MODESTUM
EURASIA Journal of Mathematics, Science and Technology Education, 2026, 22(9), em2898
ISSN:1305-8223 (online)
OPEN ACCESS
Research Paper
https://doi.org/10.29333/ejmste/19117

Effects of an integrated STEAM-informed quantum technology outreach program on high school students' attitudes towards quantum information science and technology

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Received 08 May 2026 ▪ Accepted 02 August 2026

Abstract

Rapid advances in quantum information science and technology (QIST) necessitate the preparation of pre-university students for future study and careers in this emerging field. QIST is inherently interdisciplinary, integrating concepts from physics, mathematics, engineering, computer science, humanities, and philosophy – with implications extending beyond technological innovation to socio-economic and sociopolitical dimensions. Despite the highly interdisciplinary nature of QIST and its relevance for 21st century workforce development, empirical studies explicitly applying integrated science, technology, engineering, arts, and mathematics (*i*-STEAM) pedagogy to QIST education at the pre-university level remain scarce. We address this gap by presenting the design and implementation of a fully online, *i*-STEAM informed QIST outreach program involving 29 high-achieving secondary school students (grade 9-grade 11) from the Philippines. Using a mixed-methods research design with a pre- and post-test, single-group quasi-experimental format, we report the program's influence on students' attitudes toward QIST. Quantitative results indicate a statistically significant positive shift in students' attitudes with medium effect size (Cohen's d = 0.51) after participating in the program. Quantitative results were supported by the qualitative findings as a thematic analysis of students' reflections after the program indicated themes related to positive attitude towards QIST. In addition to attitudinal themes related to positive emotions, thematic analysis identified two other major themes, i.e., students' increased appreciation of science-technology-society connections and their reflective insights into the nature of science. Our findings, supported by data and method triangulation, suggest that *i*-STEAM-informed quantum technology education has the potential to promote holistic scientific literacy extending beyond technical competencies that may foster deeper understanding of QIST's societal implications.

Keywords: STEAM education, STEM education, integrated STEM, integrated STEAM, quantum outreach, physics education, quantum education, secondary students

INTRODUCTION

The interdisciplinary domain of quantum information science and technology (QIST) is expanding rapidly in the "second quantum revolution" (Dowling & Milburn, 2003), with the quantum technology (QT) sector experiencing significant growth (Greinert et al., 2024). The QT sector promises to harness exotic quantum phenomena such as superposition and entanglement for transformative applications across various industries including computation, sensing, and communication (Deutsch, 2020). This expansion has raised urgent

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Contribution to the literature

- We present the design and implementation of a QIST outreach program explicitly informed by integrated STEAM pedagogy.
- Results from mixed methods data analysis indicate a positive shift in students' attitude towards QIST after participation in the program.
- Qualitative findings suggest that in addition to positive emotional engagement with learning QIST, students also articulated reflections on science-technology-society (STS) connections and the nature of science (NOS).

concerns regarding preparation of a "*quantum-smart workforce*" (Aiello et al., 2021) capable of meeting industry demands (Greinert et al., 2024). Since QIST is inherently interdisciplinary (Seifollahi & Singh, 2025), the QT industry requires expertise from multiple disciplines (Greinert et al., 2024). Consequently, introducing quantum mechanics (QM) and QIST concepts at the school level has become a global research priority (Darienzo et al., 2024; Hennig et al., 2024; Nautiyal et al., 2025; Tóth et al., 2025), with K-12 schooling recognized as critical for cultivating disciplinary diversity and preparing students for QT careers (Greinert et al., 2024; Merzel et al., 2024).

Limitations in Current Quantum Outreach Programs

Despite widespread acknowledgment of QIST's interdisciplinary nature (Doyle et al., 2026) and societal relevance (Roberson et al., 2021; Wolbring, 2022), most QT outreach initiatives prioritize technical competencies and affective or cognitive learning outcomes (Bondani et al., 2022; Darienzo et al., 2024; Hennig et al., 2024; Nautiyal et al., 2025). This represents a missed opportunity, as the philosophical richness of QM and interdisciplinary nature of QIST can promote holistic scientific literacy encompassing NOS, interdisciplinary connections, and STS connections. Studies addressing these aspects remain scarce. Wolbring (2022) found that socio-cultural and humanities-related dimensions remain substantially absent from QT related academic discourse. Within QIST education, the philosophical and historical richness of QM is underutilized. To address the growing demand for an interdisciplinary workforce from emerging technologies industries in the 21st century such as the QT sector, research on integrated science, technology, engineering, arts, and mathematics (*i*-STEAM) education has gained significant attention in recent years.

Integrated Science, Technology, Engineering, Arts, and Mathematics Education

Aligning with the emergence of QT and similar interdisciplinary industries (Koh et al., 2019), global education policy has emphasized integrated science, technology, engineering, and mathematics (*i*-STEM) (Kelley & Knowles, 2016; Roehrig et al., 2021)—an integrated educational approach to science, technology, engineering, and mathematics. The *i*-STEM approach focuses on authentic disciplinary integration rather than teaching STEM disciplines in isolation (Mejias et al., 2021; Roehrig et al., 2021). Recently, *i*-STEAM has emerged as a reconceptualization of *i*-STEM (Mejias et al., 2021), incorporating "A for arts" in STEM education to address a critical limitation of traditional *i*-STEM. This reconceptualization reflects growing recognition that traditional *i*-STEM education prioritizes technical expertise and workforce development whilst overlooking the sociopolitical, creative, humanistic, and ethical dimensions of technological advancements (Cook et al., 2017; Mejias et al., 2021; Plank et al., 2026; Quigley & Herro, 2016; Zeidler, 2016).

The *i*-STEAM pedagogy is particularly well-suited for QIST education. Its core principle of blurring disciplinary boundaries (Holbrook et al., 2020) aligns with QIST's inherent interdisciplinary nature (Seifollahi & Singh, 2025). Just as *i*-STEAM integrates technical and humanistic dimensions, QIST includes broader sociocultural implications with potential to transform socio-economic, cultural, and political landscapes. However, research explicitly addressing these humanistic and sociocultural dimensions in QIST remains limited (Roberson et al., 2021; Wolbring, 2022).

Delivering QM/QT education through an *i*-STEAM approach offers two key benefits. First, it makes interdisciplinary connections explicit, addressing a persistent challenge in science education where learners struggle to identify such connections independently (Guzey et al., 2019). Second, it cultivates understanding of QIST knowledge as inherently interdisciplinary and socially embedded, enabling students to recognize that QT careers extend beyond physics. For instance, students with interests in computer science can appreciate how their disciplinary expertise contributes meaningfully to the QT sector, fostering a sense of disciplinary belonging and career relevance. The authors have provided greater detail on the underlying synergy between *i*-STEAM and QT education and how *i*-STEAM can be operationalized through QT education via a history of science (HOS)-informed teaching approach (Nautiyal et al., in press).

Research Gaps

This study addresses three main research gaps identified in the literature. First, despite parallels between *i*-STEAM pedagogy and QIST's interdisciplinary nature, studies explicitly designing and implementing QM and QIST curricula through an *i*-STEAM framework are notably absent. This gap is striking given that *i*-STEAM by design, removes disciplinary boundaries and emphasizes collective application of interdisciplinary knowledge to creatively solve real-world problems —precisely the competencies demanded by the QT industry (Greinert et al., 2024; Holbrook et al., 2020; Koh et al., 2019; Quigley & Herro, 2016; Roehrig et al., 2021). Recent exceptions include the work by Escanez-Exposito et al. (2024), Satanassi et al. (2021), and Rasa et al. (2022), which demonstrate QT education's potential for enhancing STEAM competencies and futures thinking skills. However, such studies remain limited in scope and number. Extending this body of research by systematically designing and delivering QIST curricula through an *i*-STEAM approach is a primary objective of this paper.

Second, whilst cognitive and affective outcomes are reported in many QIST outreach studies (Darienzo et al., 2024; Hennig et al., 2024; Nautiyal et al., 2025; Tóth et al., 2025), empirical literature examining the effects of an *i*-STEAM approach to QM/QT education on student learning outcomes—such as attitudes and conceptual understanding—remains largely absent. A recent systematic review identified the prevalence of emerging technologies in operationalizing *i*-STEAM but found no studies reporting effects of *i*-STEAM informed QT education (Leavy et al., 2023). A recent qualitative study by Seifollahi and Singh (2025), based on interviews with university-level educators, outlines strategies for incorporating QIST through an interdisciplinary approach at undergraduate and postgraduate levels but does not explicitly address the *i*-STEAM framework or empirically measure student outcomes. In contrast, this work addresses the pre-university (high school) context and reports both the implementation of an *i*-STEAM-informed QM course and its effects on students' attitudes toward QIST and their learning experiences following engagement with an *i*-STEAM-informed QIST education intervention.

Third, most QIST outreach programs prioritize technical competencies whilst neglecting humanistic and socio-cultural dimensions (Plank et al., 2026; Quigley & Herro, 2016). Wolbring (2022) found that socio-cultural and humanities-related dimensions remain substantially absent from QT-related academic discourse. Within QIST education, the philosophical and historical richness of QM is underutilized. Most QIST outreach initiatives prioritize technical competencies and focus on affective and/or cognitive learning outcomes (Bondani et al., 2022; Darienzo et al., 2024; Hennig et al., 2024; Nautiyal et al., 2025; Tóth et al., 2025;), while literature addressing the usefulness of QIST education in promoting holistic scientific literacy – such as understanding the NOS, recognizing interdisciplinary nature of STEAM domains, and appreciating STS connections – remains scarce. This gap presents a missed opportunity. Potential of QIST education for simultaneously cultivating technical competencies while promoting holistic scientific literacy through engagement with NOS and STS dimensions require targeted research efforts using pedagogical frameworks such as *i*-STEAM pedagogy and explicit-reflective NOS instruction using HOS (Rudge & Howe, 2009).

Study Purpose and Structure of the Paper

This work addresses the above-mentioned gaps by reporting on the design and implementation of a high school quantum education STEM and research internship program (SRIP) (Nautiyal et al., 2025; Salvador & Nautiyal, 2024) informed by an *i*-STEAM framework, investigating its influence on students' attitudes toward QIST through quantitative survey and qualitative reflections. This is the second iteration of the SRIP; findings from the first iteration are reported in Nautiyal et al. (2025). Building on the first iteration, we implemented two major refinements. First, consistent with broader science education literature (Abd-El-Khalick & Lederman, 2000), HOS alone proved insufficient for addressing deep-rooted NOS misconceptions (study under review). Consequently, we complemented our HOS-informed approach with explicit-reflective NOS instruction (Rudge & Howe, 2009), with NOS learning outcomes reported separately in a study under preparation. Second, beyond the cognitive apprenticeship and discipline culture framework (Nautiyal et al., 2025), we incorporated *i*-STEAM pedagogy in curriculum design and implementation. This paper focuses on the *i*-STEAM-informed design, students' learning experiences, and effects on attitudes toward QIST.

The paper is structured as follows: We first present objectives and research questions (RQs). We then introduce the theoretical framework. Next, we describe methodology. After that we present results on attitudes toward QIST. We then discuss implications, limitations, and future directions. Finally, we present our concluding remarks.

OBJECTIVES AND RESEARCH QUESTIONS

The research objectives of this work, which is a part of a larger project on quantum internship with Filipino high school students are as follows:

1. *Explore the synergy between i-STEAM and QIST education:* Investigate the mutual benefits between *i*-STEAM pedagogy and QIST education, examining QT's potential as a platform for

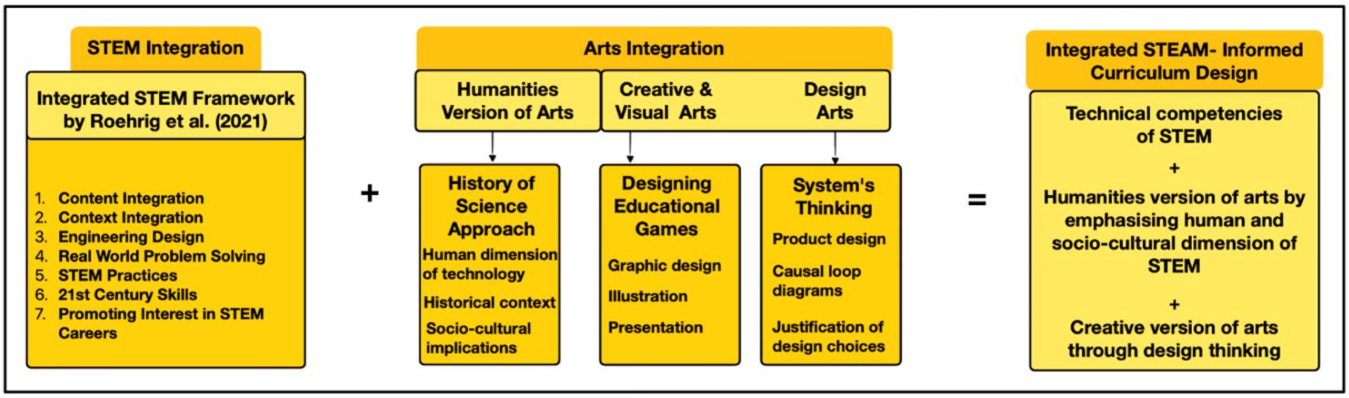

Figure 1. Integrated STEAM framework implemented in our study. We illustrate the conceptualization of "arts" within our program and how we integrated it with STEM to develop an integrated STEAM or *i*-STEAM model of curriculum design and implementation (created by the authors)

enacting *i*-STEAM and *i*-STEAM's capacity to serve as a holistic framework for quantum (or QIST) education.

2. *Foster interdisciplinary thinking:* Develop high school students' ability to integrate knowledge and practices across science, technology, engineering, arts, and mathematics disciplines.
3. *Enhance attitudes toward QIST and QT:* Promote positive attitudes, interest, confidence, and career motivation regarding QIST among pre-university students.

