Ciencia Latina Revista Científica Multidisciplinar, Ciudad de México, México.
ISSN 2707-2207 / ISSN 2707-2215 (en línea), septiembre-octubre 2026,
Volumen 10, Número 5.

https://doi.org/10.37811/cl_rcm.v10i5

THE STEM+ RESEARCH COACHING FRAMEWORK: INTEGRATING AUTHENTIC INQUIRY, HUMAN–AI CO-INTELLIGENCE, AND STEM IDENTITY DEVELOPMENT

EL MARCO DE MENTORÍA EN INVESTIGACIÓN STEM+: INTEGRACIÓN DE LA INDAGACIÓN AUTÉNTICA, LA COINTELIGENCIA HUMANO-IA Y EL DESARROLLO DE LA IDENTIDAD STEM

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DOI: https://doi.org/10.37811/cl_rcm.v10i5.26438

The STEM+ Research Coaching Framework: Integrating Authentic Inquiry, Human–AI Co-Intelligence, and STEM Identity Development

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ABSTRACT

The rapid expansion of generative artificial intelligence, authentic inquiry, and interdisciplinary STEM+ education has renewed interest in understanding how STEM identity develops in contemporary educational contexts. Although previous research has substantially advanced knowledge of STEM identity, authentic inquiry, mentoring, and artificial intelligence in education, these perspectives have largely evolved as parallel research traditions, providing limited guidance for intentionally designing Relational Research Ecosystems in which they operate as an integrated pedagogical system. This integrative literature review analyzes and integrates scholarship on STEM identity, authentic inquiry, mentoring, relational pedagogy, Human–AI Co-Intelligence, and twenty-first-century competencies to develop the STEM+ Research Coaching Framework, a relational pedagogical framework for intentionally designing Relational Research Ecosystems. The framework conceptualizes STEM+ Research Coaching as an integrated relational process in which Methodological Coherence, Intentional Mentoring, Strategic Questioning, Human–AI Co-Intelligence, and Reflective Meaning-Making function as five complementary mechanisms that collectively cultivate authentic inquiry, collaborative knowledge co-construction, scientific agency, and STEM identity development. Rather than conceptualizing artificial intelligence as a tool for task automation, the framework positions Human–AI Co-Intelligence as a relational pedagogical process that supports collaborative knowledge co-construction while preserving human intentionality, disciplinary judgment, ethical responsibility, and critical reflection. By integrating complementary theoretical traditions, the framework shifts the focus from explaining why STEM identity develops toward understanding how educators intentionally cultivate it through the orchestration of Relational Research Ecosystems.

Keywords: artificial intelligence, science education, learning, educational research, mentoring

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El Marco de Mentoría en Investigación STEM+: Integración de la Indagación Auténtica, La Cointeligencia Humano-IA y el Desarrollo de la Identidad STEM

RESUMEN

La rápida expansión de la inteligencia artificial generativa, la indagación auténtica y la educación STEM+ interdisciplinaria ha renovado el interés por comprender cómo se desarrolla la identidad STEM en los contextos educativos contemporáneos. Aunque la investigación ha ampliado significativamente el conocimiento sobre identidad STEM, indagación auténtica, mentoría e inteligencia artificial en educación, estas perspectivas han evolucionado como tradiciones paralelas, ofreciendo una orientación limitada para el diseño intencional de sistemas pedagógicos integrados. Esta revisión de la literatura sintetiza y articula investigaciones sobre identidad STEM, indagación auténtica, mentoría, pedagogía relacional, Co-Inteligencia Humano–IA y competencias del siglo XXI para desarrollar el *STEM+ Research Coaching Framework*, un marco pedagógico relacional para el diseño intencional de *Relational Research Ecosystems*. El marco conceptualiza el *STEM+ Research Coaching* como un proceso relacional integrado en el que la Coherencia Metodológica, la Mentoría Intencional, el Cuestionamiento Estratégico, la Co-Inteligencia Humano–IA y la Construcción Reflexiva de Significado actúan como cinco mecanismos complementarios que favorecen la indagación auténtica, la co-construcción del conocimiento, la agencia científica y el desarrollo de la identidad STEM. El marco concibe la Co-Inteligencia Humano–IA como un proceso pedagógico relacional que fortalece la co-construcción del conocimiento preservando la intencionalidad humana, el juicio disciplinar, la responsabilidad ética y la reflexión crítica. Al integrar tradiciones teóricas complementarias, desplaza el foco desde explicar por qué se desarrolla la identidad STEM hacia comprender cómo los educadores la cultivan mediante la orquestación intencional de Relational Research Ecosystems.

Palabras clave: inteligencia artificial, educación científica, aprendizaje, investigación educativa, mentoría

Artículo recibido 15 setiembre 2026
Aceptado para publicación: 21 octubre 2026

INTRODUCTION

The convergence of generative artificial intelligence (AI), authentic inquiry experiences, and the growing demand for interdisciplinary competencies is rapidly reshaping contemporary educational ecosystems (UNESCO, 2023). Advances in generative AI are transforming how knowledge is accessed, produced, interpreted, and communicated, while simultaneously challenging long-established assumptions about scientific inquiry, teaching, learning, and professional preparation (UNESCO, 2023). Rather than functioning solely as a technological innovation, AI is increasingly being understood as a cognitive partner capable of extending human creativity, reasoning, and problem solving through collaborative forms of intelligence (Mollick, 2024; Casebourne et al., 2025; Guo et al., 2025). At the same time, the complexity of twenty-first-century challenges—including climate change, digital transformation, public health, energy sustainability, and geopolitical instability—requires educational systems capable of preparing learners to address authentic, interdisciplinary problems through scientific reasoning, collaboration, creativity, ethical decision-making, and critical thinking (OECD, 2024). Consequently, STEM+ education has gained renewed relevance as an educational paradigm that extends beyond disciplinary integration toward the intentional development of the competencies required for active participation in knowledge societies (DeJarnette, 2018; National Academies of Sciences, Engineering, and Medicine [NASEM], 2022).

Within this evolving educational landscape, STEM identity has emerged as one of the most influential theoretical constructs for understanding students' engagement, persistence, academic achievement, and career aspirations in science, technology, engineering, and mathematics (Carlone & Johnson, 2007; Hazari et al., 2010; Darragh, 2016; Dou & Cian, 2022). During the last two decades, STEM identity has evolved from a peripheral research topic into one of the central explanatory frameworks in STEM education, supported by an expanding body of empirical studies, structural models, systematic reviews, bibliometric analyses, and conceptual syntheses (Godwin et al., 2013; Darragh, 2016; Simpson & Bouhafa, 2020; Dou & Cian, 2022; Grimalt-Álvaro et al., 2022; Zhai et al., 2024). Research consistently demonstrates that students who perceive themselves as legitimate participants in STEM communities—or who identify themselves as “STEM persons”—are substantially more likely to engage in authentic scientific practices, persist in STEM learning pathways, and pursue STEM-related careers (Carlone &

Johnson, 2007; Hazari et al., 2010; Godwin et al., 2013; Cohen, 2022; Simpson & Bouhafa, 2020; Grimalt-Álvaro et al., 2022; Zhai et al., 2024). More recently, educational scholars have shifted the discussion beyond explaining STEM identity toward intentionally cultivating it through authentic learning experiences, meaningful participation, supportive Relational Research Ecosystems, and relational educational designs (Dou & Cian, 2022; Hoffer, 2016).

The theoretical understanding of STEM identity has evolved considerably alongside these empirical advances. Early approaches were predominantly grounded in psychological and individual-centered perspectives that conceptualized identity as an individual construct associated with personal beliefs, motivation, self-concept, and role development (Gordon, 1976; Gee, 2000; Darragh, 2016). More recent perspectives have progressively adopted sociocultural and relational interpretations, conceptualizing identity as a dynamic, negotiated, and socially situated process that emerges through participation in communities of practice, recognition by others, meaningful engagement in disciplinary activities, and relational interactions across educational contexts (Lave & Wenger, 1991; Wenger, 1998; Gee, 2000; Burke & Tully, 1977; Darragh, 2016; Dou & Cian, 2022). This evolution has been shaped by the foundational contributions of Lave and Wenger's theory of situated learning and communities of practice, Gee's sociocultural theory of identity, Carlone and Johnson's Science Identity framework, Hazari and colleagues' work on Physics and STEM identity, Godwin and colleagues' engineering identity framework, and more recent syntheses emphasizing participation, recognition, competence, performance, agency, and relational interaction as fundamental mechanisms of identity development (Lave & Wenger, 1991; Wenger, 1998; Gee, 2000; Carlone & Johnson, 2007; Hazari et al., 2010; Godwin et al., 2013; Darragh, 2016; Dou & Cian, 2022; Grimalt-Álvaro et al., 2022; Zhai et al., 2024). Together, these perspectives have progressively shifted STEM identity research from viewing identity as an individual psychological construct toward understanding it as a relational process co-constructed through participation, recognition, and socially mediated educational experiences, thereby laying the conceptual foundation for relational models of STEM identity development.

