International Journal of Computing and Artificial Intelligence

E-ISSN: 2707-658X
P-ISSN: 2707-6571
Impact Factor (RJIF): 5.57
www.computersciencejournals.com/ijcai
IJCAI 2025; 6(2): 293-307
Received: 05-10-2025
Accepted: 07-11-2025

Markasioti Evangelia
Faculty of Humanities, School of Humanities and Social Sciences, Aegean College, Athens, Greece

Constantina Corazon Argyrakou
Department of Geography, School of Environment, Geography and Applied Economics, Harokopio University of Athens, Athens, Greece

Corresponding Author:
Constantina Corazon Argyrakou
Department of Geography, School of Environment, Geography and Applied Economics, Harokopio University of Athens, Athens, Greece

Co-Teaching in STEAM education: A theory-driven alignment framework for transdisciplinary learning with responsible AI integration

Markasioti Evangelia and Constantina Corazon Argyrakou

DOI: https://www.doi.org/10.33545/27076571.2025.v6.i2d.209

Abstract
This article proposes the Co-Teaching and STEAM Alignment Framework (CTSAF), a design framework that aligns established co-teaching models with the transdisciplinary, inquiry-driven, and creative character of STEAM education. The study follows a theoretical design using an integrative synthesis consistent with a hybrid model of concept development to consolidate foundations from constructivist and sociocultural traditions and extend them with insights from distributed cognition. CTSAF specifies when and why particular configurations add pedagogical value in mixed-attainment classrooms and how teachers can orchestrate them across an inquiry cycle. Its architecture comprises four components: principled definitions of quality in STEAM education (inclusivity, collaboration, innovation, and inquiry), a structural layer for roles, task and space-time organisation and formative assessment, a repertoire of conditionally selected adaptations of co-teaching models, and a lightweight evidence strategy with observable indicators of participation equity, collaborative reasoning, creative iteration, and inquiry progress. Enactment is organised as a concise cycle of planning, orchestration, facilitation, reflection, and iteration that keeps workload tractable while supporting disciplined improvement. Within a sociotechnical view of classrooms, Artificial Intelligence is positioned as an educative medium that broadens access, representation, and formative feedback under teacher oversight and transparent quality criteria. The framework provides a practical grammar for curriculum design, classroom practice, and professional learning; it clarifies boundary conditions such as time constraints and resource variability; and it establishes an agenda for empirical studies on implementation fidelity and learner outcomes in STEAM education.

Keywords: STEAM education, co-teaching, CTSAF, design framework, artificial intelligence

1. Introduction

Co-teaching has emerged as a collaborative instructional approach that brings together two or more educators to share responsibility for planning, delivering, and assessing learning in the same classroom environment [1]. This model has gained increasing attention in recent decades as educational systems strive to address the diverse learning needs of students in inclusive and heterogeneous settings [2]. Its central premise lies in leveraging the complementary expertise of different teachers, often from varied disciplinary backgrounds, to enhance instructional quality, promote differentiated learning opportunities, and create a richer, more responsive classroom environment [3].

The rationale for implementing co-teaching is grounded in both pedagogical theory and practical necessity [4]. From a pedagogical standpoint, the presence of multiple educators facilitates the adaptation of teaching methods to accommodate different learning styles, cognitive abilities, and socio-emotional needs [5]. Theoretically, this approach draws from constructivist perspectives, such as those of Piaget, who emphasised active learner engagement in knowledge construction [6], and Vygotsky, who highlighted the social and cultural dimensions of learning and the importance of guided participation within the Zone of Proximal Development [7]. Co-teaching environments are particularly conducive to scaffolding, peer learning, and the integration of multimodal resources, all of which support deeper conceptual understanding [8].

From a practical perspective, co-teaching responds to the growing complexity of educational demands, including the need for inclusive practices, personalised learning, and the integration of 21st-century skills such as collaboration, critical thinking, and creativity [9]. In diverse classrooms, especially those implementing interdisciplinary frameworks such as STEAM (Science, Technology, Engineering, Arts, and Mathematics), co-teaching offers a strategic means of combining content expertise with pedagogical innovation [10]. By integrating subject-specific knowledge with active, inquiry-based methodologies, co-teaching enables more authentic, problem-oriented learning experiences that mirror real-world challenges [11].