To achieve above stated objectives, the research was guided by the following RQs:

1. **RQ1.** *How can an integrated STEAM framework be operationalized in the design of a high-school QIST outreach program?*
2. **RQ2.** *After participating in the quantum education SRIP,*

   2.1 What are the changes in students' attitudes toward QIST? and;

   2.2 How do students describe their learning experiences?

THEORETICAL FRAMEWORK

Framework For Defining Integrated STEAM Education

This section will address **RQ1**, which focuses on design of an integrated STEAM informed QM and QIST curriculum (see **Figure 1**). There are no universal definitions of *i*-STEAM and *i*-STEM, with various scholars proposing diverse approaches (Kelley & Knowles, 2016; Mejias et al., 2021; Quigley et al., 2017; Roehrig et al., 2021). Sgro et al. (2020) even argue that integrated STEM is often so loosely defined that it effectively becomes "*whatever someone decides it means*" (p. 185). Similarly, while some scholars support integration across all four STEM disciplines (Burrows et al., 2018; Dasgupta et al., 2019), others emphasize that even partial integration involving at least two disciplines can constitute meaningful *i*-STEAM (or *i*-STEM) learning (Moore et al., 2020).

Despite these variations in definition, there is broad consensus on certain key characteristics of integrated STEAM and STEM education (Quigley et al., 2017; Roehrig et al., 2021). These include an emphasis on engineering design (Cook & Bush, 2018; Roehrig et al., 2021), integration of content (Stevenson et al., 2024) and context (Nadelson & Seifert, 2017) , the cultivation of interdisciplinary thinking, strengthening connections among STEAM disciplines, solving real world problems through STEAM and the development of 21st century skills such as critical thinking, problem-solving, creativity, and collaborative engagement (Kelley & Knowles, 2016; Quigley & Herro, 2016; Quigley et al., 2017; Roehrig et al., 2021). To operationalize these characteristics within our quantum education context, we employed the conceptual framework for integrated STEM proposed by Roehrig et al. (2021). This framework was selected because it provides specific, actionable guidance for educators and has been empirically validated across diverse STEM contexts.

Building on existing research, the framework of Roehrig et al. (2021) delineates seven central characteristics of integrated STEM education. These are

(a) a central focus on engineering design,
(b) engagement with real-world problems,
(c) integration of meaningful contexts,
(d) content integration across STEM domains,
(e) application of STEM practices,
(f) development of 21st century skills, and
(g) increasing exposure and interest towards STEM career pathways.

The significance of this framework lies in providing specific guidance to educators and supporting integrated STEM (or STEAM) research, which has been impeded by the lack of a detailed conceptualization of integrated STEM (or STEAM) characteristics (Mejias et al., 2021; Quigley et al., 2017; Ryu et al., 2019; Sgro et al., 2020). By employing this framework, we establish the groundwork for exploring how integrated STE(A)M instruction influences student outcomes in the quantum education context.

We acknowledge that the Roehrig et al. (2021) framework was developed for integrated STEM rather than integrated STEAM. Since STEAM represents a reconceptualization of STEM with the addition of "A" for arts, as shown in **Figure 1**, we modified the framework to accommodate arts in our quantum education program. Since there is no universal definition of integrated STEAM (Mejias et al., 2021), therefore proper conceptualization of STEAM itself remains an ongoing challenge being addressed in the literature (Herro et al., 2019; Quigley et al., 2017). However, common characteristics from STEAM frameworks proposed in previous research on *i*-STEAM conceptualization (Herro et al., 2019, p. 176, **Figure 1**) align with the seven core attributes articulated by Roehrig et al. (2021). Furthermore, design thinking is widely considered an integral component of STEAM education (Bevan et al., 2020; Cotantino et al., 2010; Keane & Keane, 2016; Mejias et al., 2021). Therefore, the original *i*-STEM framework by Roehrig et al. (2021) provides a useful starting point for enacting integrated STEAM. Thus, through careful integration of arts in the *i*-STEM framework of Roehrig et al. (2021), we adapted it for *i*-STEAM education for our context and to achieve our targeted learning goals. **Figure 1** shows a conceptual map of our framework, highlighting how we incorporated arts in *i*-STEM by using framework proposed by Roehrig et al. (2021).

We conceptualize *i*-STEAM as existing along a continuum of integration depth, spanning from foundational interdisciplinary linkages to comprehensive transdisciplinary frameworks (Holbrook et al., 2020). Practical constraints—including curriculum standardization, high-stakes assessment, and resource limitations—often necessitate more modest integration strategies that remain implementable and sustainable within school contexts (Plank & Chelednik, 2025). Educational research indicates that teachers develop integrative competencies more effectively through gradual, scaffolded progression rather than abrupt transitions to fully transdisciplinary instruction (Quigley & Herro, 2016). Within this paper, we define "Arts" broadly to encompass both humanistic disciplines—such as history, philosophy, economics, and social sciences—and visual and creative artistic practices.

We incorporated "A" for arts through multiple dimensions: creative and visual arts, such as designing quantum board games (Nautiyal et al., 2024), creating visual presentations, and applying design principles in engineering projects; and humanities-related definitions of arts, including socio-political and historical contexts of the topics taught. The integration of humanities-related aspects of arts was facilitated through a HOS-informed teaching approach (Thomas Becker et al., 2024). Thus, our adapted framework incorporates the seven characteristics of integrated STEM while explicitly integrating arts as both creative expression and critical humanistic inquiry into quantum education. In what follows, we describe the application of the integrated STEAM framework in the context of our quantum education program.

Finally, we emphasize that whilst *i*-STEAM emerged as a reconceptualization of *i*-STEM designed to broaden appeal to learners with creative inclinations (Quigley et al., 2017; Shernoff, 2024), proponents of integrated STEM contend that arts—in the form of creativity, human dimensions, and social aspects—are inherent to robust STEM program and not exclusive to *i*-STEAM. Indeed, many conceptual frameworks of *i*-STEM, including the Roehrig et al. (2021) framework we employ, incorporate design, creativity, socio-cultural dimensions, and human aspects of STEM. Conversely, STEAM advocates argue that integrating arts—through design thinking, systems thinking, and humanistic perspectives—makes these dimensions more explicitly accessible within STEM contexts, which traditionally prioritize science and mathematics (Quigley et al., 2017). The socio-political origins of STEAM reflect arts disciplines' historical struggle for funding, leading them to position themselves as value-adding partners to STEM rather than equal collaborators (Mejias et al., 2021). Consequently, in practice, strong integrated STEM and *i*-STEAM programs may be indistinguishable, with their differentiation rooted in historical and political contexts rather than strict pedagogical dichotomy.

Application of the Integrated STEAM Framework For Quantum Technology Education

In **Table 1**, we show how the seven *i*-STEAM attributes were systematically integrated into our QT education program through specific instructional approaches and learning activities. **Table 1** illustrates the operationalization of our adapted framework, showing the alignment between theoretical *i*-STEAM principles and their practical implementation in quantum education.

Example teaching sequence showing operationalization of i-STEAM through quantum mechanics learning topic: Blackbody radiation

To illustrate the application of *i*-STEAM attributes presented in **Table 1**, we present a specific example from our program: the blackbody radiation concept (Özdemir, 2017; Persson, 2018). This topic, part of what is often termed as "old quantum theory" (Lovisetti & Giliberti, 2025), presents QM development to students as a chronologically connected series of events. While some researchers argue that old quantum theory topics such

Table 1. Integration of *i*-STEAM attributes in the quantum technology education outreach program

Integrated STEAM attribute	Design principle(s)	Example activity
a. Focus on engineering design	• Systems thinking (Blatti et al., 2019; Fowler et al., 2019) • Social constructivism (Eastwell, 2002): Collaborative project-based learning (Gomez-del Rio & Rodriguez, 2022)	• Students tasked with designing simple tabletop quantum board games (Nautiyal et al., 2024; Piispanen et al., 2025) to creatively apply and demonstrate their learning about quantum technology concepts.
b. Engagement with real world problems	• Active learning through engagement with authentic tasks (Cooperstein & Kocevar-Weidinger, 2004)	• Projects on practical applications of concepts covered in course such as photon-based technology for air pollution detection (Lay-Ekuakille et al., 2014) and thermal imaging (Rai et al., 2017).
c. Integration of meaningful contexts	• History of science approach (Thomas Becker et al., 2024) enacted through the discipline-culture paradigm (Nautiyal et al., 2025; Tseitlin & Galili, 2005; Weissman et al., 2019) of physics knowledge.	• Classroom discussions on geopolitical and socio-cultural dimensions of quantum technology (Krelina, 2021; Roberson et al., 2021; Yadav & Rawat, 2025).
d. Content integration across STEM domains	• Combination of interdisciplinary and transdisciplinary integration of disciplines (Holbrook et al., 2020; Liao, 2016)	• Highlighting connections between physical phenomena and their mathematical representation (e.g., equation of a wave, role of matrices in physics (G, 2020).
e. Application of STEM practices; and f. 21st century skills	• Principles of constructivism learning (Mischel, 1971; Piaget, 1952, 1980, 1995) • Elements of cognitive apprenticeship model (Nautiyal et al., 2025)	• Virtual experiments, data collection and interpretation during learning activities • Group presentations to justify the design choices • Peer feedback and communication skills
g. Increasing exposure and interest towards STEM career pathways	• Dedicated sessions for student engagement with scientists and professionals closely related to the topics being covered in the course.	• Before the start of quantum computing unit, career talk with a professional working on fabrication of superconducting qubits was arranged. Similar talks were organized with scientists working on other related topics covered in the program like photon-based spectroscopy and quantum batteries.

Note. The left column lists the seven *i*-STEAM attributes from the adapted Roehrig et al. (2021) framework; The middle column describes the design principles employed to integrate each attribute; & The right column provides specific examples of how these approaches were enacted in learning activities to address each *i*-STEAM attribute

as blackbody radiation and photoelectric effect may be redundant for teaching modern QM (or QIST) postulates (Michelini & Stefanel, 2021), these topics remain prevalent in high school curricula (Stadermann et al., 2019) and offer significant pedagogical and cultural value (Lovisetti & Giliberti, 2025).

As we describe below, we leveraged this cultural and historical richness to operationalize *i*-STEAM through HOS to bring forth the connections between historical episodes, technical concepts, and scientific advancement. This sequence exemplifies how historical, social, and technological contexts were integrated with QM content to make explicit connections for students.

Context integration through history of science

Historical storytelling allows instructors to contextualize science learning within broader social and economic dimensions (Klassen, 2006). We employed historical storytelling framework proposed by Klassen (2006) and used the relevant historical papers (Crepeau, 2009; Passon & Grebe-Ellis, 2017; Reggiani & Alfinito, 2022) to reconstruct the history of blackbody radiation across four episodes, each addressing both NOS and physics content objectives. This approach contextualized blackbody radiation within its socio-economic, industrial, and historical context.

For example, in the first episode of our historical story, we discussed how late 19th century industrial competition drove scientific inquiry. German companies' efforts to develop efficient incandescent light bulbs created economic pressure for standardized electrical specifications (Giliberti & Lovisetti, 2024). leading to the establishment of the Physikalisch-Technische Bundesanstalt near Berlin in 1887. Blackbody radiation became critical for establishing universal luminosity standards, demonstrating how economic and technological demands shaped fundamental physics research. This historical example operationalized a

Table 2. Theoretical frameworks employed in our quantum education SRIP and their respective objectives

Framework	Purpose
Integrated STEAM	Curriculum design and implementation
Cognitive apprenticeship	Pedagogy (identifying suitable instructional strategy)
HOS	Contextualization of learning content
Discipline-culture framework	Teaching framework for operationalizing history of science Curriculum content design (identifying suitable learning topics)
Explicit-reflective approach to NOS instruction	Promote nature of science understanding through targeted

Note. Integrated STEAM and explicit-reflective NOS instruction were incorporated in year 2 of the program reported in the present paper

humanities-driven *i*-STEAM approach by connecting scientific advancement to historical, economic, and socio-political contexts (Carrell et al., 2020).

Interdisciplinary content integration

Historically, blackbody radiation was first described through Kirchhoff's (1860) work, which proposed an idealized blackbody (a perfect absorber) and established the existence of a universal function describing radiation emission across different wavelengths (or frequencies) and temperatures, independent of the body's shape and material properties. This historical context enabled us to introduce students to the concept of mathematical functions as tools in physics and computation. Similarly, students were tasked to apply the related concepts of Stefan-Boltzmann law and Planck's' radiation formula in the design process of a thermal imaging camera. Technology and engineering lectures were scheduled to focus on technological applications of various scientific concepts covered during the lectures. Aligned with approach proposed by Kelley and Knowles (2016), technology education included both instrumental and human dimension of technological applications of the scientific concepts.

Focus on engineering design, real world problem solving, 21st century skills and application of STEM practices

To operationalize other remaining *i*-STEAM attributes focused to promote design thinking, namely, engineering design, authentic real world problem-solving, 21st century skills and STEM practices, we used the system's thinking approach to design learning proposed in previous literature (Blatti et al., 2019; Fowler et al., 2019; Kastens & Manduca, 2017). For blackbody radiation topic, students engaged with a collaborative mini project on thermal imaging technology grounded in blackbody radiation principles. Students systematically explored guiding prompts that structured their inquiry. First, identifying the scientific foundations by articulating physical quantities relevant to their design (emissivity, intensity, temperature, wavelength), scientific phenomena, and laws/theories enabling practical application. Second, selecting a real-world application context – such as firefighting and fever screening, and justifying their design choices based on societal relevance and technological feasibility. Additional prompts guided students through component identification, cost analysis, and critical examination of technological limitations and potential misuse.