Parallel to these theoretical developments, a substantial body of literature has demonstrated that authentic inquiry, undergraduate research experiences, project-based learning, mentoring, and sustained participation in scientific communities significantly contribute to STEM identity development by

allowing learners to experience science as an authentic social practice rather than merely an academic subject (National Academies of Sciences, Engineering, and Medicine [NASEM], 2017, 2019; Barton & Tan, 2010; Stelter et al., 2021; Hoffer, 2016). Likewise, the rapid emergence of generative AI has expanded opportunities for literature exploration, information retrieval, data analysis, scientific writing, hypothesis generation, and collaborative problem solving (Mollick, 2024; UNESCO, 2023). These transformations have prompted educators and researchers to reconsider not only the instructional applications of artificial intelligence but also its broader implications for knowledge construction, scientific reasoning, educational design, and strategic educational communication (Mollick, 2024; UNESCO, 2023; OECD, 2024).

Despite these significant advances, the literature remains conceptually fragmented (Whittemore & Knafl, 2005; Snyder, 2019; Dou & Cian, 2022). Research on STEM identity has generated robust explanations of why identity matters and has identified numerous individual, social, and contextual factors associated with its development (Carlone & Johnson, 2007; Hazari et al., 2010; Godwin et al., 2013; Zhai et al., 2024). Studies on authentic inquiry and undergraduate research experiences have consistently demonstrated the educational value of engaging learners in meaningful scientific practices (National Academies of Sciences, Engineering, and Medicine [NASEM], 2017, 2019). Likewise, mentoring literature has highlighted the importance of guidance, feedback, social support, mentor preparation, and legitimate participation in fostering scientific growth (National Academies of Sciences, Engineering, and Medicine [NASEM], 2017; Stelter et al., 2021), while the rapidly expanding body of research on artificial intelligence has primarily emphasized technological capabilities, instructional applications, and productivity gains (UNESCO, 2023; Mollick, 2024). Although each of these research traditions has contributed substantially to educational knowledge, they have evolved largely as parallel lines of inquiry, offering limited theoretical guidance regarding how these elements can be intentionally integrated into coherent pedagogical designs that simultaneously promote authentic inquiry, collaborative knowledge construction, and STEM identity development. Consequently, while recent scholarship increasingly advocates the intentional cultivation of STEM identities through authentic educational experiences (Dou & Cian, 2022; Hoffer, 2016), the literature still provides limited conceptual guidance on how educators can deliberately design coherent learning environments that

integrate authentic inquiry, mentoring, Human–AI Co-Intelligence, and relational STEM identity development.

This fragmentation represents one of the most significant challenges facing contemporary STEM+ education (Dou & Cian, 2022; Zhai et al., 2024). While educators now possess substantial evidence regarding the educational outcomes associated with STEM identity, authentic inquiry experiences, mentoring, and emerging AI technologies (National Academies of Sciences, Engineering, and Medicine [NASEM], 2017, 2019; Stelter et al., 2021; Zhai et al., 2024), considerably less attention has been devoted to understanding how teachers intentionally design Relational Research Ecosystems in which these elements operate as interconnected components of a single relational learning process. Questions concerning methodological coherence, the orchestration of authentic inquiry, the intentional use of strategic questioning, reflective meaning-making, and the educational role of Human–AI Co-Intelligence remain comparatively underdeveloped within existing conceptual frameworks. Consequently, the role of the teacher continues to be described primarily as that of an instructor, facilitator, or mentor, rather than as the intentional designer of the relational conditions through which scientific agency, collaborative knowledge construction, and STEM identity emerge (Pérez, 2018; Mas et al., 2022).

The rapid emergence of generative AI further amplifies this conceptual gap. Although artificial intelligence is increasingly recognized as a transformative educational technology capable of supporting writing, data analysis, idea generation, personalized learning, and scientific inquiry (UNESCO, 2023; Mollick, 2024), considerably less attention has been devoted to understanding how Human–AI interaction can become an intentional pedagogical relationship that strengthens scientific reasoning, critical reflection, and authentic inquiry. Following Mollick's (2024) conception of co-intelligence as collaborative human–AI thinking and problem solving, this article argues that the educational value of artificial intelligence extends beyond cognitive assistance or task automation. Its greatest potential lies in becoming an integral component of intentionally designed Relational Research Ecosystems in which learners, teachers, and AI collaboratively construct knowledge through inquiry, dialogue, reflection, and shared meaning-making.

To address this conceptual gap, this integrative literature review analyzes, synthesizes, and connects contemporary scholarship on STEM identity, authentic inquiry, mentoring, relational pedagogy, Human–AI Co-Intelligence, and twenty-first-century competencies (Whittemore & Knafl, 2005; Snyder, 2019). Rather than introducing another explanatory model of STEM identity, the proposed framework advances a relational pedagogical perspective that explains how educators intentionally design Relational Research Ecosystems in which Methodological Coherence, Intentional Mentoring, Strategic Questioning, Human–AI Co-Intelligence, and Reflective Meaning-Making function as complementary and mutually reinforcing mechanisms that cultivate authentic inquiry, scientific agency, collaborative knowledge construction, and STEM identity development. In this sense, the framework extends recent perspectives advocating the intentional cultivation of STEM identities (Dou & Cian, 2022; Grimalt-Álvaro et al., 2022; Zhai et al., 2024; Hoffer, 2016) by providing a coherent pedagogical framework that explains how educators can deliberately design the relational conditions under which such identity development occurs. The proposed framework makes four principal contributions to both educational theory and pedagogical practice. First, it integrates previously disconnected theoretical traditions—including STEM Identity Theory, Relational Sociology, the New Strategic Theory, authentic inquiry, mentoring, and Human–AI Co-Intelligence—into a coherent relational model of pedagogical design. Second, it reconceptualizes the educator's role from instructor, facilitator, or mentor to STEM+ Research Coach, emphasizing the intentional design of Relational Research Ecosystems capable of fostering authentic scientific participation, collaborative knowledge construction, and STEM identity development across disciplinary contexts (Fisher et al., 2017; Paniagua & Istance, 2018; Bartels, 2024). Third, it extends Mollick's (2024) conception of co-intelligence by proposing Human–AI Co-Intelligence as a relational pedagogical mechanism embedded within Relational Research Ecosystems, thereby shifting the educational discourse beyond instrumental views of artificial intelligence toward a perspective centered on human intentionality, scientific reasoning, collaborative knowledge construction, and shared meaning-making (Tseng et al., 2022). Fourth, the framework builds upon and substantially extends the Relational Communication Framework (Collazos, 2025) by translating its relational principles into a pedagogical framework that explains how educators intentionally cultivate STEM identities through the design of authentic STEM+ research ecosystems.

Accordingly, it shifts the focus of STEM education research from explaining why STEM identity develops to understanding how educators can deliberately cultivate STEM identities by orchestrating Relational Research Ecosystems that integrate authentic inquiry, intentional mentoring, strategic questioning, Human–AI Co-Intelligence, and reflective meaning-making.

Beyond its conceptual synthesis, the framework is illustrated through three authentic International Baccalaureate (IB) Diploma Programme research projects completed by the same student across qualitative social science (Global Politics), quantitative mathematical modeling (Mathematics), and experimental natural science (Chemistry). Rather than constituting an empirical validation, these cross-disciplinary cases serve as an illustrative conceptual application showing how the five relational mechanisms can be interpreted across distinct forms of authentic inquiry across distinct epistemological traditions (Stake, 1995). As summarized in Table 1, the three projects collectively illustrate the conceptual coherence, methodological consistency, and interdisciplinary applicability of the proposed framework across diverse disciplinary and epistemological contexts, illustrating how a common relational pedagogical design can be enacted through different forms of scientific inquiry.

The remainder of this article is organized as follows. First, the theoretical foundations of STEM identity, authentic inquiry, mentoring, relational pedagogy, Human–AI Co-Intelligence, and intentional learning design are examined. Next, the STEM+ Research Coaching Framework is introduced, and its five relational mechanisms are described. Finally, the conceptual application of the framework through the three IB Diploma Programme research projects summarized in Table 1 is presented, followed by a discussion of its implications for educational research, teacher education, and the intentional design of future STEM+ learning environments.

Table 1. Illustrative Cross-Disciplinary Application of the STEM+ Research Coaching Framework

Research Project	General Objective	Inquiry Type	Illustrative Evidence
IB Extended Essay (Global Politics)	Analyze the militarization of outer space and its geopolitical implications.	Qualitative Social Science	Methodological coherence; intentional mentoring; strategic questioning; Human–AI co-intelligence; reflective meaning-making.
IB Mathematics IA	Examine the relationship between SST and hurricane frequency.	Quantitative Mathematical Modeling	
IB Chemistry IA	Analyze the effect of temperature on KCl solubility.	Experimental Natural Science	

Source: Authors' own elaboration (2026).