Furthermore, co-teaching is increasingly viewed as a vehicle for professional growth. Collaboration between educators encourages reflective practice, mutual feedback, and the sharing of instructional strategies [12]. Within the STEAM context, where projects often require simultaneous attention to scientific accuracy, creative design, and technological application, the presence of multiple educators enhances both instructional coherence and learner support [13].

Building on these perspectives, the present study seeks to establish a coherent theoretical framework for understanding and applying co-teaching within STEAM education. Although co-teaching's effectiveness is well established in inclusive and special education, the interplay between distinct co-teaching models and different pedagogical approaches has not been systematically investigated within STEAM education [14]. Given that STEAM education requires the deliberate integration of scientific, technological, engineering, artistic, and mathematical modes of inquiry, it is critical to examine how established pedagogical theories can inform collaborative teaching models that align with its philosophy.

The purpose of this research is therefore to construct a theoretical framework for co-teaching in STEAM education, grounded in the major pedagogical traditions, constructivist, sociocultural, and humanistic, that underpin both collaborative learning and transdisciplinary integration. By synthesizing these perspectives, the study aims to clarify the pedagogical logics through which co-teaching can foster inclusivity, enhance instructional coherence, and cultivate the 21st-century skills central to STEAM philosophy.

In order to achieve this purpose, the study is guided by three research questions:

1. How do constructivist, sociocultural and distributed cognition perspectives inform an evidence-driven conceptualization of co-teaching in STEAM, including the role of AI as an educative medium?
2. In what ways can established co-teaching models be conditionally adapted and switched across inquiry phases to support the transdisciplinary, inquiry-driven and creative aims of STEAM?
3. Which actionable design principles and classroom structures, together with lightweight evidence routines, align co-teaching with inclusivity, collaboration and innovation while keeping workload tractable?

Through addressing these questions, the study seeks to contribute both to the theoretical refinement of co-teaching as an instructional model and to its practical application in STEAM settings, providing a foundation for future empirical investigations and professional development initiatives.

2. Methodology

The present study adopts a theoretical research design aimed at developing a conceptual framework for the application of co-teaching in STEAM education. The methodology is grounded in a systematic synthesis of established pedagogical theories, documented co-teaching models, and the distinctive requirements of transdisciplinary learning. This approach reflects the study's objective of advancing theoretical clarity and conceptual integration, thereby laying the groundwork for future empirical investigation. Our three-stage process aligns with the Hybrid Model of concept development [15]: a theoretical phase through an integrative review, a field-informed analysis of co-teaching models and outcomes, and a final analytical synthesis into a coherent framework.

The methodological process unfolded in three interrelated stages. First, the study engaged in a critical review of foundational pedagogical theories, including constructivist, sociocultural, and humanistic perspectives. These traditions were selected for their enduring influence on collaborative and learner-centered approaches to education, as well as for their relevance to the transdisciplinary and inquiry-driven ethos of STEAM [16]. This theoretical grounding provided the lens through which the potential and limitations of co-teaching practices could be interpreted.

Second, established co-teaching models, such as One Teach, One Assist, Parallel Teaching, Team Teaching, Station Teaching, Alternative Teaching, and Supplemental Teaching, were analyzed in terms of their structural features, pedagogical rationales, and documented outcomes. The analysis was comparative in nature, examining both the general education literature, where these models have primarily been applied, and the specific adaptations required within STEAM contexts. Attention was given to how these models might be reconfigured to support transdisciplinary integration, differentiated learning, and the cultivation of 21st-century competencies.

Third, the findings from the theoretical review and the comparative analysis of co-teaching models were synthesized into a coherent framework. This synthesis sought to identify the pedagogical logics that align co-teaching with STEAM philosophy, with particular emphasis on inclusivity, creativity, collaboration, and authentic problem-solving. The framework thus represents a conceptual model that positions co-teaching not merely as a method of instructional support but as a strategic mechanism for fostering transdisciplinary integration and innovation.