Other Guiding Frameworks

The integrated STEAM framework described above was complemented by frameworks already existing and found to work in the SRIP from year 1 (Nautiyal et al., 2025). These included:

(1) the discipline-culture framework (Nautiyal et al., 2025; Tseitlin & Galili, 2005; Weissman et al., 2019, 2021) which guided what we taught through the selection and organization of curricular subtopics, and

(2) the cognitive apprenticeship model (Dennen & Burner, 2008), which guided how we taught through instructional and student engagement strategies.

To maintain focus on the operationalization of *i*-STEAM for holistic scientific learning in this paper, we avoid describing these existing frameworks in detail here. Instead, we refer readers to Nautiyal et al. (2025) for comprehensive details regarding these frameworks and their application in the first SRIP iteration. The second iteration of the quantum education SRIP described here followed the same overall design and implementation process while explicitly incorporating the integrated STEAM framework described above. **Table 2** presents various frameworks used in our program and their respective functions.

METHODS

Description of Participants

We employed a mixed methods single-group quasi-experimental research design with pre- and post-test assessment format (Gopalan et al., 2020). The study involved thirty high-achieving students from grade 9-grade 11 (aged 15-17) enrolled in a merit-based, science and research-focused high school in the Philippines. One student did not complete the post-test attitudinal survey and was excluded from analysis, resulting in a final sample of twenty-nine students. Out of remaining 29 participants, 14 were females and 15 were males. Eleven students were grade 9 students, 15 were in grade 10, and 3 were in grade 11.

The participating school system has a relatively advanced syllabus and follows a spiral curriculum. Thus, all participants had prior experience with introductory QM in their grade 9 chemistry curriculum, which included a unit titled "quantum theory" having following topics – blackbody radiation, EM waves, photoelectric effect, atomic models, and qualitative introduction to Schrödinger equation and electron cloud model of the atom. Quantum theory unit with same content but more advanced treatment is repeated for grade 11 students, who choose to pursue physics as their major subject after grade 9.

The school system's competitive admission process, involving a nationwide entrance examination, and selective faculty recruitment procedures establish a learning environment where students and teachers demonstrate strong science and mathematics competencies. Consequently, all program participants possessed high aptitude in mathematics and science and relatively stronger academic standing compared to the general student population in the Philippines. This enabled fostering a highly conducive learning environment during the internship. Therefore, findings from this study may be transferable to educational settings and student populations operating under comparable circumstances. Specifically, contexts where participants are high-aptitude students in mathematics and science.

Context of the Study and Recruitment Process: Quantum Education STEM and Research Internship Program

This research was conducted within a high school SRIP in the Philippines. The SRIP functions as a core element of the K-12 curriculum at a selective STEM-focused secondary school in the Philippines. The program mandates student participation in a single internship spanning two to three weeks, ordinarily undertaken during school breaks prior to entering grade 10 through grade 12. Consequently, preparation for this internship commences in grade 9 and extends until students either finish the program or advance to grade 12. We direct the reader to Salvador and Nautiyal (2024) for details on participating high school system's profile, general objectives, policies and organizational structure of the SRIP.

Throughout the internship, students are required to complete a minimum of 80 hours of structured work-based learning with a partner organization. These internships are customized according to individual student interests and correspond with their selected STEM specialization areas for grade 11 and grade 12. Thus, while completing 80 hours of work immersion is a mandatory requirement, their participation in our quantum education SRIP was voluntary. Promotional posters of the program were designed and forwarded to internship coordinators of 16 campuses. The campus coordinators, in turn, shared the promotional posters with the students eligible for participating in the internship and students from four campuses enrolled for the program. Interested students were requested to email their expressions of interest to the internship coordinator for the school. Fourteen female and sixteen male students registered for the program, representing a self-selected sample that may have held more favorable pre-existing attitudes toward QIST than peers in other internship programs.

Daily Schedule and Logistics of the Program

The quantum education SRIP spanned two weeks, during which students completed 80 hours of structured work-based learning. The primary author served as the main instructor and various experts delivered online career and keynote talks for the students. The program operated online via Zoom, maintaining standard industry working hours (9 AM to 5 PM, Monday through Friday). The daily timetable comprised two sessions, morning and afternoon, each spanning approximately four hours. Daily schedules incorporated a one-hour lunch break and three 15-minute breaks, with additional breaks available on student request.

An online student advisory portal on Google Drive was established and managed by the second author. Through this portal, students received the following day's schedule in advance, accompanied by relevant learning materials and worksheets pertaining to the forthcoming topic, which they were expected to complete prior to attending live online instruction. Students were required to upload their output, including completed worksheets and project presentations, to the Google Drive advisory portal. Even for group projects, each student was required to submit individual outputs after completing and discussing the project collaboratively. Following each session, related slides were also uploaded to the portal, enabling students to review the instructional content. The program culminated with group presentations of students' final engineering design projects. Subsequently, students completed a reflective essay (RE) on the program. Twenty-six of the twenty-nine students submitted their essays.

Ethics Approval and Consent Statement

The research team designed a research proposal that clearly articulated the learning goals, research objectives, learning activity plan, and program structure. The research proposal and ethics documentation from the participating high school were completed and reviewed by two independent committees: an academic research committee to evaluate the research feasibility and merit, and an ethics committee to assess the ethical considerations of the research and ensure compliance with ethical guidelines. Following recommendations from both committees, permission to conduct the research was obtained from the campus director of the high school. Informed consent was obtained from parents or legal guardians of the participants. Written assent was also obtained from the students themselves. On the orientation day, participants received verbal induction and were informed about all research aspects of their program. As the program is integrated with students' curricular requirement; it was clearly communicated to them that while their participation is required for program completion, their performance on the pre- and post-intervention tests and feedback would not affect their school grades. They were informed that their schoolteachers would not have access to their responses, data will be anonymized before analysis, and their names would remain confidential in the research reports. Completing learning activities is a formal requirement for students, and upon program completion, certificates of completion were awarded based solely on active participation in the program activities, not on the merit of their performance or scores in any of the surveys.

Instruments For Data Collection and Data Analysis Approach

To triangulate our findings, we employed a mixed-methods approach to data collection and analysis (Wilson, 2014). We used multiple validated instruments used in prior studies to assess learning outcomes related to conceptual understanding of QM (Bondani et al., 2022; Nautiyal et al., 2025; Wuttiprom et al., 2009), NOS (Das et al., 2019; Liang et al., 2008) and students' attitudes towards QIST (Darienzo et al., 2024). While the program's effects on conceptual understanding and NOS will be reported in multiple forthcoming publications, this paper focuses exclusively on attitudinal outcomes. Research indicates that attitudes play a crucial role in shaping future career trajectories and domain-specific achievements (Neale et al., 1970; Tempelaar et al., 2007). Therefore, we examine attitudinal shifts in detail here. The following sections describe our qualitative and quantitative data collection and analysis approaches.

Quantitative data collection and analysis

We used the QIST attitudinal survey developed and validated by Darienzo et al. (2024) for our study. The original instrument was validated with a similar demographic in a different location, i.e., high school students in the USA, and in a comparable educational context, i.e., a high school quantum outreach program. Since the aims and demographics of their QT outreach program are aligned with ours, this instrument is a suitable choice for our study. The survey consists of 25 items that assess QIST-related attitudinal constructs, including self-concept, self-efficacy, interest, relevance, and career aspirations. Additional items evaluated students' perceptions of quantitative and conceptual fluency in relation to QIST concepts and problem-solving abilities. We used the same survey as none of the items required any modification. The instrument was administered online.

The original survey instrument was reviewed and validated by experts in physics and science education. Given that participants had limited prior exposure to QIST, the survey preamble provided contextual guidance:

> "Please indicate the extent of your agreement or disagreement with the following statements. Use the following definition of quantum information science and technology (QIST): A general field that brings together the disciplines of quantum mechanics and information technology" (Darienzo et al., 2024, p. 7).

Participants recorded their responses to the 25 items using a five-point Likert scale administered through Google Forms, completed at both pre-intervention (i.e., on the first day of the program before any learning activities began) and post-intervention (i.e., on the last day of the program after completing all the learning activities) timepoints. The response scale was structured as follows: 5 = strongly agree, 4 = agree, 3 = neutral, 2 = disagree, 1 = strongly disagree. Composite attitudinal scores were calculated by summing individual item responses. Higher aggregate scores reflected more positive attitudinal orientations toward QIST. Two items (no. 7 and no. 23) were reverse coded during score calculation, whereby strongly agree responses were assigned a value of 1, agree = 2, and so on. The entire survey can be found in (Darienzo et al., 2024, p. 7).

To maintain validity and consistency with the original instrument, we followed Darienzo et al. (2024) and calculated a composite attitudinal score rather than analyzing separate dimensions. Although the QIST items were developed to capture different aspects of students' attitudes toward quantum science, including self-efficacy, career interest, relevance, and self-concept, the instrument does not currently have an empirically validated subscale structure. Darienzo et al. (2024) therefore analyzed the instrument as a composite measure and highlighted the need for future exploratory factor analysis with a larger sample to establish its underlying dimensionality. As the instrument developers did not define validated item groupings for these dimensions, deriving separate subscale scores in the present study would require imposing an unvalidated measurement structure that has not yet been empirically established. Given our smaller sample size ($n = 29$), compared with the original study ($n = 77$), conducting factor analysis or deriving separate subscale scores would not be statistically or psychometrically justified. We therefore retained the composite scoring

Table 3. Cronbach's alpha coefficients as a measure of internal reliability of the attitudinal scale

N = 29	Internal reliability coefficient (Cronbach's alpha)
Pre-test	0.857
Post-test	0.879

Note. Values of Cronbach's alpha greater than 0.7 indicate strong internal reliability

Table 4. Items in the qualitative data collection instrument, i.e., the student reflection essay

Essay title
A. My summary of experiences (5-10 sentences)
1. Which part(s) of the immersion did I like the most and why?
2. Which part(s) of the immersion did I like the least and why?
B. My personal reflection (5-10 sentences)
C. My future prospects (5-10 sentences)

Note. The open-ended prompts given above guided students to write their reflections on program experiences

approach to align with the current validation status of the instrument.

Cronbach's alpha was calculated to establish the reliability of the survey in our context for both pre- and post-test data. The values of Cronbach's alpha are presented in Table 3, and as can be seen, both are greater than 0.7 for both pre and post-tests, indicating high internal reliability (Tavakol & Dennick, 2011). A dependent paired-sample t-test was conducted to compare pre- and post-intervention QIST attitudinal scores and determine whether a statistically significant attitudinal shift occurred following program participation.

Qualitative data collection and analysis

To triangulate the findings from the quantitative survey and further evaluate the factors relevant to the attitudinal shifts of students participating in the program, all participants were asked to complete a RE with open-ended questions highlighting their experiences during the program. The essay prompts guided students to consider various aspects they found useful and challenging throughout the program. The RE prompts are presented in Table 4.

Reflexive thematic analysis (Braun & Clarke, 2019) with an inductive-deductive hybrid approach (Proudfoot, 2023) was employed to analyze the qualitative data. The deductive component involved analyzing students' reflections using predefined categories drawn from the integrated STEM framework. At the same time, inductive thematic analysis was conducted to identify additional themes that emerged directly from the data, providing deeper insight into students' experiences. In practice, these inductive and deductive processes are not applied in isolation but interact iteratively and reflexively throughout the analysis. Our thematic analysis was informed by the analytical frameworks established by Braun and Clarke (2006) and the systematic procedures articulated by Swain (2018). Details of the process are provided in next section with the qualitative results.

Table 5. Pre- and post-test mean composite attitudinal scores of 29 students (N = 29)

	M	SD	SEM
Pre-test	99.44	8.890	1.650
Post-test	105.68	9.362	1.738

Note. Maximum achievable score = 125; SEM: Standard error mean; & Composite scores were calculated by summing responses to 25 items, each scored from 1 (strongly disagree) to 5 (strongly agree). Scores for two items (Q7 and Q23) were reverse-coded

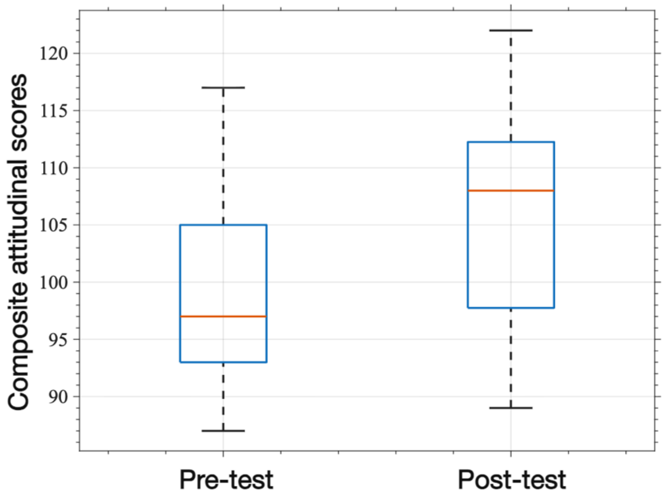

Figure 2. Box plot showing the distribution of 29 students' pre- and post-test composite attitudinal scores (each box represents interquartile range and the horizontal line inside each box represents the median; whiskers represent minimum and maximum scores while outliers are usually shown as individual points [which are absent here as we had no outliers]) (created by the authors)

RESULTS

In this section, we address **RQ2** by presenting the findings on the overall impact of our integrated STEAM informed quantum education SRIP on students' attitudes.

Quantitative Results: Dependent Paired t-Test to Compare Pre- and Post-Test Attitudinal Score

Quantitative analysis was done using MATLAB software. Table 5 presents descriptive statistics from the pre- and post-test QIST attitudinal survey. As shown, the mean attitudinal score increased from approximately 99 to 105 out of a maximum achievable score of 125 in the post-test. This represents an increase of approximately 6 percent in attitudinal score. Figure 2 shows the distribution of composite attitudinal scores of participants in the pre- and post-tests.