METHOD

Research Design

This study employed an integrative literature review (ILR) as its methodological approach to analyze, synthesize, and integrate contemporary scholarship on STEM identity, authentic inquiry, research mentoring, relational pedagogy, Human–AI Co-Intelligence, and twenty-first-century competencies. Integrative literature reviews are particularly appropriate when knowledge is dispersed across multiple disciplinary traditions, theoretical perspectives, and methodological approaches, and when the objective extends beyond summarizing previous findings toward generating new conceptual understandings, theoretical integration, and conceptual models (Torraco, 2005; Whittemore & Knafl, 2005; Snyder, 2019; Næss, 2026).

Unlike systematic reviews, which primarily seek to answer narrowly defined research questions through the aggregation and critical appraisal of empirical evidence, integrative reviews allow the inclusion of both theoretical and empirical literature, enabling researchers to identify conceptual relationships, synthesize diverse perspectives, develop higher-order interpretations, and construct novel theoretical frameworks (Whittemore & Knafl, 2005; Snyder, 2019). Rather than privileging evidence aggregation alone, ILRs emphasize conceptual integration, theory development, and the generation of new explanatory perspectives capable of advancing interdisciplinary scholarship (Torraco, 2005). This approach is especially valuable in emerging interdisciplinary fields where conceptual fragmentation limits the development of coherent explanatory models and where multiple forms of evidence must be synthesized to inform conceptual innovation (Næss, 2026; Akudjedu et al., 2026).

The interdisciplinary nature of STEM+ education, together with the rapid expansion of generative artificial intelligence and its implications for educational research and authentic inquiry, requires a methodological approach capable of transcending disciplinary boundaries while integrating multiple complementary bodies of knowledge. Consequently, the integrative literature review methodology was selected because it provides a rigorous process for critically examining existing scholarship, identifying convergent and complementary theoretical perspectives, and synthesizing them into a coherent pedagogical framework (Torraco, 2005; Snyder, 2019; Næss, 2026).

Rather than evaluating the effectiveness of a specific educational intervention, this review sought to explain how diverse theoretical traditions converge toward a relational understanding of authentic inquiry experiences and to develop a conceptual framework that supports the intentional design of Relational Research Ecosystems capable of fostering scientific agency, collaborative knowledge construction, and STEM identity development. The review followed the methodological framework proposed by Whittemore and Knafl (2005), encompassing the stages of problem identification, literature search, data evaluation, data analysis, and presentation of the integrated synthesis.

Literature Search Strategy

The literature search was conducted through a structured, systematic, and iterative exploration of four major international academic databases: Scopus, Web of Science (WoS), ERIC, and Google Scholar. These databases were selected because, collectively, they provide comprehensive coverage of educational research, STEM education, learning sciences, educational technology, artificial intelligence, and interdisciplinary pedagogical scholarship.

To ensure conceptual breadth while maintaining methodological coherence, the search strategy was organized around six interrelated conceptual domains that constitute the theoretical foundation of the proposed framework:

STEM Identity

Authentic Inquiry

Research Mentoring

Relational Pedagogy

Artificial Intelligence in Education

Twenty-First-Century Competencies

Search strings combined controlled vocabulary and free-text keywords using Boolean operators (AND, OR) to identify studies situated at the intersections of these conceptual domains. Representative search terms included combinations such as STEM identity, science identity, authentic inquiry, research-based learning, project-based learning, research mentoring, research coaching, relational pedagogy, communities of practice, generative artificial intelligence, Human–AI Co-Intelligence, co-intelligence, scientific agency, critical thinking, collaboration, and creativity.

Priority was given to peer-reviewed journal articles, theoretical papers, systematic reviews, meta-analyses, and influential conceptual publications that contributed to understanding the relational dimensions of authentic inquiry experiences, STEM identity development, and Human–AI Co-Intelligence. Although no strict chronological restriction was imposed, particular emphasis was placed on publications published during the last decade (approximately 2015–2025) to capture recent advances in STEM education and generative artificial intelligence while simultaneously incorporating seminal theoretical works that continue to inform contemporary scholarship.

The initial database search identified 235 potentially relevant publications. After removing 65 duplicate records, 170 full-text publications were screened for conceptual relevance and methodological suitability. Following the iterative evaluation process characteristic of integrative literature reviews, 28 publications were retained as the core database-derived corpus contributing directly to the conceptual synthesis. Consistent with the objectives of an integrative literature review, study selection prioritized theoretical relevance, conceptual richness, interdisciplinary complementarity, and explanatory value rather than exhaustive numerical coverage or quantitative aggregation of evidence (Whittemore & Knafl, 2005; Snyder, 2019; Næss, 2026).

Given that the purpose of an integrative literature review is conceptual synthesis rather than exhaustive numerical representation, the literature search remained iterative throughout the review process. In addition to the 28 core database-derived publications, supplementary seminal and conceptually relevant sources were identified through backward and forward citation tracking when they provided significant theoretical contributions, strengthened emerging conceptual relationships, or enhanced the conceptual integration of the proposed framework. Accordingly, the figure of 28 refers to the core database-derived corpus rather than to the complete set of works cited in the article. This iterative strategy is consistent with contemporary evidence synthesis approaches that emphasize conceptual completeness and theoretical integration over exhaustive study enumeration in interdisciplinary research (Akudjedu et al., 2026; Næss, 2026).

Study Selection Criteria

The inclusion and exclusion criteria were established to ensure that the selected literature contributed directly to the conceptual objectives of the review rather than merely addressing isolated instructional

practices or technological applications. Consistent with the principles of integrative literature reviews, the selection process prioritized studies capable of informing theoretical integration, conceptual development, and interdisciplinary synthesis rather than exhaustive coverage of a single research domain (Whittemore & Knafl, 2005; Snyder, 2019; Næss, 2026).

Publications were included when they addressed one or more of the following areas:

STEM identity development or closely related identity constructs. authentic inquiry, research-based learning, project-based STEM education, or undergraduate research experiences. mentoring, coaching, or pedagogical guidance within educational or research contexts. relational, sociocultural, or community-based perspectives on learning and identity development. educational applications of artificial intelligence relevant to inquiry, knowledge construction, or scientific reasoning; or conceptual and theoretical contributions informing the design of interdisciplinary STEM+ learning environments. Conversely, studies were excluded when they focused exclusively on technical aspects of artificial intelligence without explicit educational implications, discipline-specific instructional interventions lacking broader conceptual relevance, opinion papers without theoretical grounding, or publications that provided insufficient methodological or conceptual transparency. Publications whose primary focus was limited to technological performance, software development, or algorithmic optimization without clear connections to educational theory or authentic inquiry were also excluded.

Following the initial search, titles, abstracts, and full-text publications were reviewed iteratively to determine their relevance to the emerging conceptual synthesis. Rather than applying selection criteria solely to maximize the number of included studies, the review emphasized theoretical relevance, conceptual richness, interdisciplinary complementarity, explanatory value, and the potential contribution of each publication to the construction of the proposed STEM+ Research Coaching Framework. This approach is consistent with integrative literature review methodology, which seeks conceptual coherence and theoretical innovation through the synthesis of complementary perspectives rather than quantitative aggregation of evidence (Whittemore & Knafl, 2005; Snyder, 2019; Akudjedu et al., 2026).

Conceptual Analysis and Synthesis

The selected literature was analyzed through an iterative process of conceptual mapping, relational synthesis, and theoretical integration rather than through statistical aggregation, bibliometric analysis, or quantitative meta-analysis. Consistent with the objectives of an integrative literature review, the analytical process sought to identify convergent theoretical patterns across diverse research traditions, explain how these perspectives collectively contribute to a relational understanding of authentic inquiry experiences, and generate a coherent conceptual framework capable of advancing interdisciplinary educational scholarship (Whittemore & Knafl, 2005; Snyder, 2019; Næss, 2026).

Rather than treating individual studies as isolated units of analysis, the review emphasized the conceptual relationships among theoretical constructs originating from different disciplinary domains. This relational perspective enabled the identification of recurring pedagogical principles that transcend disciplinary boundaries while contributing to a coherent understanding of STEM identity development within authentic inquiry environments (Jabareen, 2009; Snyder, 2019). Accordingly, the synthesis prioritized conceptual convergence and explanatory complementarity over disciplinary categorization, allowing the emergence of higher-order theoretical relationships across the reviewed literature.

