancing high school students' understanding and attitude towards quantum mechanics through discipline-culture framework and cognitive apprenticeship, EPJ Quantum Technol. 12 (1) (2025) 104, http://dx.doi.org/10.1140/epjqt/s40507-025-00407-5.

[58] S. Khodaeifaal, Curriculum, Pedagogy, and the Practical: From Waves to Quantum Physics (Ph.D. thesis), Simon Fraser University, 2022, URL: https://summit.sfu.ca/item/34969.

[59] S. Khodaeifaal, Updated and adapted curriculum and pedagogy of physics with the fourth industrial revolution and quantum revolution: From waves principles to quantum mechanics fundamentals, in: 2022 IEEE International Conference on Quantum Computing and Engineering , QCE, 2022, pp. 653–668, http://dx.doi.org/10.1109/QCE53715.2022.00088.

[60] D.L. Tucker, Leveraging dual enrollment programs to expand secondary education in quantum computation, in: 2023 IEEE International Conference on Quantum Computing and Engineering, QCE, Vol. 03, 2023, pp. 10–14, http://dx.doi.org/10.1109/QCE57702.2023.20319.

[61] M.I. Mihailescu, S.L. Nita, V. Marascu, M. Rogobete, Integrating quantum computing into new learning technologies, in: EDULEARN24 Proceedings, in: 16th International Conference on Education and New Learning Technologies, IATED, 2024, pp. 0022–0031, http://dx.doi.org/10.21125/edulearn.2024.0022.

[62] L.V. Lehka, Methods of Teaching the Basics of Quantum Informatics to Lyceum Students (PhD dissertation), Kryvyi Rih State Pedagogical University, Kryvyi Rih, Ukraine, 2021, http://dx.doi.org/10.31812/123456789/7042, Speciality 13.00.02 — Theory and Methods of Teaching (Informatics).

[63] L.V. Lehka, S.V. Shokaliuk, Hardware and software tools for teaching the basics of quantum informatics to lyceum students, Educ. Dimens. 4 (2021) 102–121, http://dx.doi.org/10.31812/educdim.v56i4.4440.

[64] F.S. Malik, O. Terzidis, A hybrid framework for creating artificial intelligence-augmented systematic literature reviews, Manag. Rev. Q. (2025) http://dx.doi.org/10.1007/s11301-025-00522-8.

[65] J. Logan, J. Webb, N.K. Singh, N. Tanner, K. Barrett, M. Wall, B. Walsh, A.P. Ayala, Scoping review search practices in the social sciences: A scoping review, Res. Synth. Methods 15 (6) (2024) 950–963, http://dx.doi.org/10.1002/jrsm.1742.

[66] L.V. Lehka, S.V. Shokaliuk, Y.Y. Bohunenko, Propaedeutics of quantum informatics in institutions of general secondary education, Phys. Math. Educ. 28 (2) (2021) 51–56, http://dx.doi.org/10.31110/2413-1571-2021-028-2-009.

[67] F.M. Mateko, Digital technologies and economic development in Zimbabwe, Dev. (Basingstoke) 67 (1) (2024) 85–90, http://dx.doi.org/10.1057/s41301-024-00400-y.

[68] H. Amber, B.B. Chichaibelu, Narrowing the gender digital divide in Pakistan: Mobile phone ownership and female labor force participation, Rev. Dev. Econ. 27 (3) (2023) 1354–1382, http://dx.doi.org/10.1111/rode.12994.

[69] A. Forbes, F. Petruccione, F.S. Roux, Toward a quantum future for South Africa, AVS Quantum Sci. 3 (4) (2021) 040501, http://dx.doi.org/10.1116/5.0060426.

[70] Department of Science and Technology, Cabinet approves National Quantum Mission to Accelerate Quantum Technology-Led Economic Growth, Press Information Bureau, Government of India, 2023, URL: https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1917861.

[71] C. Chakraborty, M. Bhattacharya, S. Pal, G. Agoramoorthy, India's quantum move: From budget allocation, action and future challenges, Mol. Biotechnol. 66 (12) (2024) 3449–3461, http://dx.doi.org/10.1007/s12033-023-00975-w.

[72] J. Kirchherr, F. Urban, Technology transfer and cooperation for low carbon energy technology: Analysing 30 years of scholarship and proposing a research agenda, Energy Policy 119 (2018) 600–609, http://dx.doi.org/10.1016/j.enpol.2018.05.001.

[73] D.R. Čubrilo, Z.L. Crvenković, D. Obadović, M. Segedinac, The application of multimedia and its effects on teaching physics in secondary school, Zb. Inst. Pedagos. Istraz. 46 (2) (2014) 339–363, http://dx.doi.org/10.2298/ZIPI1402339R.