Table 6. Paired-sample t-test results comparing pre- and post-test composite attitudinal scores (N = 29)

t	df	p-value (two sided)	Cohen's d
2.76	28	0.01	0.51

Note. The p-value of 0.01 indicates a statistically significant difference (p < 0.05), with a Cohen's d value of 0.51 & A Cohen's d value of 0.5 indicates a moderate effect size

However, for more robust analysis, we performed inferential statistical test in the form of a dependent paired-sample t-test comparing pre- and post-test mean scores of students. Normality of paired differences was assessed using the Shapiro-Wilk test, which is appropriate for small samples ($n = 29$) (Shapiro et al., 1968). The test yielded a W statistic of 0.96 with a p-value of 0.28 ($p > 0.05$), indicating that paired differences were approximately normally distributed. This result satisfies the normality assumption required for parametric paired t-test analysis.

Outliers were examined using two complementary methods. The interquartile range method identified one outlier with a paired difference of -24.0, which fell below the lower bound of -20.1250. However, the Z-score method ($|z| > 3$) (Chikodili et al., 2020), which identifies more extreme outliers, detected no cases exceeding three standard deviations from the mean. This suggests the identified outlier was mild and did not represent an extreme value. Given that the outlier was detected by only one method and the Shapiro-Wilk test confirmed approximate normality, the outlier was retained in the analysis.

A paired samples t-test (see **Table 6**) revealed a statistically significant increase ($p < 0.05$) in post-test scores (mean [M] = 105.68, standard deviation [SD] = 9.36) compared to pre-test scores (M = 99.44, SD = 8.89) with $t(28) = 2.76$, $p = 0.01$, $d = 0.514$. The mean difference of 6.24 points was accompanied by a 95% confidence interval of [1.59, 10.89]. The 95% confidence interval [1.59, 10.89] was calculated using the standard deviation of the paired differences (SD = 12.31) and the t-critical value ($t = 2.048$) for $df = 28$. The medium effect size (Cohen's $d = 0.51$) finding suggests a moderate practical effect between the intervention and positive shift in students' attitude.

Qualitative Results: Emergent Themes From Students' Reflection Essays

Literature indicates that mixed methods research can facilitate more reliable and robust conclusions by addressing the limitations of one data collection approach (qualitative or quantitative) with the strengths of the other (Onwuegbuzie & Leech, 2004). Therefore, to address **RQ2** more comprehensively and to further support the findings of our quantitative analysis, we conducted a qualitative thematic analysis of students' reflection essays (REs) after completing the program.

Table 7. List of pre-defined codes

List of a priori (predefined) codes
Connection of QM to other disciplines
Scientific concepts in everyday technology
Aspirations to pursue QT careers
Clarity about possible STEM careers
Application of new knowledge in collaborative projects
Negative learning experiences
NOS codes:
• Tentative
• Socio-cultural
• Laws versus theory
• Inferential
• Creativity and imagination
• Science as human endeavor

Our qualitative analysis is grounded in a constructivist epistemology (Rockmore, 2005). Consequently, we employed collaborative reflexive discussion among the two coding authors to iteratively refine codes, examine exemplars, and resolve disagreements through collective sense-making. This approach prioritizes transparency and acknowledges researcher positionality or subjectivity as a strength rather than a limitation, allowing us to mitigate individual bias and enhance the validity of our thematic analysis through shared critical reflection. Through collaborative sense-making and ongoing reflexivity, the research team constructed subjective yet deeply meaningful interpretations of the data, thereby enhancing the study's validity. Further, as highlighted by Morgan (2022), reflexive thematic analysis aims to comprehend "*trends in the data*" (p. 2081) that may or may not align with researchers' preconceptions. Therefore, Morgan (2022) argues that "*high-quality qualitative research is based on a dual inductive-deductive process of developing themes*" (p. 2081). For this reason, our approach employs a hybrid deductive-inductive methodology, which we detail below.

Qualitative analysis was performed by the first two authors (VVN and EEPS). The authors followed the step-by-step process described by Swain (2018) to perform the hybrid deductive thematic analysis across three phases.

In phase 1, the two authors familiarized themselves with the data iteratively by reviewing the reflection essays multiple times. Initial familiarization provided a sense of the data's richness to both authors. Next, within phase 1, all student responses were collated into a text document by the primary author. All qualitative data were anonymized and organized in an MS Word document. The final stage of phase 1 involved the two authors convening to establish a set of pre-defined codes. The list of pre-defined codes is given in **Table 7**. These codes were finalized on the basis of our theoretical framework – the integrated STEAM approach – and thus encompassed codes related to core *i*-STEAM characteristics and NOS. Further codes related to STS

Table 8. Five main themes and corresponding sub-themes related to students' positive learning experiences derived through reflexive thematic analysis of twenty-six students' reflection essays

Theme	Sub-theme	n
1. *Recognizing the connections between science, technology and society*	Real world applications of science	15
	Recognizing interdisciplinary nature of STEM fields	12
2. Increased motivation to pursue quantum and/or STEM in future	*Motivation due to engagement with designed learning activities*	16
	Motivation due to organized career talks with invited professionals	8
3. Positive emotions with learning quantum	Feelings of fun, joy and engagement	12
	Quantum humor	2
4. Accessible view of quantum mechanics	-	10
5. *Reflections on the nature of science*	-	9

Note. The final column indicates the number of students whose responses reflected each theme; Italicized themes (or sub-themes) represent those derived from pre-defined codes (deductive coding), whilst inductive (emergent) themes appear in regular text; Additional codes and illustrative student quotes are provided in the **Appendix A**; & n: Number of students reporting this learning experience (out of 26)

dimensions were partly derived from previous literature (Akcay & Yager, 2010). Additionally, since HOS was employed with explicit-reflective NOS instruction, the two authors also agreed to incorporate aspects of NOS as pre-defined codes. To refine future iterations, we included negative learning experiences as one of the pre-defined codes. This code was prompted by a reflection essay question asking students to describe aspects they did not enjoy or that could be improved in future iterations.

In phase 2, the primary author initiated the initial coding process after re-familiarizing himself with the data. The process began with searching for meanings and patterns in the reflection essays, applying both the a priori (pre-defined) codes and generating a new series of a posteriori (inductive) codes. This iterative process continued until all reflection essays were thoroughly reviewed. At the end of this phase, a comprehensive list of codes emerged, encompassing both pre-defined codes and a posteriori (inductive) code that arose from the data. Subsequently, the primary author reviewed the codes in detail, describing and summarizing each code alongside relevant student responses to specific questions in the reflection essays. Following this, the two authors convened to review the refined set of codes and examine exemplars from the dataset from which they were derived. Any disagreements were resolved through discussion, and a final list of codes was produced.

The final phase, phase 3, started with the primary author organising and synthesizing coded data. As the primary author reviewed the coded reflection essays, sections of text corresponding to each code were extracted and organized into a MS Word document. These excerpts were selected based on their illustrative value – instances where students articulated points or insights particularly relevant to the themes being developed. Each reflection essay was assigned a unique identifier (e.g., RE 1, RE 2) for tracking and reference purposes. Finally, the last stage involved grouping related codes into family codes and developing them further into the final themes and sub-themes presented here. Complete list of family codes, example from data set (student quotes) and their corresponding themes and sub-themes are presented in **Appendix A**. Below we discuss the resultant themes.

Table 8 presents the five main emergent themes obtained through reflexive thematic analysis of students' reflection essays. The themes are presented in decreasing order of frequency, reflecting how often each theme appeared in the students' reflection essays, which were submitted by twenty-six of thirty participants. However, we emphasize that, aligning with the recommendations and philosophy of Braun and Clarke (2019), theme frequency or the number of students reporting a particular theme (as shown in **Table 8**) is not associated with how important that theme is or its meaningfulness. The number of students per theme is purely descriptive, intended to highlight what was most commonly reported learning experience, but does not indicate that one theme is more important or "dominant" than another. For example, the sub-theme "*quantum humor*," reported by only two participants, is as meaningful as the more commonly reported sub-theme of "*real world applications of science*." To summarize, theme frequency was not used as the basis for analytical interpretation and structural organization or in determining theme importance. The salience of a theme derives from its conceptual richness and relevance to RQs, rather than from how frequently it appears in the data. Below, we describe the main themes and corresponding sub-themes in detail with illustrative quotes.

Theme 1: Recognizing the connection between science, technology and society

The most frequently reported experience among students was related to an increased appreciation of the relationship between STS (Akcay & Yager, 2010). This theme included two interrelated *sub-themes* that were consistently reflected in student responses.

The first sub-theme involved students' deepened appreciation for how scientific principles manifest in their everyday life, technology and their societal impact, i.e., the "*real-world application of science*". Through integrated STEAM informed lectures, collaborative engineering design projects, learning activities, and mentor talks from industry professionals, students began to recognize that science transcends textbook abstractions and is fundamentally embedded in the technologies they encounter daily. As one student articulated this transformation,

> "This immersion gave me a new perspective on what it means to "do science". I used to think of physics as equations and abstract rules, but through this program, I saw how those rules power the technologies we use every day." (RE 2)

The second *sub-theme* was students' "*recognizing the interdisciplinary nature of STEAM fields*". They acknowledged that QM and other STEM disciplines more broadly are not isolated domains but interconnected with a range of fields, including chemistry, materials science, industry, humanities and even the creative arts. As one student expressed,

> "I've learned that I don't have to be a physicist to engage with scientific ideas or benefit from them. In the future, I might explore science communication, design, or interdisciplinary fields that bridge physics with creative work." (RE 1)

Theme 2: Increased motivation to pursue quantum and/or STEM in future

The second prominent theme centered on students' heightened motivation to pursue QM in higher education and careers within STEM or QT-related fields. This motivation emerged from two distinct sources. The first sub-theme within this motivational theme reflected students' self-reported increased motivation crystallized through direct engagement with the program's *i*-STEAM informed learning activities. Rather than external inspiration alone, students' reflections suggest that their motivation to pursue QT- and STEM-related careers was strengthened by their hands-on participation in integrated STEAM projects, collaborative problem-solving, and inquiry-based explorations of quantum phenomena. For example, one student reflected,

> "I think I can use a lot of what we learned in my grade 11 and 12 classes and in my studies in college. I'm also considering Quantum Software as a possible course in the future." (RE 16)

The second sub-theme suggest that students' inspiration to pursue quantum may also be catalyzed by career talks from industry professionals. Students articulated how exposure to practitioners working at the intersection of QT and diverse disciplines rekindled or increased their career interest towards pursuing quantum or STEM fields in future. For instance, one student shared,

> "I also liked the portion with the guest speakers, since I was able to listen to their life story and what led them to become such great scientists. It just felt like I needed the seminars …" (RE 13)

Theme 3: Positive emotions with learning quantum

The third prominent theme was related to affective dimension of learning QM, specifically, the emotions such as joy, fun, and engagement experienced by students throughout the program, as reflected in their essays. Students' reflections related to this theme suggest a perceived transformation of QM from an intimidating subject into an enjoyable experience, which manifested in two interrelated sub-themes: expressions of fun and joy in learning activities, and playful application of quantum concepts to convey emotions.

Students highlighted their shift towards positive attitude and emotions towards quantum as the program progressed, particularly through collaborative engineering design projects and creative problem-solving related activities. For example, one student reflected on their initial skepticism,

> "Surprisingly, things changed. I found myself gaining interest midway through the immersion, especially in the engineering projects where I used my creativity and formed bonds with amazing groupmates … I thought it would be too difficult since I had no background knowledge, but it was not hard at all." (RE 25)

Similarly, the second sub-theme within this theme highlighted the intersection of cognitive and affective dimensions associated with learning quantum. Few students applied the quantum concepts that they had learned to convey their emotions and reflections on the program. This playful integration of conceptual knowledge with emotional expression demonstrates how students had internalized quantum terminology sufficiently to repurpose it creatively. For example, one student concluded their reflection through an accurate verbalization of their emotions in terms of quantum superposition,

> "All in all, my experiences with quantum will forever be in a state of superposition, neither happy or (nor) sad, but a new thing in it of itself that I can't bring to words, but I can appreciate." (RE 22)

Theme 4: Accessible view of quantum mechanics

Fourth prominent theme revealed students' transformed perception of QM – from an exclusive, intimidating domain to an accessible and approachable field of study. Prior to the program, many students harbored the belief that QM was reserved exclusively for elite scientists, researchers, or individuals with exceptional intellectual capacity. However, the reflections suggest that through participation in collaborative group projects, hands-on engineering design activities, and scaffolded learning tasks, students developed newfound confidence in their own capacity to engage meaningfully with quantum concepts. This shift from perceived exclusivity to perceived accessibility indicates a positive transformation in students' self-efficacy and disciplinary identity. For instance, one student reflected,

> "When I think of quantum, I often refer to it as something complex to understand, and only professionals with PhDs could understand it. But by joining this 10-day program, I was not only able to do something while in vacation and preparing my brain to go to grade 10 but also inquiring more knowledge about a concept I thought only people with huge minds can handle." (RE 5)

Within this theme, some students further articulated a shift in how they viewed QM – from a mysterious and abstract theory to a coherent and intelligible framework. While acknowledging the inherent conceptual challenges, they came to see QM as a comprehensible system of knowledge that could be meaningfully understood. As two students captured this transformation,

> "I used to think quantum mechanics was too abstract, but I now understand how its rules make sense within its own framework. It's no longer a mysterious subject to me, it's an exciting challenge." (RE 24)

Theme 5: Reflections on the nature of science

An explicit and reflective approach to the NOS through the use of historical storytelling (Rudge & Howe, 2009; Witucki et al., 2024) was integral to our *i*-STEAM curriculum design. Therefore, we expected some NOS related reflections in students' essays. Indeed, qualitative analysis revealed that the final most frequently observed theme was students' reflection on the nature science. In their reflection essays, many students articulated their reflections on NOS, acknowledging specific aspects of scientific inquiry. Their reflections suggest that they perceived a sense of growth regarding their understanding of how scientific knowledge is advanced and generated.