The analytical procedure comprised four iterative and progressively integrative phases

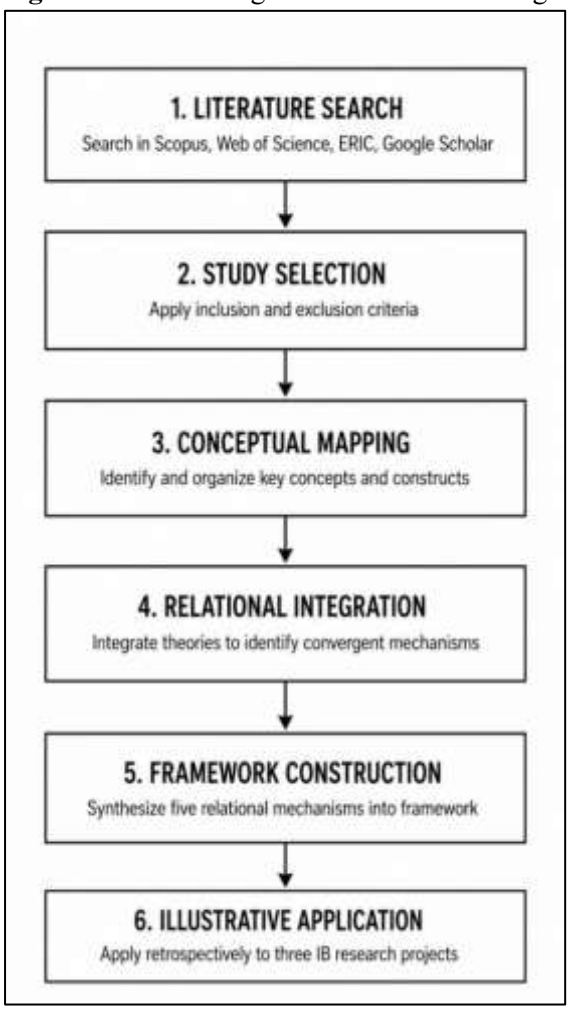
Literature Identification: Relevant publications were identified through systematic searches of the selected academic databases, complemented by backward and forward citation tracking. Throughout this process, additional studies were incorporated whenever they contributed substantially to the conceptual development of the emerging framework or strengthened theoretical connections among the principal domains of analysis.

Conceptual Mapping: During the second phase, the selected literature was examined to identify core concepts, theoretical constructs, and recurring pedagogical principles. These concepts were subsequently organized into preliminary thematic categories representing the principal dimensions addressed across the literature, including STEM identity, authentic inquiry, research mentoring, relational pedagogy, Human–AI Co-Intelligence, and twenty-first-century competencies (Jabareen, 2009). Rather than functioning as independent categories, these themes served as analytical entry points for exploring broader conceptual relationships among diverse theoretical traditions.

Relational Integration: The third phase constituted the central analytical component of the review. Instead of synthesizing the literature according to disciplinary boundaries, the identified categories were examined through a relational perspective to determine how different theoretical traditions converged in explaining authentic inquiry, scientific participation, collaborative knowledge construction, and identity development. Particular attention was devoted to identifying pedagogical mechanisms that consistently appeared across otherwise independent bodies of literature. This relational synthesis enabled the integration of concepts originating from STEM education, mentoring research, sociocultural learning theory, relational sociology, communication studies, and Human–AI Co-Intelligence into a unified explanatory perspective centered on the intentional design of Relational Research Ecosystems (Jabareen, 2009).

Framework Construction: The final analytical phase consisted of constructing the STEM+ Research Coaching Framework through the integration of the recurring relational mechanisms identified during the previous stages of analysis. Rather than emerging from a single theoretical tradition, the proposed framework represents the conceptual convergence of multiple complementary perspectives that consistently emphasize authentic inquiry as a fundamentally relational educational process. This synthesis resulted in the identification of five interdependent pedagogical mechanisms that collectively explain how educators intentionally design Relational Research Ecosystems capable of fostering authentic inquiry, collaborative knowledge construction, scientific agency, and STEM identity development: Methodological Coherence, Intentional Mentoring, Strategic Questioning, Human–AI Co-Intelligence, and Reflective Meaning-Making.

Figure 1. Methodological Process of the Integrative Literature Review



Note. The figure summarizes the methodological process followed to develop the STEM+ Research Coaching Framework through an integrative literature review.

Unlike conventional thematic reviews, which typically organize previous studies into descriptive categories, the present analysis emphasized the identification and integration of conceptual relationships across diverse theoretical traditions (Jabareen, 2009; Snyder, 2019). Consequently, the proposed framework should be understood as an integrative theoretical framework that explains how these relational mechanisms operate collectively to support authentic STEM+ research experiences, rather than as a simple classification of the existing literature.

The overall methodological process underlying the development of the framework is summarized in Figure 1, which illustrates the progression from literature identification and conceptual mapping to relational integration, framework construction, and its subsequent illustrative cross-disciplinary application.

Illustrative Conceptual Application

Following the construction of the proposed framework, its conceptual coherence was retrospectively illustrated through three authentic inquiry projects completed by a single International Baccalaureate (IB) Diploma Programme student. This illustrative application was not conceived as an empirical validation or effectiveness study but as an analytical extension of the integrative literature review designed to examine whether the proposed framework provides a coherent and interpretable representation of authentic inquiry coaching across distinct forms of scientific inquiry.

The three projects were purposefully selected because they represent diverse epistemological traditions while encompassing complete inquiry processes, from problem formulation to the communication of findings. Collectively, they include qualitative social science inquiry (Global Politics Extended Essay), quantitative mathematical modeling (Mathematics Internal Assessment), and experimental natural science investigation (Chemistry Internal Assessment). Together, these projects offered an opportunity to examine the conceptual applicability of the framework across substantially different disciplinary contexts while maintaining a common pedagogical approach centered on authentic inquiry.

As summarized in Table 1, the three projects served as illustrative examples through which the proposed framework could be interpreted across multiple forms of inquiry. Rather than comparing disciplinary outcomes, the retrospective analysis examined whether the five relational mechanisms of the STEM+ Research Coaching Framework were consistently identifiable throughout each research process despite differences in disciplinary content, methodological traditions, and epistemological assumptions. Collectively, the three projects illustrate the conceptual coherence, pedagogical interpretability, and interdisciplinary transferability of the proposed framework across diverse forms of authentic scientific inquiry.

The retrospective analysis examined each project according to the five pedagogical mechanisms identified during the integrative literature review (Whittemore & Knafl, 2005; Snyder, 2019):

Methodological Coherence, referring to the progressive alignment among the research question, objectives, theoretical foundations, methodological decisions, evidence, analysis, and conclusions throughout the inquiry process.

Intentional Mentoring, reflected in the continuous pedagogical guidance provided by the STEM+ Research Coach to strengthen conceptual understanding, methodological rigor, learner autonomy, and scientific reasoning.

Strategic Questioning, evidenced through the deliberate use of reflective questioning to refine research problems, challenge assumptions, identify conceptual gaps, support decision-making, and promote higher-order thinking.

Human–AI Co-Intelligence, represented by the collaborative interaction among the student, the research coach, and generative artificial intelligence to facilitate literature exploration, conceptual refinement, methodological decision-making, critical evaluation of information, and collaborative knowledge co-construction.

Reflective Meaning-Making, manifested through the learner's progressive construction of personal meaning, increasing ownership of the research process, development of scientific agency, and consolidation of an authentic STEM identity.

Accordingly, the illustrative cross-disciplinary application should be understood as a conceptual illustration of the explanatory capacity of the proposed framework rather than as a separate empirical phase of the investigation (Whittemore & Knafl, 2005; Snyder, 2019). Its primary purpose is to illustrate the internal conceptual coherence, pedagogical interpretability, and interdisciplinary transferability of the STEM+ Research Coaching Framework while identifying directions for future empirical research. Future studies may examine the framework across diverse educational levels, institutional settings, disciplinary contexts, and learner populations to further explore its applicability, transferability, and educational impact.

Results: The STEM+ Research Coaching Framework

The Emergence of a Relational Structure Across the Literature

The integrative review revealed a consistent conceptual pattern despite the diversity of theoretical traditions represented in the selected literature. Research concerning STEM identity, authentic inquiry, mentoring, relational pedagogy, artificial intelligence in education, and twenty-first-century competencies has expanded considerably during the last two decades (Darragh, 2016; Snyder, 2019; Grimalt-Álvaro et al., 2022; Zhai et al., 2024). However, these research traditions have generally

evolved independently, each explaining specific dimensions of educational practice while providing limited theoretical integration across domains.

Studies grounded in STEM Identity Theory primarily explain how learners develop a sense of belonging and recognition within scientific communities (Carlone & Johnson, 2007; Hazari et al., 2010; Zhai et al., 2024). Research on authentic inquiry emphasizes participation in meaningful scientific practices as a mechanism for learning and identity development (National Academies of Sciences, Engineering, and Medicine [NASEM], 2017; Hoffer, 2016). Mentoring literature highlights the importance of interpersonal guidance, feedback, and social support, whereas recent studies on generative artificial intelligence focus predominantly on technological capabilities and instructional applications (Mollick, 2024; UNESCO, 2023). Although each perspective contributes valuable insights, they largely explain isolated dimensions of educational practice rather than the relational processes through which these dimensions are intentionally integrated within authentic inquiry environments. This conceptual fragmentation revealed the need for a unifying relational framework capable of explaining how these complementary educational processes operate collectively during authentic STEM+ research experiences.