[74] E. Marshman, C. Singh, QuILTs: Validated teaching–learning sequences for helping students learn quantum mechanics, in: J. Borg Marks, P. Galea, S. Gatt, D. Sands (Eds.), Physics Teacher Education: What Matters? Springer International Publishing, Cham, 2022, pp. 15–35, http://dx.doi.org/10.1007/978-3-031-06193-6_2.

[75] A. Merzel, E.Y. Weissman, N. Katz, I. Galili, Toward teacher training for teaching quantum physics in high school, in: J. Borg Marks, P. Galea, S. Gatt, D. Sands (Eds.), Physics Teacher Education: What Matters? Springer International Publishing, Cham, 2022, pp. 161–172, http://dx.doi.org/10.1007/978-3-031-06193-6_12.

[76] K. Tóth, Integrating Dirac approach to quantum mechanics into physics teacher education, AIP Conf. Proc. 2843 (1) (2023) 050011, http://dx.doi.org/10.1063/5.0150429.

[77] F. Hennig, K. Tóth, J. Veith, P. Bitzenbauer, Introducing quantum physics concepts and Dirac notation at the secondary school level: Insights into student reasoning from an acceptance survey, Phys. Rev. Phys. Educ. Res. 20 (2) (2024) 020147, http://dx.doi.org/10.1103/PhysRevPhysEducRes.20.020147.

[78] S. Montagnani, A. Stefanel, M.L.M. Chiofalo, L. Santi, M. Michelini, An experiential program on the foundations of quantum mechanics for final-year high-school students, Phys. Educ. 58 (3) (2023) 035003, http://dx.doi.org/10.1088/1361-6552/acb5da.

[79] K.L. Bates, C. Hung, J. Jordan Steel, Biotechnology immersion program: professional development where the participants do the preparation, teaching, and outreach to maximize learning gains, FEMS Microbiol. Lett. 369 (1) (2022) fnac111, http://dx.doi.org/10.1093/femsle/fnac111.

[80] S. Krainara, S. Chatmaneerungcharoen, Building a professional learning community with team endeavors while creating elementary-focused STEM-integrated lesson plans, J. Phys.: Conf. Ser. 1340 (1) (2019) 012015, http://dx.doi.org/10.1088/1742-6596/1340/1/012015.

[81] B.J.S. Barron, D.L. Schwartz, N.J. Vye, A. Moore, A. Petrosino, L. Zech, J.D. Bransford, Doing with understanding: Lessons from research on problem- and project-based learning, J. Learn. Sci. 7 (3–4) (1998) 271–311, http://dx.doi.org/10.1080/10508406.1998.9672056.

[82] G.A. Brown, J. Bull, M. Pendlebury, Assessing Student Learning in Higher Education, Routledge, London, 1997, http://dx.doi.org/10.4324/9781315004914.

[83] C. Makalima, Y. Gwala, L. Makasi, A. Baza, A.M. Lwanga, Co-designing an integrated digital education portal for the eastern cape rural learners, in: Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems, in: CHI EA '23, Association for Computing Machinery, New York, NY, USA, 2023, p. 579, http://dx.doi.org/10.1145/3544549.3583839.

[84] C. Heymans, M. Schur, National and provincial PPPs: Issues of supervision and accountability, Dev. South. Afr. 16 (4) (1999) 607–622, http://dx.doi.org/10.1080/03768359908440104.

[85] C.M. Stracke, I.-A. Chounta, W. Holmes, A. Tlili, A. Bozkurt, A standardised PRISMA-based protocol for systematic reviews of the scientific literature on artificial intelligence and education (AI&ED), J. Appl. Learn. Teach. 6 (2) (2023) 64–70, http://dx.doi.org/10.37074/jalt.2023.6.2.38.

[86] G. Song, X. Wang, R. Ghannam, Immersive quantum: A systematic literature review of XR in quantum technology education, Comput. Educ.: X Real. 5 (2024) 100087, http://dx.doi.org/10.1016/j.cexr.2024.100087.

[87] S. Im, M. Kwon, High school students' preference for physics and interest in learning quantum physics, New Phys.: Sae Mulli 72 (10) (2022) 769–781, http://dx.doi.org/10.3938/NPSM.72.769.

[88] N.V. Rashevska, S.O. Semerikov, From philosophical immersion to digital reality: A unified theoretical framework for understanding and classifying immersive technologies in education, Comput. Educ.: X Real. 8 (2026) 100147, http://dx.doi.org/10.1016/j.cexr.2026.100147.

[89] V. Borish, H. Lewandowski, Affordances and challenges of incorporating a remote, cloud-accessible quantum experiment into undergraduate courses, Phys. Rev. Phys. Educ. Res. 21 (1) (2025) 010133, http://dx.doi.org/10.1103/PhysRevPhysEducRes.21.010133.