Students' reflections included their views on diverse NOS aspects, including the distinction between scientific laws and theories, the tentative NOS, theory-laden (subjective) nature of scientific knowledge, and the creative dimension inherent in scientific inquiry. For instance, one student articulated the subjective, tentative, and inferential aspects of science (including the role of scientific models) in the following statement,

> "I would also never forget, through the multiple lessons and discussions about how it affected my views on science and how it made me learn - how science is constantly changing, how people can interpret things differently, and how models are valuable representations of concepts, and more." (RE 18)

More examples are given in **Appendix A**.

Themes related to negative experiences reported by students

To ensure that students' negative experiences were highlighted for refinement in future iterations of the program, a dedicated prompt was included in the reflection essays: *"Which part/s of the immersion did I like least and why?"* Since the prompt was part of the students' reflection essays, it ensured that all participants shared their negative experiences, enabling us to refine the program in future iterations. Although most students viewed their experience as a net positive, several themes related to negative experiences emerged. The responses revealed three recurring sources of difficulty: the online format, feelings of fatigue due to workload, and challenges with group work and social dynamics. In what follows, we describe these negative learning experiences, analyze their underlying reasons, and discuss the design implications to inform future program iterations

Online Format

The online format was the most frequent source of dissatisfaction among students. Students expressed that the online setup limited both social interaction and hands-on engagement. For instance, one student remarked

> "What I liked the least was the fact it was online. I feel like I would have enjoyed listening to career talks and Sir Vijit's lectures if it were physical." (RE 16)

Similarly, others noted that the fully online format was a hindrance to meaningful collaboration. As one student reflected:

> "… but it was hard working with my groupmates. The main problem was that it was an online immersion, so communication was a big part, and it was difficult to communicate with my group." (RE 15)

This sentiment underscores the need for a more engaging online environment that could simulate in-person interactions. In terms of design implications for future iterations, this negative experience suggests implementing structured online collaboration scaffolds grounded in existing literature on online learning. For example, we could focus more on task-oriented and idea-oriented online scaffolding through designated online discussion forums to promote both social and cognitive engagement among students as suggested by Zhang et al. (2025).

Fatigue Due to Workload

Students also reported feelings of fatigue and information overload, particularly when or long sessions or multiple tests and worksheets were scheduled in a single day. As one student described,

> "For me there are just some days when I am tired and I cant take how long the immersion is, but i still manage and tend to do my best." (RE 7),

and another student quoted,

> "Honestly, the part of the immersion that I liked the least was answering the tests given because, my brain and body does not feel like learning since my brain and body is still at vacation mode:)). But I still liked doing them since they give me more knowledge about science." (RE 6)

This negative experience may be directly attributed to the workload distribution inherent in the program's structure. The standard SRIP schedule compresses 80 hours of instruction into 10 working days, requiring 8 hours of daily engagement. While this intensive format aligns with typical work-based internship models, the cognitive demands of an online format – particularly for a conceptually demanding subject such as QIST – compound the challenge. Students must simultaneously attend lectures, engage with complex material, and complete assessments, apply their learning to solve new problems creating substantial cognitive load.

With regards to design implications, one potential improvement involves extending the program duration to 20 days, distributing the 80 hours across this longer timeframe so that students engage in only 4 hours of daily workload instead of 8. This adjustment would reduce cognitive overload while maintaining program depth, provided it remains logistically feasible for all participants and instructors. Additionally, improving workload distribution through staggered assessment schedules and incorporating more asynchronous learning components could help students manage fatigue more effectively. Further providing a balance between synchronous and asynchronous learning would also be beneficial.

Challenges With Group Work and Social Dynamics

Many students found group work challenging, primarily due to communication barriers in the online setting. As one student reflected,

> "The groupwork was terrible, mainly to the fact that my groupmates were completely inactive during the entirety of the program. I had to pull the weight of 3 other students, who mind you were grades higher than me." (RE 8)

Similarly, another student quoted,

> "It was often difficult to coordinate effectively due to unresponsiveness or a lack of initiative from some group members. The collaborative aspect felt limited, and at times progress felt slow. … I just feel that with a better communication and teamwork, it could have been much more productive and enjoyable." (RE 17)

Establishing clear roles and responsibilities within groups can enhance accountability and improve collaboration. Additionally, implementing peer support systems could facilitate better communication and bridge gaps in understanding among group members.

DISCUSSION

Operationalizing i-STEAM Through QIST

We addressed **RQ1**, exploring the operationalization of *i*-STEAM pedagogy for QIST education through the design of our quantum education SRIP. To achieve this, we surveyed the literature from broader STEM/STEAM education landscape (Herro et al., 2019; Kelley & Knowles, 2016; Roehrig et al., 2021), identified overlapping attributes of effective STEAM and STEM education from various conceptual frameworks and integrated them in our QIST curriculum. In doing so, we made deliberate efforts to dissolve traditional disciplinary boundaries within QIST and quantum education, with the objective of enabling students to adopt a holistic perspective on 21st century challenges and recognize that interdisciplinary and transdisciplinary competencies play an integral role in enhancing their future career prospects.

We acknowledge that physics education research community recognizes the interdisciplinary nature of QIST (Seifollahi & Singh, 2025). Consequently, an inherent implicit interdisciplinary approach is evident in various QIST education programs with high school students (Bondani et al., 2022; Darienzo et al., 2024; Merzel et al., 2024; Hennig et al., 2024; Nautiyal et al., 2025; Tóth et al., 2025; Weissman et al., 2024). For instance, programs employ skills and contexts beyond physics competencies—such as block programming (Escanez-Exposito et al., 2025), quantum games

(Chiofalo et al., 2022; Seskir et al., 2022), classical computing context for conveying quantum ideas (Beardow & Stappers, 2026; Bondani et al., 2022; Sun et al., 2024) and creative visual arts based teaching approaches (Archer, 2022; Dündar-Coecke et al., 2023). However, the primary aim of incorporating these interdisciplinary approaches is typically to enhance understanding of QIST-related technical skills. As highlighted in previous literature, majority of QIST educational initiatives are operationalized through a "*physics-led*" approach (Beardow & Stappers, 2026). In doing so, the interdisciplinary or transdisciplinary connections between disciplines can remain hidden from the students, particularly when instructional focus is on advanced skills such as quantum computing.

Indeed, a recent study by Greinert et al. (2024), highlighted that some industry stakeholders have shown concerns regarding worsening disciplinary diversity in QT industry. These concerns and ground situation of industry as reported by the stakeholders contrasts with existing focused efforts on interdisciplinary quantum outreach initiatives. Therefore, more adaption of practices from broader STEM education literature may be beneficial for QIST education. Thus, our approach differs from existing literature in that we deliberately aligned pedagogical suggestions from broader STEAM education literature to QIST. We made targeted efforts to foreground our QIST lessons on the transdisciplinary connections between STEAM disciplines in the QIST domain. In this regard, while addressing **RQ1**, we have studied a relatively underexplored domain of using QIST education as a platform to operationalize *i*-STEAM pedagogy. Widespread adoption of our proposal may assist, at least partly, in increasing disciplinary diversity in future QT industry.

Students' Affective Outcomes After Engaging With i-STEAM Informed QIST Instruction

RQ2 involved investigating the effect of *i*-STEAM informed QIST education on students' attitudes towards QIST and analysis of their self-reported learning experiences after participation in the quantum education SRIP. Our results suggested that overall, our quantum education SRIP had a positive effect on the affective dimension of learning. In addition, we also analyzed students' self-reported negative learning experiences and framed those in terms of design implications for future implementations of our program.

i-STEAM-informed QIST education represents a relatively novel instructional design framework; consequently, evaluating its affective efficacy is essential. One of the most widely used and thoroughly validated instructional design models is Keller's (1987) ARCS model of motivational design that identifies four essential affective components of instructional design. These are, capturing and sustaining student *attention* (A), establishing *relevance* (R) by explaining why the content matters, fostering *confidence* (C) by helping students believe they can succeed with effort, and cultivating a sense of accomplishment and *satisfaction* (S) in their learning (Li & Keller, 2018). These constructs also align closely with the constructs of the quantitative attitudinal survey used in this study, and in other STEM domains (Dele-Ajayi et al., 2019) . Therefore, any instructional design should have positive effects on these dimensions as they are essential for improving student attitudes.

Our results indicate alignment with the constructs of ARCS model. Motivation to pursue quantum careers emerged as a major theme, while students' increasingly accessible view of QM suggests they gained confidence and were satisfied with their ability to engage with the subject. Additionally, positive emotional themes – such as engagement, joy, and fun are related to the "attention" construct. Finally, the "relevance" construct was visible in the theme related to students' recognition of connections between science, technology, and society, as they articulated the importance of science in their everyday lives and its personal significance for their future career aspirations. These qualitative findings were also supported by quantitative results.

Our findings align with those of Darienzo et al. (2024), who also reported positive shifts in students' attitudes after participating in their educational program, which shared some similar characteristics with ours, even though they did not explicitly foreground their approach as an *i*-STEAM framework. Our results align with the findings of Darienzo et al. (2024), with quantitative surveys revealing a positive shift in students' attitudes towards QIST after the program. Similarly, emergent themes from qualitative data analysis showed comparable patterns. Participants in both studies reported positive social engagement as integral to their learning experience, valuing support from peers and instructors. In our study, this was further enriched by interactions with keynote speakers and guest professionals during career talks. Similarly, themes related to students' motivation to pursue QT careers and their growing self-efficacy and confidence in engaging with QM also aligned with Darienzo et al.'s (2024) findings.

Main Contribution to Literature on QIST Education Research

The primary contribution of this work to the broader discourse in science education and physics education research is that our findings indicate that QIST education, when implemented through an explicit *i*-STEAM framework, can create meaningful opportunities for students to connect quantum science with technology, society, careers, creativity, and NOS. Integrated STEM education and QIST share overlapping inherent characteristics, including an interdisciplinary focus, workforce development orientation, and high priority status in government policies (Greinert et al., 2023; Tytler, 2020). Ironically, these same shared characteristics – partly responsible for high interest from policymakers and the global economies – also generate shared concerns and criticism within academic discourse, i.e., an overemphasis on workforce and technical development that systematically marginalizes the creative, artistic, social, political and humanities related dimensions essential for genuine scientific literacy (Quigley & Herro, 2016; Roberson et al., 2021; Wolbring, 2022; Zeidler, 2016). Thus, exploring how QIST education can facilitate learning outcomes beyond technical expertise is equally important. Our findings reveal promising avenues for leveraging QIST to enhance scientific literacy.

Students' affective outcomes indicate that QT learning extends beyond technical skills, with potential to contribute towards overall scientific literacy development – an aspect largely neglected in high school quantum outreach literature, which has predominantly focused on technical competencies. Our results suggest that QM and QIST education, when explicitly structured around integrated STEAM principles alongside history and philosophy of science instruction, provides richer learning opportunities including NOS, realizing connections between STEAM disciplines and societal relevance of science and a more human view of technology as it connects to our personal lives. These dimensions are increasingly relevant to 21st century skills students need (Alpaydın & Demirli, 2022; McFarlane, 2013).

To convey our point, we return to comparison of our results with the qualitative findings of Darienzo et al. (2024). Despite overall similarities in educational context, nature of intervention and positive results related to affective dimension of learning, some crucial distinctions emerged from our qualitative analysis that may directly be attributed to *i*-STEAM informed pedagogy. While program of Darienzo et al. (2024) demonstrated overall interdisciplinary characteristics, the themes related to STS (see theme 1 in **Table 8**) and NOS (theme 5 in **Table 8**) were not foregrounded in their reported qualitative findings. In contrast, our study, grounded in an explicit *i*-STEAM pedagogical framework with HOS-informed instruction, identified "*Recognizing the connection between science, technology, and society*" and "*Reflections on the nature of science*" as two of the five major themes (see **Table 8**), with STS theme emerging as the most prominent. This distinction underscores that QIST education possesses utilities beyond QIST concepts and, through practices from broader science education literature, can also be leveraged to achieve broader goals related to overall scientific literacy and developing a scientific temperament in the younger generation. In this regard, the results of our study show some degree of parallel with the study by Rasa et al. (2022), who explored the utility of quantum computing education for promoting futures thinking abilities among the students.

Implications for Policy and Practice Related to Quantum Mechanics Education Research

To summarize our findings and contribution, we relate them to the implications. This study suggests two main implications for policy, practice, and research related to K-12 QIST education. First, QIST education research and physics education may benefit from more targeted efforts to integrate established pedagogical practices and theoretical frameworks from broader STEM and science education literature. Student-centered constructivism informed instructional approaches, integrated STEAM frameworks, and explicit-reflective NOS instruction represent practices from broader science education literature that remain underutilized in physics and quantum education. These approaches may enhance students' confidence and self-efficacy while addressing the goals of 21st century scientific literacy. This requires strengthened collaboration between physics education research and broader science education research communities to translate research findings into sustainable, scalable classroom practices.

Second, QIST educational outreach efforts may serve broader purposes by extending beyond technical competencies to encompass broader scientific literacy. QIST education's rich disciplinary history, philosophy, and sociocultural dimensions offer valuable resources for this holistic approach – increasingly essential in the 21st century, where scientific literacy must integrate technical competencies with sociocultural and humanistic dimensions to counter misinformation and navigate rapid technological change.