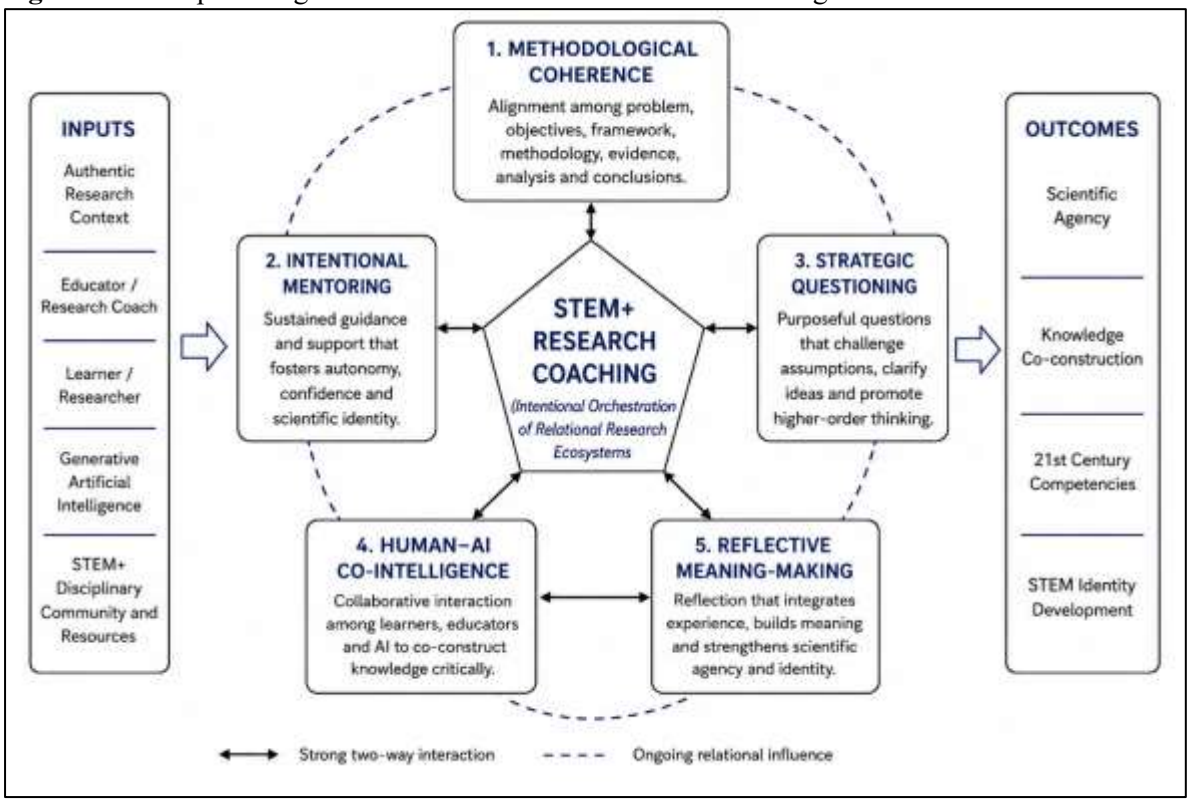
Across the reviewed literature, successful research experiences consistently involved multiple interacting relational mechanisms rather than isolated instructional strategies. Methodological coherence, mentoring relationships, strategic questioning, reflective dialogue, collaborative knowledge construction, Human–AI Co-Intelligence, and opportunities for meaning-making repeatedly emerged as mutually reinforcing pedagogical mechanisms that collectively supported authentic scientific inquiry and STEM identity development (Lave & Wenger, 1991; Wenger, 1998; Gee, 2000; Hoffer, 2016). Rather than functioning independently, these mechanisms consistently interacted to create educational conditions that enabled learners to engage meaningfully in authentic inquiry while progressively developing scientific agency and STEM identity.

Consequently, the principal finding of this integrative literature review was not the identification of isolated educational variables but the recognition of an underlying relational structure connecting previously fragmented theoretical perspectives (Jabareen, 2009; Snyder, 2019). This relational structure provided the conceptual foundation for the development of the STEM+ Research Coaching Framework,

which conceptualizes authentic inquiry coaching as the intentional design of Relational Research Ecosystems through the dynamic integration of these five interdependent relational mechanisms.

The STEM+ Research Coaching Framework

Figure 2. Conceptual Organization of the STEM+ Research Coaching Framework



Note. The framework illustrates the five interdependent relational mechanisms that operate within intentionally designed Relational Research Ecosystems to foster authentic inquiry, Human–AI Co-Intelligence, collaborative knowledge co-construction, scientific agency, and STEM identity development.

The principal outcome of the integrative literature review was the identification of a coherent relational structure that consistently connected previously fragmented theoretical traditions (Jabareen, 2009; Snyder, 2019). This conceptual synthesis culminated in the development of the STEM+ Research Coaching Framework, a relational pedagogical framework explaining how educators intentionally design Relational Research Ecosystems that promote authentic inquiry, collaborative knowledge co-construction, Human–AI Co-Intelligence, scientific agency, and STEM identity development. Rather than functioning as a descriptive model, the framework is intended as an explanatory and design-oriented pedagogical framework that explains how these relational mechanisms operate collectively to intentionally cultivate authentic STEM+ research experiences.

Unlike existing models that primarily describe factors associated with STEM identity or authentic learning (Carlone & Johnson, 2007; Hazari et al., 2010; Hoffer, 2016; Zhai et al., 2024), the proposed framework reconceptualizes research coaching as an intentional process of relational design. Rather than viewing inquiry, mentoring, artificial intelligence, reflection, and methodological rigor as independent pedagogical mechanisms, it understands them as complementary relational mechanisms operating within a coherent pedagogical system.

Accordingly, STEM+ Research Coaching is conceptualized as the intentional design and facilitation of Relational Research Ecosystems in which students progressively develop scientific agency through authentic inquiry, collaborative meaning-making, and sustained interaction with mentors, peers, disciplinary knowledge, and generative artificial intelligence. This perspective is consistent with contemporary theories that understand identity development as a relational, participatory, and socially situated process (Lave & Wenger, 1991; Wenger, 1998; Gee, 2000; Carlone & Johnson, 2007; Darragh, 2016). Rather than positioning research coaching as instructional supervision, the proposed framework conceptualizes it as the intentional orchestration of relational conditions through which authentic inquiry, Human–AI Co-Intelligence, and STEM identity are simultaneously cultivated.

The Five Relational Mechanisms

The five mechanisms did not emerge as independent categories but as recurrent relational functions that consistently appeared across the reviewed literature. Their identification was guided by conceptual convergence rather than frequency alone, reflecting those pedagogical functions that collectively explain how authentic inquiry environments intentionally cultivate scientific agency, collaborative knowledge co-construction, Human–AI Co-Intelligence, and STEM identity development. Accordingly, the framework is organized around five interdependent relational mechanisms that collectively explain how authentic inquiry experiences are intentionally designed, enacted, and sustained. Each mechanism contributes a distinct pedagogical function while remaining intrinsically connected to the others, forming an integrated relational system whose educational value emerges from their continuous interaction rather than from their isolated implementation.

Methodological Coherence: Methodological Coherence constitutes the structural foundation of the framework. It refers to the intentional alignment among the research problem, objectives, theoretical

framework, methodological decisions, evidence, analysis, and conclusions. Beyond ensuring technical rigor, methodological coherence enables students to understand research as an internally consistent process in which each methodological decision contributes to the progressive construction of scientific knowledge (Torraco, 2005; Whittemore & Knafl, 2005; Johnson & Christensen, 2017; Akudjedu et al., 2026).

Intentional Mentoring: Intentional Mentoring represents the relational dimension through which educators guide, challenge, and support learners throughout authentic inquiry experiences. Within the framework, mentoring extends beyond supervision or feedback, becoming a deliberate pedagogical process aimed at fostering learner autonomy, confidence, critical thinking, scientific identity, and sustained engagement through continuous relational interaction (Lave & Wenger, 1991; Wenger, 1998; Hoffer, 2016; National Academies of Sciences, Engineering, and Medicine, 2019; Stelter et al., 2021). Rather than directing the research process, intentional mentoring creates relational conditions in which learners progressively assume greater responsibility, ownership, and agency while developing the competencies required for authentic scientific inquiry.