3. Theoretical Foundations

3.1 Jean Piaget's Theory of Cognitive Development

Jean Piaget's theory of cognitive development is a foundational framework in developmental psychology that has significantly influenced educational practice, including approaches to co-teaching [17]. Piaget proposed that children actively construct their understanding of the world through interaction with their environment, and that this cognitive development occurs in a series of qualitatively distinct stages. These stages, sensorimotor (0-2 years), preoperational (2-7 years), concrete operational (7-11 years), and formal operational (11 years and above), each represent shifts in the way children think, reason, and solve problems [18].

In the sensorimotor stage, learning occurs through sensory experiences and physical actions. Children develop object permanence, recognizing that objects continue to exist even when not directly perceived [19]. The preoperational stage is characterized by symbolic thought, language development, and imaginative play, yet thinking remains egocentric and intuitive rather than logical [20]. The concrete operational stage marks the emergence of logical reasoning applied to tangible, concrete situations, enabling understanding of concepts such as conservation, reversibility, and classification [21]. Finally, in the formal operational stage, learners acquire the ability to engage in abstract, hypothetical, and systematic reasoning, allowing for advanced problem-solving and moral reasoning [22].

Central to Piaget's framework are the processes of assimilation and accommodation, which together enable adaptation. Assimilation involves integrating new experiences into existing cognitive schemas, whereas accommodation requires modifying those schemas to incorporate new information [23]. Cognitive growth occurs through a dynamic equilibrium between these two processes, a principle that resonates strongly with the adaptive and responsive nature of co-teaching [24].

3.2 Lev Vygotsky's Sociocultural Theory

Lev Vygotsky's sociocultural theory positions social interaction, cultural tools, and language at the centre of cognitive development [25]. Contrary to Piaget's emphasis on individual exploration, Vygotsky argued that learning is inherently a socially mediated process, shaped by the cultural context in which it occurs [26]. His most influential concept, the Zone of Proximal Development (ZPD), is defined as the gap between what a learner can accomplish independently and what they can achieve with the guidance of a more knowledgeable other, such as a teacher or peer [27].

A key pedagogical application of the ZPD is scaffolding, the temporary support provided to help learners accomplish tasks they could not complete alone [28]. As competence increases, this support is gradually withdrawn, promoting autonomy and mastery [29]. Vygotsky also highlighted the role of language as both a cultural tool and a cognitive instrument [30]. External dialogue, whether with a teacher or peer, facilitates problem-solving, while inner speech, the internalization of that dialogue, supports self-regulation and complex reasoning [31].

3.3 Jerome Bruner's Constructivism

Jerome Bruner's constructivist theory reframed learning as an active process in which learners build new knowledge by connecting it to their prior experiences, engaging in exploration, and reflecting on their understanding [32]. Rejecting the notion of passive knowledge transmission, Bruner argued that the role of the educator is to create conditions in which students can make discoveries for themselves, a principle known as discovery learning [33]. In this approach, the teacher acts as a facilitator, guiding inquiry, posing challenging questions, and providing resources, rather than delivering fully pre-structured information [34].

A central element of Bruner's theory is the spiral curriculum, in which key concepts are revisited at increasing levels of complexity over time [35]. This progression enables learners to deepen their understanding, integrate new perspectives, and apply their knowledge in more sophisticated ways [36]. Bruner also identified three modes of representation, enactive (learning through action), iconic (learning through images), and symbolic (learning through language and abstract symbols), arguing that effective instruction should incorporate and connect these modes to accommodate different learning preferences and developmental stages [37].

3.4 Steam Education

STEAM education denotes the deliberate integration of Science, Technology, Engineering, Arts and Mathematics within a unified, transdisciplinary pedagogy [38]. The Arts are not additive embellishments but constitutive components that extend representational repertoires, enable imaginative reasoning, and connect conceptual understanding with design, aesthetic judgement and communication [39]. Framed in this way, STEAM education treats interdisciplinary problems as complex systems that call for multiple modes of inquiry and expression rather than segmented subject coverage [40].