Limitations and Future Research Directions

We acknowledge some limitations that of this study that may affect generalizability to broader populations and contexts, primarily stemming from logistical and administrative constraints. First, the relatively small sample of 29 students and absence of a control group, while ethically justified given the program's design as a voluntary internship, constrains causal claim. We partly mitigate interpretive limitations by adopting a mixed-methods design aligned with Kember's (2003) recommendation of utilizing "*triangulation across multi-methods evaluation from several sources*" (p. 89). This approach can, to a limited extent, compensate for the lack of a control group. Triangulated evidence from mixed methods analysis suggests some degree of correlation between the intervention and observed improvements in students' understanding and attitudes. However, more robust analysis is needed with a control group and larger participant pool to ascertain the merit of the proposed approach comprehensively.

Second, our participant pool involved self-enrolled, high-achieving students, which may have resulted in relatively more positive baseline attitudes towards QIST and greater openness to possibilities in the field. This may not be indicative of general student populations with broader interests across domains. Further modifications may be needed to adapt to the intervention for more diverse student populations, that we plan to address in future research. However, we emphasize that the high-achieving participant pool of gifted students represents both a limitation and a design strength, depending on the reader's perspective. Whilst transferability is constrained, our design and sampling were deliberately chosen for this population. Research on interventions with high-achieving students is a well-developed field in itself (García-Martínez et al., 2021; Peters et al., 2014; Robertson & Pfeiffer, 2016). As highlighted in a systematic review by García-Martínez et al. (2021), educational research with gifted students calls for interventions tailored to specific student characteristics rather than general approaches for the wider population. García-Martínez et al. (2021) further conclude that "further research with quasi-experimental designs with this (gifted/high achieving) population" (p. 1) to develop quality, contextualized interventions, rather than generalized approaches, that accommodate individual needs and interests, ultimately increasing motivation and reducing failure rates. Additionally, due to potential ceiling effects, it is more challenging to observe substantial change in learning outcomes or affective measures when students already demonstrate high baseline performance/attitudes. In this regard, we consider the program a success, as we observed an overall positive shift in attitudes towards QT following the intervention.

Third, career aspirations were self-reported rather than tracked longitudinally, preventing us from determining whether expressed intentions translated into sustained career pursuit. This will be addressed in future longitudinal studies where we plan to track our graduate interns' from two years career trajectories and their perception of to what degree our program influenced their career decisions. Although we ensured feedback on negative experiences, factors such as social desirability bias and the instructor-as-researcher role cannot be ruled out and may have partially affected the responses and positive experiences reported.

Fourth and finally, this study focused exclusively on affective outcomes and attitudes. In studies currently under preparation, we will report the effects of learning activities on students' understanding of NOS using a validated dual-response instrument (Gerondio et al., 2024; Liang et al., 2008). Other cognitive outcomes – including model thinking in QM (Ubben et al., 2023), conceptual understanding of QM (Wuttiprom et al., 2009), QT (Bondani et al., 2022), and their attitudes (Ardies et al., 2015) and conception of technology in general (DiGironimo, 2011) – will be reported separately in upcoming publications.

In future research, we plan to refine the curriculum and implement it via practitioners, that is, in-service teachers rather than the researchers, as in this work. It would then be interesting to compare the learning outcomes of teacher-delivered and researcher-delivered *i*-STEAM courses. However, should this curriculum be adopted by teachers in subsequent research, systematic fidelity protocols—including observation checklists, instructor reflection frameworks, and external monitoring—will be essential to ensure consistent and high-quality implementation across different educational settings. Such protocols will help identify whether observed outcomes are attributable to curriculum design or implementation quality, thereby strengthening causal claims and informing iterative refinements for broader dissemination.

CONCLUSIONS

This paper reports findings from a fully online high school quantum outreach initiative in the Philippines. We investigated the effect of an integrated STEAM-informed teaching approach on high school students' attitudes towards QIST. Our results, supported by method and data triangulation, indicate that the designed *i*-STEAM-informed quantum education program yielded several positive attitudinal outcomes. Beyond enhancing confidence and self-efficacy in QIST, students developed recognition of connections between science, technology, and society, reflected on their understanding of NOS, and appreciated the interdisciplinary nature of STEM disciplines integrated with QM and the arts. This work provides a framework for future initiatives at larger scale and sustainable implementation of *i*-STEAM-informed quantum outreach for integrating 21st century skills education with mainstream classroom teaching.

Author contributions: VVN: conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, validation, visualization, writing—original draft, writing – review & editing; **EEPS:** conceptualization, data curation, formal analysis, investigation, methodology, project administration, visualization, writing – original draft, writing – review & editing; **PB:** conceptualization, formal analysis, investigation, methodology, visualization, supervision, writing-original draft, writing – review & editing. All authors agreed with the results and conclusions.

Funding: This study was supported by the Open Access Publishing Fund of Leipzig University.

Acknowledgments: The authors would like to thank the teaching and administrative staff of the participating high school system and to the student interns for their enthusiasm and active participation throughout the program. The authors would also like to thank the keynote speakers and invited guests who delivered career talks. VVN acknowledges financial support from Keith & Dorothy Mackay Travel Scholarship (https://www.une.edu.au/scholarships/higher-degree-research-scholarships/keith-and-dorothy-mackay-postgraduate-travelling-award) that funded his research visit to Leipzig University, Germany. VVN also acknowledges financial support from the Australian Government Research and Training Program (https://doi.org/10.82133/C42F-K220) and Destination Australia Program (https://www.education.gov.au/destination-australia).

Ethical statement: The Academic Research Committee and the Institutional Ethics Committee of the host school independently reviewed and approved the study. In addition, permission from campus director of the host school was sought prior to conducting the research. Data collection proceeded after obtaining written informed consent from parents or legal guardians and written informed assent from students. The study adhered to local legislation.

AI statement: Generative AI tools were used to enhance the clarity and readability of the English language in this manuscript. The AI tool was employed solely for proofreading and stylistic refinement. The authors state that no substantive contributions to the research were performed by AI. All research design, findings, interpretations, and conclusions are entirely the work of the authors.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

REFERENCES

Abd-El-Khalick, F., & Lederman, N. G. (2000). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching, 37*(10), 1057-1095. https://doi.org/10.1002/1098-2736(200012)37:10<1057::AID-TEA3>3.0.CO;2-C

Aiello, C. D., Awschalom, D. D., Bernien, H., Brower, T., Brown, K. R., Brun, T. A., Caram, J. R., Chitambar, E., Di Felice, R., Edmonds, K. M., Fox, M. F. J., Haas, S., Holleitner, A. W., Hudson, E. R., Hunt, J. H., Joynt, R., Koziol, S., Larsen, M., Lewandowski, H. J., … Zwickl, B. M. (2021). Achieving a quantum smart workforce. *Quantum Science and Technology, 6*(3), Article 030501. https://doi.org/10.1088/2058-9565/abfa64

Akcay, H., & Yager, R. E. (2010). The impact of a science/technology/society teaching approach on student learning in five domains. *Journal of Science Education and Technology, 19*(6), 602-611. https://doi.org/10.1007/s10956-010-9226-7

Alpaydın, Y., & Demirli, C. (2022). *Educational theory in the 21st century: Science, technology, society and education*. Springer. https://doi.org/10.1007/978-981-16-9640-4

Archer, N. (2022). Visual design of quantum physics – Lessons learned from nine gamified and artistic quantum physics projects. *Aaltodoc*. https://aaltodoc.aalto.fi/items/e05af20f-6aed-481c-b336-48e0b4bafd30

Ardies, J., De Maeyer, S., Gijbels, D., & van Keulen, H. (2015). Students attitudes towards technology. *International Journal of Technology and Design Education, 25*(1), 43-65. https://doi.org/10.1007/s10798-014-9268-x

Beardow, C., & Stappers, P. J. (2026). Towards metaphors for quantum computational thinking. *EPJ Quantum Technology, 13*, Article 55. https://doi.org/10.1140/epjqt/s40507-026-00502-1

Bevan, B., Peppler, K., Rosin, M., Scarff, L., Soep, E., & Wong, J. (2020). Purposeful pursuits: Leveraging the epistemic practices of the arts and sciences. In A. J. Stewart, M. P. Mueller, & D. J. Tippins (Eds.), *Converting STEM into STEAM programs. Environmental discourses in science education, vol 5* (pp. 21-38). Springer. https://doi.org/10.1007/978-3-030-25101-7_3

Blatti, J. L., Garcia, J., Cave, D., Monge, F., Cuccinello, A., Portillo, J., Juarez, B., Chan, E., & Schwebel, F. (2019). Systems thinking in science education and outreach toward a sustainable future. *Journal of Chemical Education, 96*(12), 2852-2862. https://doi.org/10.1021/acs.jchemed.9b00318

Bondani, M., Chiofalo, M. L., Ercolessi, E., Macchiavello, C., Malgieri, M., Michelini, M., Mishina, O., Onorato, P., Pallotta, F., Satanassi, S., Stefanel, A., Sutrini, C., Testa, I., & Zuccarini, G. (2022). Introducing quantum technologies at secondary school level: Challenges and potential impact of an online extracurricular course. *Physics, 4*(4), 1150-1167. https://doi.org/10.3390/physics4040075

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77-101. https://doi.org/10.1191/1478088706qp063oa

Braun, V., & Clarke, V. (2019). Reflecting on reflexive thematic analysis. *Qualitative Research in Sport, Exercise and Health, 11*(4), 589-597. https://doi.org/10.1080/2159676X.2019.1628806

Burrows, A., Lockwood, M., Borowczak, M., Janak, E., & Barber, B. (2018). Integrated STEM: Focus on informal education and community collaboration through engineering. *Education Sciences, 8*(1), Article 4. https://doi.org/10.3390/educsci8010004

Carrell, J., Keaty, H., & Wong, A. (2020). Humanities-driven STEM—Using history as a foundation for STEM education in honors. *Honors in Practice, 16*.

Chikodili, N. B., Abdulmalik, M. D., Abisoye, O. A., & Bashir, S. A. (2020). Outlier detection in multivariate time series data using a fusion of K-medoid, standardized Euclidean distance and Z-score. In *Proceedings of the 3rd International Conference on Information and Communication Technology and Applications* (pp. 259-271). https://doi.org/10.1007/978-3-030-69143-1_21

Chiofalo, M. L., Foti, C., Michelini, M., Santi, L., & Stefanel, A. (2022). Games for teaching/learning quantum mechanics: A pilot study with high-school students. *Education Sciences, 12*(7), Article 446. https://doi.org/10.3390/educsci12070446

Cook, K. L., & Bush, S. B. (2018). Design thinking in integrated STEAM learning: Surveying the landscape and exploring exemplars in elementary grades. *School Science and Mathematics, 118*(3-4), 93-103. https://doi.org/10.1111/ssm.12268

Cook, K. L., Bush, S. B., & Cox, R. (2017). Engineering encounters: From STEM to STEAM. *Science and Children, 54*(6), Article 86. https://doi.org/10.2505/4/sc17_054_06_86

Cooperstein, S. E., & Kocevar-Weidinger, E. (2004). Beyond active learning: A constructivist approach to learning. *Reference Services Review, 32*(2), 141-148. https://doi.org/10.1108/00907320410537658

Cotantino, T., Kellam, N., Cramond, B., & Crowder, I. (2010). An interdisciplinary design studio: How can art and engineering collaborate to increase students' creativity? *ART Education, 63*(2), 49-53. https://doi.org/10.1080/00043125.2010.11519062

Crepeau, J. (2009). A brief history of the T^4 radiation law. In *Proceedings of the Heat Transfer Summer Conference*. https://doi.org/10.1115/HT2009-88060

Darienzo, M., Kelly, A. M., Schneble, D., & Wei, T.-C. (2024). Student attitudes toward quantum information science and technology in a high school outreach program. *Physical Review Physics Education Research, 20*, Article 020126. https://doi.org/10.1103/PhysRevPhysEducRes.20.020126

Das, P. M., Faikhamta, C., & Punsuvon, V. (2019). Bhutanese students' views of nature of science: A case study of culturally rich country. *Research in Science Education, 49*(2), 391-412. https://doi.org/10.1007/s11165-017-9611-9

Dasgupta, C., Magana, A. J., & Vieira, C. (2019). Investigating the affordances of a CAD enabled learning environment for promoting integrated STEM learning. *Computers & Education, 129*, 122-142. https://doi.org/10.1016/j.compedu.2018.10.014

Dele-Ajayi, O., Strachan, R., Pickard, A. J., & Sanderson, J. J. (2019). Games for teaching mathematics in Nigeria: What happens to pupils' engagement and traditional classroom dynamics? *IEEE Access, 7*, 53248-53261. https://doi.org/10.1109/ACCESS.2019.2912359

Dennen, V. P., & Burner, K. J. (2008). The cognitive apprenticeship model in educational practice. In *Handbook of research on educational communications and technology* (pp. 425-439). Routledge.

Deutsch, I. H. (2020). Harnessing the power of the second quantum revolution. *PRX Quantum, 1*(2), Article 020101. https://doi.org/10.1103/PRXQuantum.1.020101

DiGironimo, N. (2011). What is technology? Investigating student conceptions about the nature of technology. *International Journal of Science Education, 33*(10), 1337-1352. https://doi.org/10.1080/09500693.2010.495400

Dowling, J. P., & Milburn, G. J. (2003). Quantum technology: The second quantum revolution. *Philosophical Transactions of the Royal Society A, 361*(1809), 1655-1674. https://doi.org/10.1098/rsta.2003.1227

Doyle, L., Seifollahi, F., & Singh, C. (2026). Navigating hype, interdisciplinary collaboration, and industry partnerships in quantum information science and technology: Perspectives from leading quantum educators. *European Journal of Physics, 47*(2), Article 025705. https://doi.org/10.1088/1361-6404/ae3ae6

Dündar-Coecke, S., Yeh, L., Puca, C., Pfaendler, S. M. L., Waseem, M. H., Cervoni, T., Kissinger, A., Gogioso, S., & Coecke, B. (2023). Quantum picturalism: Learning quantum theory in high school. In *Proceedings of the 2023 IEEE International Conference on Quantum Computing and Engineering* (pp. 21-32). IEEE. https://doi.org/10.1109/QCE57702.2023.20321

Eastwell, P. (2002). Social constructivism. *Science Education Review, 1*(3), 82-86.