Strategic Questioning: Strategic Questioning functions as the principal mechanism for promoting higher-order thinking and conceptual refinement. Rather than providing direct answers, educators intentionally formulate questions that encourage students to examine assumptions, identify conceptual inconsistencies, evaluate evidence critically, and progressively strengthen their scientific reasoning. Strategic questioning also serves as a metacognitive process that promotes reflective dialogue, conceptual refinement, and increasingly autonomous decision-making throughout authentic inquiry (King, 1991; Davoudi & Sadeghi, 2015; Chen, 2026). Through this process, learners progressively assume greater intellectual ownership of the research process while strengthening scientific reasoning and STEM identity (Gee, 2000; Hoffer, 2016).

Human–AI Co-Intelligence: Human–AI Co-Intelligence is conceptualized as a relational process of collaborative knowledge co-construction involving students, educators, and generative artificial intelligence. Within this framework, artificial intelligence is not understood as a substitute for human cognition or as a tool for task automation. Instead, it functions as a cognitive partner that expands opportunities for exploration, reflection, argument development, and critical analysis while preserving

human intentionality, disciplinary judgment, and ethical responsibility (UNESCO, 2023; Mollick, 2024; Casebourne et al., 2025). Recent advances in large language models further suggest that Human–AI Co-Intelligence can enhance collective reasoning, knowledge co-construction, and complex problem solving when embedded within intentionally designed educational interactions rather than treated as autonomous technological solutions (Guo et al., 2025).

Reflective Meaning-Making: Reflective Meaning-Making integrates the entire research experience by enabling learners to interpret, internalize, and attribute personal significance to their scientific inquiry. Rather than reflecting only on completed tasks, learners progressively reinterpret evidence, negotiate understanding, and construct disciplinary meaning through continuous reflection and dialogue, transforming research experiences into personally meaningful learning (Ignelzi, 2000; Hwang et al., 2026). Through this systematic reflective process, students progressively construct scientific agency, strengthen their STEM identity, and develop a deeper understanding of themselves as legitimate participants within research communities (Gee, 2000; Carlone & Johnson, 2007; Darragh, 2016; Zhai et al., 2024).

Relational Dynamics of the Framework

The integrative literature review revealed the emergence of a coherent relational structure despite the diversity of theoretical traditions represented in the selected literature. Research concerning STEM identity, authentic inquiry, mentoring, relational pedagogy, artificial intelligence in education, and twenty-first-century competencies has expanded considerably during the last two decades (Darragh, 2016; Snyder, 2019; Grimalt-Álvaro et al., 2022; Zhai et al., 2024). However, these research traditions have largely evolved in parallel, each explaining important dimensions of educational practice while offering limited theoretical integration across domains. Rather, meaningful learning outcomes emerge through the continuous and reciprocal interaction among Methodological Coherence, Intentional Mentoring, Strategic Questioning, Human–AI Co-Intelligence, and Reflective Meaning-Making, which collectively shape the conditions under which authentic inquiry, scientific agency, and STEM identity develop (Lave & Wenger, 1991; Wenger, 1998; Carlone & Johnson, 2007; Hazari et al., 2010).

From this perspective, the proposed framework departs from instructional models that conceptualize inquiry, mentoring, reflection, or artificial intelligence as discrete educational components. Instead, it

positions these mechanisms as interdependent relational processes whose educational effectiveness depends on their dynamic integration within intentionally designed Relational Research Ecosystems (Jabareen, 2009; Snyder, 2019). Consequently, STEM+ Research Coaching is understood not as the implementation of isolated instructional strategies but as the deliberate orchestration of relational conditions that support collaborative knowledge construction, sustained scientific participation, and progressive identity development.

As illustrated in Figure 2, the Relational Research Ecosystem constitutes the conceptual core of the framework. Within this ecosystem, the five pedagogical mechanisms operate simultaneously rather than sequentially, continuously influencing one another throughout the research process. Their interaction enables learners to progressively align methodological decisions with scientific reasoning, engage in purposeful dialogue with mentors, employ strategic questioning to deepen conceptual understanding, collaborate critically with generative artificial intelligence, and construct personal meaning from authentic inquiry experiences.

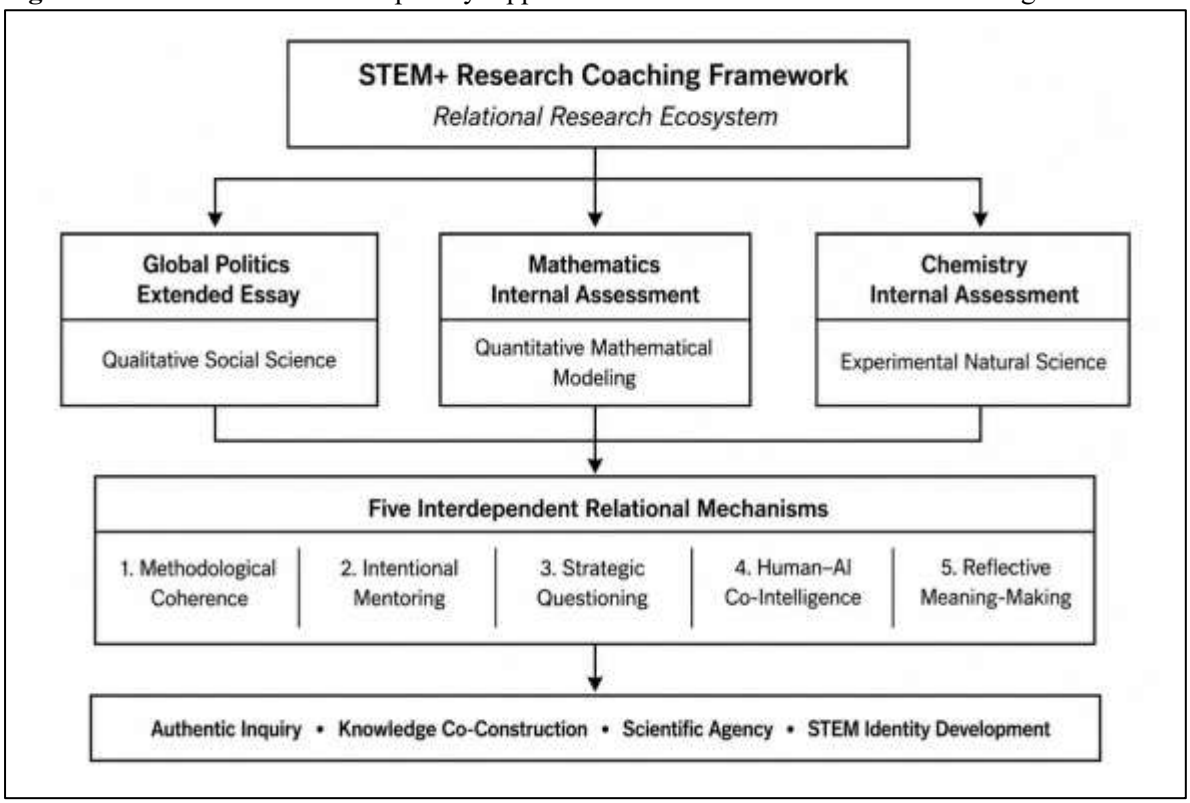
Accordingly, the framework reconceptualizes authentic STEM+ research as a fundamentally relational educational process in which knowledge, identity, and scientific agency emerge through sustained interaction among learners, educators, disciplinary knowledge, and intelligent technologies (Lave & Wenger, 1991; Wenger, 1998; Gee, 2000; Carlone & Johnson, 2007). In doing so, it shifts the analytical focus of STEM education from identifying isolated predictors of successful learning toward understanding how educators intentionally design relational conditions that cultivate authentic inquiry, collaborative knowledge co-construction, Human–AI Co-Intelligence, scientific agency, and STEM identity simultaneously.

Illustrative Cross-Disciplinary Application of the Framework

Following its conceptual development, the STEM+ Research Coaching Framework was retrospectively interpreted across three authentic International Baccalaureate (IB) Diploma Programme research projects representing distinct epistemological traditions: qualitative social science (Global Politics Extended Essay), quantitative mathematical modeling (Mathematics Internal Assessment), and experimental natural science (Chemistry Internal Assessment). Rather than functioning as an empirical validation, this illustrative application illustrates how the five relational mechanisms of the framework

provide a coherent interpretative lens for understanding authentic inquiry experiences across diverse disciplinary contexts.

Figure 3. Illustrative Cross-Disciplinary Application of the STEM+ Research Coaching Framework



Note**.** The figure illustrates the conceptual application of the STEM+ Research Coaching Framework across three authentic International Baccalaureate (IB) research projects representing qualitative, quantitative, and experimental inquiry, highlighting its disciplinary transferability and conceptual coherence.

Although the three investigations differed substantially in their research questions, methodological approaches, analytical procedures, and disciplinary objectives, the retrospective analysis revealed a remarkably consistent relational structure underlying each inquiry process. Across all three projects, authentic inquiry was characterized not by the isolated application of disciplinary methods but by the continuous interaction among Methodological Coherence, Intentional Mentoring, Strategic Questioning, Human–AI Co-Intelligence, and Reflective Meaning-Making (Lave & Wenger, 1991; Wenger, 1998; Carlone & Johnson, 2007).

Methodological Coherence was evident in the progressive alignment between each project's research question, objectives, theoretical foundations, methodological decisions, evidence, analysis, and conclusions. Despite substantial differences in disciplinary methodologies, each investigation evolved through an internally coherent inquiry process that enabled the systematic construction of knowledge (Torraco, 2005; Whittemore & Knafl, 2005).

Intentional Mentoring was reflected in the sustained pedagogical relationship between the research coach and the student throughout each investigation. Rather than focusing exclusively on technical supervision, mentoring functioned as a relational process that progressively strengthened conceptual understanding, methodological rigor, learner autonomy, and scientific confidence while supporting increasingly sophisticated forms of inquiry (Lave & Wenger, 1991; Wenger, 1998; Hoffer, 2016).

Strategic questioning emerged across the reviewed literature as a central relational mechanism through which research coaches intentionally stimulate scientific reasoning, challenge assumptions, support methodological decision-making, and promote higher-order thinking (King, 1991; Davoudi & Sadeghi, 2015; Chen, 2026). Rather than functioning simply as a pedagogical technique, strategic questioning facilitates reflective dialogue, conceptual refinement, and progressive learner autonomy throughout authentic inquiry.

Human–AI Co-Intelligence was consistently observed as a process of collaborative knowledge co-construction involving the learner, the research coach, and generative artificial intelligence. Rather than replacing human reasoning or automating intellectual work, artificial intelligence functioned as a cognitive partner supporting literature exploration, conceptual clarification, methodological reflection, argument development, and critical evaluation while preserving human intentionality and disciplinary judgment (Mollick, 2024; UNESCO, 2023).

Reflective Meaning-Making integrated the entire inquiry process by enabling the student to progressively interpret the significance of each research experience beyond the completion of academic requirements. Reflection facilitated the development of scientific agency, strengthened ownership of the research process, and contributed to the progressive consolidation of a STEM identity across three substantially different forms of inquiry (Gee, 2000; Carlone & Johnson, 2007; Darragh, 2016; Zhai et al., 2024).

Taken together, these illustrative applications suggest that the proposed framework may not be restricted to a particular discipline, research methodology, or educational context. Instead, they suggest that authentic STEM+ research can be understood as a relational educational process whose underlying pedagogical dynamics remain conceptually consistent across qualitative, quantitative, and experimental inquiry.

Importantly, these illustrative applications should not be interpreted as empirical evidence of the framework's effectiveness. Rather, they provide an analytical illustration of its conceptual coherence and disciplinary transferability while establishing a foundation for future empirical research examining its implementation across diverse educational settings and learner populations.

DISCUSSION

From Explaining STEM Identity to Designing STEM Identity

The principal contribution of this study extends beyond the development of a new conceptual framework. More fundamentally, it proposes a shift in the central question that has guided much of the contemporary literature on STEM identity and authentic inquiry. Whereas previous research has primarily sought to explain why STEM identity develops and which educational factors influence its formation, the present framework shifts attention toward understanding how educators intentionally design the relational conditions through which authentic inquiry, scientific agency, Human–AI Co-Intelligence, and STEM identity emerge simultaneously. Over the past two decades, research has generated substantial evidence demonstrating that STEM identity, authentic inquiry, mentoring, recognition, participation, competence, and self-efficacy are critical determinants of students' engagement, persistence, and success in STEM disciplines. Collectively, these contributions have significantly advanced understanding of why STEM identity develops and which educational experiences are associated with its formation.

Despite these advances, considerably less attention has been devoted to understanding how educators intentionally design Relational Research Ecosystems in which these diverse processes converge into coherent and meaningful research experiences. Existing theoretical perspectives have successfully identified influential variables and educational conditions, yet they provide limited guidance regarding the pedagogical architecture through which these elements interact to cultivate scientific agency and STEM identity. Consequently, the challenge is no longer identifying additional determinants of STEM identity but understanding how these complementary educational processes can be intentionally orchestrated within coherent pedagogical systems.

The STEM+ Research Coaching Framework addresses this conceptual gap by repositioning pedagogical design as the principal unit of analysis. Rather than conceptualizing STEM identity as the

outcome of isolated educational experiences or independent instructional practices, the framework proposes that identity emerges through intentionally designed Relational Research Ecosystems in which Methodological Coherence, Intentional Mentoring, Strategic Questioning, Human–AI Co-Intelligence, and Reflective Meaning-Making operate as interdependent relational mechanisms.

Accordingly, the principal contribution of the proposed framework is not the identification of additional determinants of STEM identity but the reconceptualization of pedagogical design itself as the primary explanatory unit through which authentic inquiry, Human–AI Co-Intelligence, scientific agency, and STEM identity are intentionally cultivated. In doing so, the framework shifts educational attention from identifying successful instructional practices toward understanding the relational architecture that enables those practices to become educationally meaningful, scientifically rigorous, and developmentally transformative.

Theoretical Contributions

The proposed framework does not seek to replace existing theories of STEM identity, authentic inquiry, mentoring, relational pedagogy, or artificial intelligence in education. Instead, it contributes by integrating these complementary perspectives into a unified relational pedagogical framework capable of explaining how authentic STEM+ research experiences are intentionally designed. Rather than proposing an additional explanatory theory of STEM identity, the framework repositions pedagogical design itself as the principal explanatory unit through which authentic inquiry, collaborative knowledge co-construction, Human–AI Co-Intelligence, scientific agency, and STEM identity emerge simultaneously.

STEM Identity Theory has provided a robust explanation of how learners develop scientific identities through participation, competence, recognition, performance, and agency (Carlone & Johnson, 2007; Hazari et al., 2010; Dou & Cian, 2022). Similarly, research on authentic inquiry has consistently demonstrated that meaningful engagement in scientific practices promotes both conceptual learning and identity formation (National Academies of Sciences, Engineering, and Medicine, 2017). Mentoring research has highlighted the importance of sustained pedagogical guidance (National Academies of Sciences, Engineering, and Medicine, 2019; Stelter et al., 2021), while sociocultural and relational perspectives have emphasized that learning emerges through participation in communities of practice

and meaningful interpersonal relationships rather than through isolated individual processes (Lave & Wenger, 1991; Wenger, 1998). Likewise, the New Strategic Theory contributes a broader understanding of intentional relational design as a fundamental principle governing interaction within complex human systems (Pérez, 2018).

Rather than treating these perspectives as parallel explanatory traditions, the STEM+ Research Coaching Framework illustrates how they converge within a coherent relational pedagogical architecture. Consequently, the framework contributes to the literature not only by explaining why these educational mechanisms are important individually but also by explaining how they become pedagogically interconnected through the intentional design of Relational Research Ecosystems. This shift from identifying educational variables to explaining their relational orchestration represents one of the framework's principal theoretical contributions.

This relational synthesis further advances contemporary discussions by moving educational analysis beyond isolated variables toward the dynamic relationships that connect them. Consequently, authentic inquiry is no longer understood simply as an instructional methodology, mentoring as an interpersonal support strategy, artificial intelligence as a technological resource, or STEM identity as an educational outcome. Instead, these elements become mutually reinforcing relational mechanisms operating within an intentionally designed pedagogical system through which scientific participation, collaborative knowledge co-construction, Human–AI Co-Intelligence, scientific agency, and STEM identity develop simultaneously.

The framework also extends previous conceptual work by introducing STEM+ Research Coaching as a distinct pedagogical construct. Whereas traditional educational models typically characterize teachers as instructors, facilitators, or mentors, the proposed framework conceptualizes educators as intentional designers and orchestrators of Relational Research Ecosystems. This reconceptualization broadens the educator's role beyond instructional delivery toward the intentional orchestration of the relational conditions through which authentic inquiry, collaborative knowledge co-construction, Human–AI Co-Intelligence, scientific agency, and STEM identity become educationally possible.

Human–AI Co-Intelligence as a Relational Pedagogical Process

One of the principal theoretical contributions of the STEM+ Research Coaching Framework concerns the reconceptualization of Human–AI Co-Intelligence as a fundamentally relational pedagogical process rather than as a technological capability. While recent scholarship has demonstrated the transformative potential of generative artificial intelligence for writing, information retrieval, reasoning, and personalized learning (UNESCO, 2023; Mollick, 2024), most discussions continue to frame AI primarily as an instructional resource or cognitive assistant. The present framework argues that its educational significance depends less on technological sophistication than on the intentional relational design of the pedagogical ecosystem within which Human–AI interaction occurs.