Escanez-Exposito, D., Correa-Marichal, J., & Caballero-Gil, P. (2024). Using game-based learning and quantum computing to enhance STEAM competencies in K-16 education. *IEEE Transactions on Education, 67*(6), 807-816. https://doi.org/10.1109/TE.2024.3422315

Escanez-Exposito, D., Rodriguez-Vega, M., Rosa-Remedios, C., & Caballero-Gil, P. (2025). QScratch: Introduction to quantum mechanics concepts through block-based programming. *EPJ Quantum Technology, 12*, Article 12. https://doi.org/10.1140/epjqt/s40507-025-00314-9

Fowler, W. C., Ting, J. M., Meng, S., Li, L., & Tirrell, M. V. (2019). Integrating systems thinking into teaching emerging technologies. *Journal of Chemical Education, 96*(12), 2805-2813. https://doi.org/10.1021/acs.jchemed.9b00280

G, P. (2020). The math found EVERYWHERE in physics: MATRICES – Get ahead by learning this topic. *YouTube*. https://youtu.be/Ujvy2-o1I9c?si=yFXkVksZVvFm_QdZ

García-Martínez, I., Gutiérrez Cáceres, R., Luque de la Rosa, A., & León, S. P. (2021). Analysing educational interventions with gifted students.

systematic review. *Children, 8*(5), Article 365. https://doi.org/10.3390/children8050365

Gerondio, L. B., Unabia, W. A. R., Mayang, Z. M., & Alimbon, J. A. (2024). Junior high school students' views of nature of science: Evidence from a private school in Davao Region, Philippines. *International Journal of Science Education, 46*(9), 839-857. https://doi.org/10.1080/09500693.2023.2260522

Giliberti, M., & Lovisetti, L. (2024). Black-body radiation. In *Old quantum theory and early quantum mechanics. Challenges in physics education* (pp. 3-25). Springer. https://doi.org/10.1007/978-3-031-57934-9_1

Gomez-del Rio, T., & Rodriguez, J. (2022). Design and assessment of a project-based learning in a laboratory for integrating knowledge and improving engineering design skills. *Education for Chemical Engineers, 40*, 17-28. https://doi.org/10.1016/j.ece.2022.04.002

Gopalan, M., Rosinger, K., & Ahn, J. B. (2020). Use of quasi-experimental research designs in education research: Growth, promise, and challenges. *Review of Research in Education, 44*(1), 218-243. https://doi.org/10.3102/0091732X20903302

Greinert, F., Müller, R., Goorney, S., Sherson, J., & Ubben, M. S. (2023). Towards a quantum ready workforce: The updated European competence framework for quantum technologies. *Frontiers in Quantum Science and Technology, 2*. https://doi.org/10.3389/frqst.2023.1225733

Greinert, F., Ubben, M. S., Dogan, I. N., Hilfert-Rüppell, D., & Müller, R. (2024). Advancing quantum technology workforce: Industry insights into qualification and training needs. *EPJ Quantum Technology, 11*, Article 82. https://doi.org/10.1140/epjqt/s40507-024-00294-2

Guzey, S. S., Ring-Whalen, E. A., Harwell, M., & Peralta, Y. (2019). Life STEM: A case study of life science learning through engineering design. *International Journal of Science and Mathematics Education, 17*, 23-42. https://doi.org/10.1007/s10763-017-9860-0

Hennig, F., Tóth, K., Förster, M., & Bitzenbauer, P. (2024). A new teaching-learning sequence to promote secondary school students' learning of quantum physics using Dirac notation. *Physics Education, 59*(4), Article 045007. https://doi.org/10.1088/1361-6552/ad353d

Herro, D., Quigley, C., & Cian, H. (2019). The challenges of STEAM instruction: Lessons from the field. *Action in Teacher Education, 41*(2), 172-190. https://doi.org/10.1080/01626620.2018.1551159

Holbrook, J., Rannikmäe, M., & Soobard, R. (2020). STEAM education—A transdisciplinary teaching and learning approach. In B. Akpan, & T. J. kennedy (Eds.), *Science education in theory and practice. Springer texts in education* (pp. 465-477). Springer. https://doi.org/10.1007/978-3-030-43620-9_31

Kastens, K. A., & Manduca, C. A. (2017). Using systems thinking in the design, implementation, and evaluation of complex educational innovations, with examples from the InTeGrate project. *Journal of Geoscience Education, 65*(3), 219-230. https://doi.org/10.5408/16-225.1

Keane, L., & Keane, M. (2016). STEAM by design. *Design and Technology Education, 21*(1), 61-82.

Keller, J. M. (1987). Development and use of the ARCS model of instructional design. *Journal of instructional development, 10*(3), 2-10. https://doi.org/10.1007/BF02905780

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education, 3*(1), Article 11. https://doi.org/10.1186/s40594-016-0046-z

Kember, D. (2003). To control or not to control: The question of whether experimental designs are appropriate for evaluating teaching innovations in higher education. *Assessment & Evaluation in Higher Education, 28*(1), 89-101. https://doi.org/10.1080/02602930301684

Kirchhoff, G. (1860). I. On the relation between the radiating and absorbing powers of different bodies for light and heat. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 20*(130), 1-21. https://doi.org/10.1080/14786446008642901

Klassen, S. (2006). A theoretical framework for contextual science teaching. *Interchange, 37*(1), 31-62. https://doi.org/10.1007/s10780-006-8399-8

Koh, L., Orzes, G., & Jia, F. (2019). The fourth industrial revolution (Industry 4.0): Technologies disruption on operations and supply chain management. *International Journal of Operations & Production Management, 39*(6-7-8), 817-828. https://doi.org/10.1108/IJOPM-08-2019-788

Krelina, M. (2021). Quantum technology for military applications. *EPJ Quantum Technology, 8*, Article 24. https://doi.org/10.1140/epjqt/s40507-021-00113-y

Lay-Ekuakille, A., Vergallo, P., Morello, R., & De Capua, C. (2014). Indoor air pollution system based on LED technology. *Measurement, 47*, 749-755. https://doi.org/10.1016/j.measurement.2013.09.040

Leavy, A., Dick, L., Meletiou-Mavrotheris, M., Paparistodemou, E., & Stylianou, E. (2023). The prevalence and use of emerging technologies in STEAM education: A systematic review of the literature. *Journal of Computer Assisted Learning,* *39*(4), 1061-1082. https://doi.org/10.1111/jcal.12806

Li, K., & Keller, J. M. (2018). Use of the ARCS model in education: A literature review. *Computers & Education, 122*, 54-62. https://doi.org/10.1016/j.compedu.2018.03.019

Liang, L. L., Chen, S., Chen, X., Kaya, O. N., Adams, A. D., Macklin, M., & Ebenezer, J. (2008). Assessing preservice elementary teachers' views on the nature of scientific knowledge: A dual-response instrument. *Asia-Pacific Forum on Science Learning and Teaching, 9*.

Liao, C. (2016). From interdisciplinary to transdisciplinary: An arts-integrated approach to STEAM education. *ART Education, 69*(6), 44-49. https://doi.org/10.1080/00043125.2016.1224873

Lovisetti, L., & Giliberti, M. (2025). Can old-quantum-theoretical description of physical reality be considered worth teaching? In I. Testa, M. Michelini, & S. Esposito (Eds.), *Connecting physics education research and practice. Challenges in physics education* (pp. 155-172). Springer. https://doi.org/10.1007/978-3-031-86609-8_10

McFarlane, D. A. (2013). Understanding the challenges of science education in the 21st century: New opportunities for scientific literacy. *International Letters of Social and Humanistic Sciences, 4*, 35-44. https://doi.org/10.18052/www.scipress.com/ILSHS.4.35

Mejias, S., Thompson, N., Sedas, R. M., Rosin, M., Soep, E., Peppler, K., Roche, J., Wong, J., Hurley, M., Bell, P., & Bevan, B. (2021). The trouble with STEAM and why we use it anyway. *Science Education, 105*(2), 209-231. https://doi.org/10.1002/sce.21605

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

Michelini, M., & Stefanel, A. (2021). Approaches on T/L quantum physics from PER literature. In B. Jarosievitz, & C. Sükösd (Eds.), *Teaching-learning contemporary physics. Challenges in physics education* (pp. 3-17). Springer. https://doi.org/10.1007/978-3-030-78720-2_1

Mischel, T. (1971). Piaget: Cognitive conflict and the motivation of thought. In T. Mischel (Ed.), *Cognitive development and epistemology* (pp. 311-355). Academic Press. https://doi.org/10.1016/B978-0-12-498640-4.50015-9

Moore, T. J., Johnston, A. C., & Glancy, A. W. (2020). STEM integration: A synthesis of conceptual frameworks and definitions. In *Handbook of research on STEM education* (pp. 3-16). Routledge. https://doi.org/10.4324/9780429021381-2

Morgan, H. (2022). Understanding thematic analysis and the debates involving its use. *The Qualitative Report, 27*(10), 2079-2091. https://doi.org/10.46743/2160-3715/2022.5912

Nadelson, L. S., & Seifert, A. L. (2017). Integrated STEM defined: Contexts, challenges, and the future. *The Journal of Educational Research, 110*(3), 221-223. https://doi.org/10.1080/00220671.2017.1289775

Nautiyal, V. V., Salvador, E. E. P., & Stadermann, H. K. E. (in press). Quantum technology education through i-STEAM: Leveraging the discipline–culture paradigm for sustainable practice. In *Sustainability in and of STEM education: Theoretical foundations and practical applications (sociocultural explorations of science education)*. Springer.

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

Nautiyal, V. V., Silverio, S. A., & Salvador, E. E. P. (2024). Let's get on-board: A practical framework for designing and implementing educational board games in K-12 classrooms. *Frontiers in Education, 9*. https://doi.org/10.3389/feduc.2024.1420515

Neale, D. C., Gill, N., & Tismer, W. (1970). Relationship between attitudes toward school subjects and school achievement. *The Journal of Educational Research, 63*(5), 232-237. https://doi.org/10.1080/00220671.1970.10883995

Onwuegbuzie, A. J., & Leech, N. L. (2004). Enhancing the interpretation of "significant" findings: The role of mixed methods research. *The Qualitative Report, 9*(4), 770-792.

Özdemir, E. (2017). Comics in modern physics: Learning blackbody radiation through quasi-history of physics. *Studies in Educational Research and Development, 1*(1), 41-59.

Passon, O., & Grebe-Ellis, J. (2017). Planck's radiation law, the light quantum, and the prehistory of indistinguishability in the teaching of quantum mechanics. *European Journal of Physics, 38*(3), Article 035404. https://doi.org/10.1088/1361-6404/aa6134

Persson, J. (2018). Evolution of quasi-history of the Planck blackbody radiation equation in a physics textbook. *American Journal of Physics, 86*(12), 887-892. https://doi.org/10.1119/1.5054005

Peters, S. J., Matthews, M. S., McBee, M. T., & McCoach, D. B. (2014). *Beyond gifted education: Designing and implementing advanced academic programs*. Routledge. https://doi.org/10.4324/9781003233299

Piaget, J. (1952). The origins of intelligence in children. W. W. Norton & Company. https://doi.org/10.1037/11494-000

Piaget, J. (1980). The psychogenesis of knowledge and its epistemological significance. In M. Piattelli-Palmarini (Ed.), *Language and learning: The debate between Jean Piaget and Noam Chomsky* (pp. 1-23). Harvard University Press.

Piaget, J. (1995). *Sociological studies*. Psychology Press.

Piispanen, L., Pfaffhauser, M., Wootton, J., Togelius, J., & Kultima, A. (2025). Defining quantum games. *EPJ Quantum Technology, 12*, Article 7. https://doi.org/10.1140/epjqt/s40507-025-00308-7

Plank, H. M., Livers, S. D., & Roberts, T. (2026). Preservice elementary teachers' perceptions of integrated STEM after participating in an integrated STEAM course. *Education Sciences, 16*(2), Article 214. https://doi.org/10.3390/educsci16020214

Proudfoot, K. (2023). Inductive/deductive hybrid thematic analysis in mixed methods research. *Journal of Mixed Methods Research, 17*(3), 308-326. https://doi.org/10.1177/15586898221126816

Quigley, C. F., & Herro, D. (2016). "Finding the joy in the unknown": Implementation of STEAM teaching practices in middle school science and math classrooms. *Journal of Science Education and Technology, 25*(3), 410-426. https://doi.org/10.1007/s10956-016-9602-z

Quigley, C. F., Herro, D., & Jamil, F. M. (2017). Developing a conceptual model of STEAM teaching practices. *School Science and Mathematics, 117*(1-2), 1-12. https://doi.org/10.1111/ssm.12201

Rai, M., Maity, T., & Yadav, R. (2017). Thermal imaging system and its real time applications: A survey. *Journal of Engineering Technology, 6*(2), 290-303.

Rasa, T., Palmgren, E., & Laherto, A. (2022). Futurising science education: Students' experiences from a course on futures thinking and quantum computing. *Instructional Science, 50*(3), 425-447. https://doi.org/10.1007/s11251-021-09572-3

Reggiani, L., & Alfinito, E. (2022). Revisiting the Boltzmann derivation of the Stefan law. *Fluctuation and Noise Letters, 21*(5), Article 2230001. https://doi.org/10.1142/s0219477522300014

Roberson, T., Leach, J., & Raman, S. (2021). Talking about public good for the second quantum revolution: Analysing quantum technology narratives in the context of national strategies. *Quantum Science & Technology, 6*(2), Article 025001. https://doi.org/10.1088/2058-9565/abc5ab

Robertson, S., & Pfeiffer, S. (2016). Development of a procedural guide to implement response to intervention (RtI) with high-ability learners. *Roeper Review, 38*(1), 9-23. https://doi.org/10.1080/02783193.2015.1112863

Rockmore, T. (2005). *On constructivist epistemology*. Rowman & Littlefield Publishers.

Roehrig, G. H., Dare, E. A., Ellis, J. A., & Ring-Whalen, E. (2021). Beyond the basics: A detailed conceptual framework of integrated STEM. *Disciplinary and Interdisciplinary Science Education Research, 3*(1), Article 11. https://doi.org/10.1186/s43031-021-00041-y

Rudge, D. W., & Howe, E. M. (2009). An explicit and reflective approach to the use of history to promote understanding of the nature of science. *Science & Education, 18*(5), 561-580. https://doi.org/10.1007/s11191-007-9088-4

Ryu, M., Mentzer, N., & Knobloch, N. (2019). Preservice teachers' experiences of STEM integration: Challenges and implications for integrated STEM teacher preparation. *International Journal of Technology and Design Education, 29*(3), 493-512. https://doi.org/10.1007/s10798-018-9440-9

Salvador, E. E., & Nautiyal, V. (2024). High school STEM internship program policy transitions during COVID-19 pandemic. *The Normal Lights*. https://doi.org/10.56278/tnl.vi.2452

Satanassi, S., Fantini, P., Spada, R., & Levrini, O. (2021). Quantum computing for high school: An approach to interdisciplinary in STEM for teaching. *Journal of Physics: Conference Series, 1929*, Article 012053. https://doi.org/10.1088/1742-6596/1929/1/012053

Seifollahi, F., & Singh, C. (2025). Preparing students for the quantum information revolution: Interdisciplinary teaching, curriculum development, and advising in quantum information science and engineering. *European Journal of Physics, 46*, Article 055709. https://doi.org/10.1088/1361-6404/ae0200

Seskir, Z. C., Migdał, P., Weidner, C., Anupam, A., Case, N., Davis, N., Decaroli, C., Ercan, İ., Foti, C., & Gora, P. (2022). Quantum games and interactive tools for quantum technologies outreach and education. *Optical Engineering, 61*(8), Article 081809. https://doi.org/10.1117/1.OE.61.8.081809

Sgro, C. M., Bobowski, T., & Oliveira, A. W. (2020). Current praxis and conceptualization of STEM education: A call for greater clarity in integrated curriculum development. In V. L. Akerson, & G. A. Buck (Eds.), *Critical questions in STEM education. Contemporary trends and issues in science education, vol 51* (pp. 185-210). Springer. https://doi.org/10.1007/978-3-030-57646-2_11

Shapiro, S. S., Wilk, M. B., & Chen, H. J. (1968). A comparative study of various tests for normality. *Journal of the American Statistical Association, 63*(324), 1343-1372. https://doi.org/10.1080/01621459.1968.10480932

Shernoff, D. J. (2024). The emergence of STEAM instruction and curricula worldwide. In *Integrative STEM and STEAM education for real-life learning. Advancing responsible adolescent development* (pp. 110-114). Springer. https://doi.org/10.1007/978-3-031-69824-8_5

Stadermann, H., van den Berg, E., & Goedhart, M. (2019). Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic. *Physical Review Physics Education Research, 15*, Article 010130. https://doi.org/10.1103/PhysRevPhysEducRes.15.010130

Stevenson, E., van Driel, J., & Millar, V. (2024). How to support teacher learning of integrated STEM curriculum design. *Journal for STEM Education Research, 9*, 59-84. https://doi.org/10.1007/s41979-024-00133-0

Sun, Q., Zhou, S., Chen, R., Feng, G., Cheung, K. T., Li, J., Hou, S.-Y., & Zeng, B. (2024). From computing to quantum mechanics: Accessible and hands-on quantum computing education for high school students. *EPJ Quantum Technology, 11*, Article 58. https://doi.org/10.1140/epjqt/s40507-024-00271-9

Swain, J. (2018). *A hybrid approach to thematic analysis in qualitative research: Using a practical example*. SAGE. https://doi.org/10.4135/9781526435477

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education, 2*, Article 53. https://doi.org/10.5116/ijme.4dfb.8dfd

Tempelaar, D. T., Gijselaers, W. H., van der Loeff, S. S., & Nijhuis, J. F. (2007). A structural equation model analyzing the relationship of student achievement motivations and personality factors in a range of academic subject-matter areas. *Contemporary Educational Psychology, 32*(1), 105-131. https://doi.org/10.1016/j.cedpsych.2006.10.004

Thomas Becker, M. H., Heidemann, L. A., & Lima, N. W. (2024). History of science in physics education in the last decade: Which direction we are heading? *Science & Education, 34*, 3041-3078. https://doi.org/10.1007/s11191-024-00537-9

Tóth, K., Hennig, F., Veith, J. M., & Bitzenbauer, P. (2025). Secondary school learners' reasoning about quantum randomness in the context of single-photon interferometer and double-slit experiments. *Eurasia Journal of Mathematics, Science and Technology Education, 21*(8), Article em2686. https://doi.org/10.29333/ejmste/16736

Tseitlin, M., & Galili, I. (2005). Physics teaching in the search for its self. *Science & Education, 14*(3), 235-261. https://doi.org/10.1007/s11191-004-7943-0

Tytler, R. (2020). STEM education for the twenty-first century. In J. Anderson, & Y. Li (Eds.), *Integrated approaches to STEM education: An international perspective* (pp. 21-43). Springer. https://doi.org/10.1007/978-3-030-52229-2_3

Ubben, M. S., Veith, J. M., Merzel, A., & Bitzenbauer, P. (2023). Quantum science in a nutshell: fostering students' functional understanding of models. *Frontiers in Education, 8*. https://doi.org/10.3389/feduc.2023.1192708

Weissman, E. Y., Merzel, A., Katz, N., & Galili, I. (2019). Teaching quantum mechanics in high-school – Discipline-culture approach. *Journal of Physics: Conference Series, 1287*, Article 012003. https://doi.org/10.1088/1742-6596/1287/1/012003

Weissman, E. Y., Merzel, A., Katz, N., & Galili, I. (2021). Teaching quantum physics as a structured physics theory in high school. *Journal of Physics: Conference Series, 1929*, Article 012051. https://doi.org/10.1088/1742-6596/1929/1/012051

Weissman, E. Y., Merzel, A., Nadav, K., & Galili, I. (2024). Keep it secret, keep it safe: Teaching quantum key distribution in high school. *EPJ Quantum Technology, 11*, Article 64. https://doi.org/10.1140/epjqt/s40507-024-00276-4

Wilson, V. (2014). Research methods: Triangulation. *Evidence Based Library and Information Practice, 9*, 74-75. https://doi.org/10.18438/B8WW3X

Witucki, A., Beane, W., Pleasants, B., Dai, P., & Rudge, D. W. (2024). An explicit and reflective approach to teaching nature of science in a course-based undergraduate research experience. *Science & Education, 33*(6), 1371-1399. https://doi.org/10.1007/s11191-023-00441-8

Wolbring, G. (2022). Auditing the 'social' of quantum technologies: A scoping review. *Societies, 12*(2), Article 41. https://doi.org/10.3390/soc12020041

Wuttiprom, S., Sharma, M. D., Johnston, I. D., Chitaree, R., & Soankwan, C. (2009). Development and use of a conceptual survey in introductory quantum physics. *International Journal of Science Education,* *31*(5), 631-654. https://doi.org/10.1080/09500690701747226

Yadav, M., & Rawat, K. S. (2025). Knowledge mapping of quantum computing for climate change research and sustainable innovation. *Quality & Quantity, 60*, 3511-3544. https://doi.org/10.1007/s11135-025-02413-2

Zeidler, D. L. (2016). STEM education: A deficit framework for the twenty first century? A sociocultural socioscientific response. *Cultural Studies of Science Education, 11*(1), 11-26. https://doi.org/10.1007/s11422-014-9578-z

Zhang, N., Lao, S., Qiu, Z., Yang, Y., & Ouyang, F. (2025). The effects of online collaborative environments and scaffoldings on student engagement in collaborative problem-solving process. *Education and Information Technologies, 30*, 22521-22546. https://doi.org/10.1007/s10639-025-13648-9

APPENDIX A

Table A1. Themes, sub-themes related codes and examples from data (quotes)

Theme	Sub-theme	Codes	Example from data (student quotes)
1. Recognizing connection between science, technology and society	a. Real world applications of science	• *Scientific concepts in everyday technology*	*"Not only that, I also learned about how quantum physics is everywhere in our daily lives, from electricity to computers to medical uses and many more!"* (RE 11)
		• Translating theory to sociocultural practice	*"I worked on hands-on design tasks, like building systems maps and causal loop diagrams, which helped me visualize how scientific concepts connect with technology, people, and policy."* (RE 2)
		• Role of science in daily life	*"This SIP was a very eye-opening experience, and it actually made me appreciate physics more, especially how it is applied to our daily lives."* (RE 11)
	b. Interdisciplinary nature of STEAM fields	• *Connection of QM to other disciplines*	*"It pushed me to see the bigger picture, to connect dots across disciplines, and to be comfortable with uncertainty."* (RE 21)
		• Diversity of possible STEM pathways	*"My second favorite part of immersion, the career talks were really eye opening to me as I viewed quantum to be limited to physics only. I didn't expect it to be applied in industry, chemistry, material physics, and more!"* (RE 22)
		• Creativity and art in STEM	*"This experience showed me how science and creativity are deeply intertwined. Personal experiences shape the way we approach science."* (RE 12)
2. Increased motivation to pursue QM or STEM careers	a. Motivation due to talks by invited speakers	• Inspiration from journey of professionals	*"It was just a neat feeling to know that I am hearing from someone all the way across the globe to teach me about their world."* (RE 8)
		• Clarity on possible STEM careers due to career talks	*"I also learned from the career talks and the career paths and the opportunities that come with pursuing this field."* (RE 18)
	b. Increased motivation after participating in learning activities	• Application of new knowledge in collaborative projects	*"… the hands-on nature of the design projects allowed us interns to apply the concepts we had learned in collaborative ways."* (RE 10)
		• *Aspirations to pursue QT careers*	*"This immersion program has opened my eyes to the vast potential of quantum technology, and I'm seriously considering pursuing it in college and beyond."* (RE 24)
		• Increased interest leading to more motivation	*"This immersion experience has sparked an interest in exploring more advanced topics in quantum mechanics and related technologies for me. It encouraged me to consider new possibilities in science and technology that I hadn't thought about before."* (RE 17)
		• *Desire to continue learning QT/STEM*	*"Moving forward I think I'll continue to learn more about the field of quantum physics, especially in relation to technology and computer science."* (RE 20)
		• *Considering QT as alternative/back-up career*	*"After attending this SIP, I believe that I now have a back-up career plan in engineering or technologies, and possibly something that has to do with working in a lab to do quantum related experiments."* (RE 19)
3. Positive emotions with learning quantum	a. Fun, joy and engagement	• Enjoyment due to interesting topics in lectures	*"I really just enjoyed listening to Sir Vijit's lectures as the topics were genuinely interesting."* (RE 16)
		• Fun in collaborative activities	*"I also loved the interactions with my co-interns in the SIP, as it helped me learn how to collaborate more efficiently with people that had different work styles,…"* (RE 11)
		• Appreciation of engaging nature of learning activities	*"…the complexity of the subject matter, the structured lectures, worksheets, and projects made it manageable and even enjoyable"* (RE 10)
	b. Quantum humor	• Using quantum concepts to convey humor	*"The photoelectric effect has finally arrived! Armed with our one hour lecture of its overview, we fought the monster of a worksheet 4 both individually and by group (somehow possible at the same time, superposition maybe? jk)!"* (RE 22)
4. Accessible view of quantum mechanics	-	• Overcoming initial intimidation	*"Additionally, I was surprised and felt proud that I was able to understand some concepts that were so overwhelming at first…"* (RE 19)
		• Recognition of personal capacity to learn QM	*"Learning about concepts like superposition and uncertainty with my groupmates, and applying them through worksheets and games, made the subject more approachable and even enjoyable…"* (RE 14)
		• Quantum no longer mysterious or abstract	*"I used to think quantum mechanics was too abstract, but I now understand how its rules make sense within its own framework. It's no longer a mysterious subject to me, it's an exciting challenge…"* (RE 24)
		• Reduction in perceived exclusivity	*"The lectures, worksheets, activities, and career talks covered topics that I thought were only accessible and understandable for people fully devoted to physics…"* (RE 10)
5. Reflection on various aspects of nature of science	-	• *Tentative and dynamic nature of science*	*"It helped me realize a lot of things about science in general, about how it evolves, how people work on understanding science, and a lot more…"* (RE 11)
		• *Nature of scientific laws and theories*	*"What stood out to me was how the program didn't stop at quantum concepts as it also took time to revisit the fundamentals of science, like what scientific laws and theories really mean…"* (RE 17)
		• *Creativity in science*	*"I developed not just a deeper understanding of quantum phenomena, but also an appreciation for the iterative, creative process behind engineering solutions"* (RE 2)
		• *Subjective and inferential nature of science*	*"how people can interpret things differently, and how models are valuable representations of concepts, and more."* (RE 18)
		• *Science as a human endeavor*	*"I loved how they conveyed their experiences, their struggles and how they (scientists) overcame those struggles…"* (RE 6)

Note. Italicized codes are deductive while normal text codes are inductive in nature