Accordingly, Human–AI Co-Intelligence is understood not simply as collaborative problem solving between humans and artificial intelligence but as a relational process of collaborative knowledge co-construction involving learners, educators, disciplinary knowledge, and generative AI. Within this perspective, artificial intelligence does not replace scientific reasoning, disciplinary judgment, or human intentionality. Instead, it expands opportunities for literature exploration, conceptual refinement, methodological decision-making, reflective dialogue, strategic questioning, and collaborative meaning-making while preserving the educator's central role in orchestrating authentic inquiry experiences (Mollick, 2024; UNESCO, 2023; Casebourne et al., 2025).

This perspective also extends emerging discussions on collective intelligence by emphasizing that educational innovation arises not from the capabilities of artificial intelligence alone but from the quality of the relational interactions through which knowledge is collaboratively constructed. Consequently, the framework shifts attention away from questions concerning whether AI should be incorporated into education toward understanding how educators intentionally orchestrate Human–AI Co-Intelligence to strengthen authentic inquiry, scientific reasoning, and STEM identity development.

Rather than conceptualizing AI integration as the adoption of a new educational technology, the proposed framework positions Human–AI Co-Intelligence as one of five interdependent relational mechanisms operating within intentionally designed Relational Research Ecosystems. Its educational value therefore emerges not from the presence of AI itself but from its pedagogically meaningful interaction with Methodological Coherence, Intentional Mentoring, Strategic Questioning, and

Reflective Meaning-Making. From this perspective, artificial intelligence becomes educationally significant only when embedded within coherent relational systems that cultivate scientific agency, collaborative knowledge co-construction, and authentic STEM+ research experiences.

Educational Implications

The STEM+ Research Coaching Framework has implications that extend beyond individual classroom practice toward curriculum design, teacher education, institutional research programs, and educational leadership. Rather than proposing an additional instructional methodology, the framework offers a relational pedagogical perspective for intentionally designing authentic STEM+ learning environments in which inquiry, mentoring, Human–AI Co-Intelligence, and STEM identity development operate as mutually reinforcing educational processes.

For educators, the framework suggests a reconceptualization of professional practice. Rather than functioning primarily as instructors, facilitators, or supervisors, teachers become intentional designers and orchestrators of Relational Research Ecosystems that cultivate authentic inquiry through Methodological Coherence, Intentional Mentoring, Strategic Questioning, Human–AI Co-Intelligence, and Reflective Meaning-Making. This perspective aligns with contemporary views of teachers as designers of learning environments capable of creating conditions for meaningful participation, knowledge construction, and innovation (Paniagua & Istance, 2018; Fisher et al., 2017; Oliveras-Ortiz, 2023).

At the curricular level, the framework suggests that authentic inquiry experiences should not be conceived as isolated capstone projects or extracurricular activities but as relational learning processes progressively embedded throughout educational programs. Designing coherent opportunities for inquiry across disciplines may strengthen students' scientific agency, interdisciplinary thinking, collaborative knowledge co-construction, and long-term STEM identity development.

The framework also contributes to current discussions regarding the educational integration of generative artificial intelligence. Rather than emphasizing the adoption of increasingly sophisticated AI technologies, it suggests that educational innovation depends primarily on the intentional orchestration of pedagogical relationships through which Human–AI Co-Intelligence becomes intellectually meaningful, ethically responsible, and scientifically rigorous.

Consequently, the educational value of artificial intelligence lies less in technological capability than in its integration within coherent Relational Research Ecosystems that support authentic inquiry and collaborative meaning-making.

Beyond STEM education, the relational principles underlying the framework may also be transferable to other disciplinary contexts in which authentic inquiry, collaborative knowledge construction, and reflective learning constitute central educational objectives. Although developed within STEM+ education, the proposed framework offers a broader pedagogical perspective for understanding how intentionally designed relational ecosystems can support research-based learning across diverse educational settings and levels.

Limitations and Future Research

Several limitations should be acknowledged when interpreting the present study. First, the proposed STEM+ Research Coaching Framework was developed through an integrative literature review and therefore represents a conceptual synthesis rather than an empirically validated instructional model. Although the framework is grounded in convergent theoretical traditions and illustrated through authentic cross-disciplinary research projects, its educational effectiveness has not yet been systematically examined across diverse educational contexts, populations, or institutional settings.

Second, the illustrative application presented in this study was intentionally designed to demonstrate the conceptual coherence and pedagogical interpretability of the framework rather than to establish causal relationships or evaluate instructional effectiveness. Consequently, the three International Baccalaureate Diploma Programme research projects should be understood as analytical illustrations of the framework's explanatory capacity rather than as empirical evidence of its educational impact.

Third, although the framework integrates scholarship from STEM identity, authentic inquiry, mentoring, relational pedagogy, Human–AI Co-Intelligence, and twenty-first-century competencies, additional theoretical perspectives may further enrich its conceptual development. As research on generative artificial intelligence, relational learning, and authentic inquiry experiences continues to evolve, the framework should likewise be understood as a dynamic conceptual model that remains open to refinement and theoretical extension.

Future research should therefore examine the applicability, transferability, and educational impact of the framework across diverse educational levels, disciplinary contexts, and institutional settings. In particular, empirical studies employing qualitative, quantitative, mixed-methods, and design-based research approaches could investigate how the five relational mechanisms interact dynamically to influence authentic inquiry, collaborative knowledge co-construction, Human–AI Co-Intelligence, scientific agency, and STEM identity development. Comparative studies across educational systems and cultural contexts may further contribute to understanding the framework's generalizability and contextual adaptability.

Future investigations may also explore the transferability of the proposed relational pedagogical framework beyond STEM+ education. Because its central contribution concerns the intentional design of Relational Research Ecosystems rather than discipline-specific instructional practices, the framework may offer valuable insights for research-based learning in the social sciences, humanities, health sciences, teacher education, and professional learning environments.

CONCLUSIONS

Contemporary STEM+ education is undergoing a profound transformation driven by the convergence of generative artificial intelligence, authentic inquiry, and the growing demand for interdisciplinary competencies. While previous scholarship has substantially advanced understanding of STEM identity, authentic inquiry, mentoring, and artificial intelligence in education, these perspectives have largely evolved as parallel research traditions, providing limited guidance for intentionally designing Relational Research Ecosystems in which they function as an integrated pedagogical system.

This study addressed that conceptual gap through the development of the STEM+ Research Coaching Framework, a relational pedagogical framework explaining how educators intentionally design Relational Research Ecosystems that cultivate authentic inquiry, Human–AI Co-Intelligence, collaborative knowledge co-construction, scientific agency, and STEM identity development. Rather than proposing another explanatory model of STEM identity, the framework repositions pedagogical design as the primary unit of educational analysis, emphasizing that meaningful learning emerges from the intentional orchestration of relationships among learners, educators, disciplinary knowledge, research methodology, reflective dialogue, and generative artificial intelligence.

The principal theoretical contribution of the framework lies not simply in integrating previously fragmented theoretical traditions—including STEM Identity Theory, authentic inquiry, mentoring, Relational Sociology, the New Strategic Theory, and emerging perspectives on artificial intelligence in education—but in explaining how these complementary perspectives become pedagogically interconnected through the intentional design of Relational Research Ecosystems. In doing so, the framework shifts the analytical focus from explaining why STEM identity develops toward understanding how educators intentionally cultivate STEM identity through the orchestration of authentic Relational Research Ecosystems.

Beyond its theoretical contribution, the framework provides educators, researchers, and educational institutions with a coherent conceptual foundation for designing authentic inquiry experiences in which inquiry, methodological coherence, intentional mentoring, strategic questioning, reflective meaning-making, and Human–AI Co-Intelligence operate as mutually reinforcing relational mechanisms within a single pedagogical system. Accordingly, STEM+ Research Coaching should be understood not as a prescriptive instructional model but as a relational pedagogical framework that offers educators a coherent conceptual architecture for intentionally designing Relational Research Ecosystems in an increasingly AI-mediated educational landscape.

Future research should examine the applicability, transferability, and educational impact of the proposed framework across diverse educational levels, institutional settings, disciplinary domains, and cultural contexts. In particular, empirical investigations employing qualitative, quantitative, mixed-methods, and design-based research approaches may further examine how the five relational mechanisms dynamically interact to cultivate authentic inquiry, collaborative knowledge co-construction, Human–AI Co-Intelligence, scientific agency, and STEM identity development. Such investigations will contribute to refining the framework while advancing broader understanding of relational pedagogical design in contemporary education.

Ultimately, the future of STEM+ education may be determined not by how intelligently artificial intelligence performs, but by how intentionally educators design the relational ecosystems in which humans and artificial intelligence learn, inquire, and construct knowledge together.

From this perspective, the defining innovation of the AI era is not the technology itself, but the intentional orchestration of educational relationships that cultivate authentic inquiry, collaborative knowledge co-construction, scientific agency, and enduring STEM identities.

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