In operational terms, STEAM education privileges inquiry and collaborative project work around authentic challenges [41]. Learning designs typically mobilize digital fabrication, coding, and automation together with AI-mediated tools for data analysis, generative ideation, and adaptive feedback, alongside artistic composition and critique, aiming for technical functionality that is coherent with concept and form [42]. Effective orchestration makes roles, tools and criteria explicit, fosters student agency and builds classroom routines that sustain visible reasoning across the participating disciplines [43]. Within mixed-ability contexts, STEAM education advances differentiation and inclusion as complementary aims [44]. Intercultural design strengthens these outcomes by embedding local knowledge, linguistic resources and cultural perspectives within STEAM tasks [45].

Assessment in STEAM education should mirror its pedagogy [46]. Beyond correctness and topic coverage, evaluation attends to process quality, collaboration, creative risk taking and the alignment of concept, function and form [47]. In practice, this entails combining performance tasks and analytic rubrics with reflective artefacts that make reasoning visible at individual and group levels [48]. Coherent, adaptable assessment frameworks recognize learner achievements while also capturing features of the designed learning environment that enable equitable participation and sustained transdisciplinary problem solving [49].

4. Forms of Co-Teaching

4.1 One Teach, One Assist

The *One Teach, One Assist* model is one of the most widely implemented forms of co-teaching, characterized by a division of roles in which one educator assumes primary responsibility for delivering the lesson to the entire class, while the second educator provides targeted support to individual students or small groups as needed [50]. This support may include clarifying instructions, offering additional explanations, managing classroom materials, or monitoring student engagement without interrupting the overall flow of instruction [51].

A key strength of this model is its capacity to provide immediate, individualized assistance without disrupting whole-class teaching [52]. The theoretical underpinnings of this model can be traced to Vygotsky's sociocultural theory and the concept of the Zone of Proximal Development, which emphasizes the value of guided support or *scaffolding* provided by a more knowledgeable other [53]. The assisting teacher, by engaging with students at their specific point of need, helps bridge the gap between their current abilities and their learning goals [54]. Piaget's constructivist perspective further supports this model by highlighting the importance of active engagement with content, where the assisting teacher can prompt learners to connect new information with existing cognitive structures [55].

However, this model also has potential limitations. Over time, there is a risk that the assisting teacher's role may become passive, reducing opportunities for shared instructional leadership [56]. This can be mitigated through intentional planning that rotates roles between educators and ensures that both contribute meaningfully to lesson design and delivery [57]. Another challenge lies in maintaining student perception of equal authority between teachers, if students see one as the "main" teacher and the other as merely a helper, the collaborative dynamic can be undermined [58].

4.2 Parallel Teaching

The *Parallel Teaching* model involves dividing a class into two relatively equal groups, with each educator delivering the same or closely aligned content simultaneously to their respective group [59]. Unlike the *One Teach, One Assist* model, both educators assume the role of lead instructor, allowing for more active engagement between teacher and students and reducing the student-teacher ratio [60]. This smaller group size creates opportunities for increased participation, more personalized feedback, and more effective monitoring of student understanding [61].

One of the primary advantages of *Parallel Teaching* lies in its capacity to foster a more interactive learning environment [62]. By halving the class size, educators can more easily adapt instruction to student needs, address misconceptions in real time, and facilitate richer discussion [63]. In heterogeneous classrooms, this model allows teachers to tailor examples, language, and pacing to specific student groups without compromising the integrity of the lesson [64]. From a Piagetian perspective, this supports the progression from concrete operational to formal operational thinking by providing learners with more scaffolded opportunities to test and refine their reasoning [65].

From the standpoint of Vygotsky's sociocultural theory, *Parallel Teaching* enhances the conditions for scaffolding by enabling each teacher to work more closely with students within their Zone of Proximal Development [66]. Additionally, Bruner's constructivist principles, particularly discovery learning, are more readily implemented in smaller groups where students have greater opportunities to ask questions, manipulate materials, and engage in hands-on inquiry [67].

However, *Parallel Teaching* demands a high degree of coordination between educators to ensure instructional consistency and to prevent divergence in content delivery [68]. Lesson planning must be synchronized in terms of objectives, materials, and assessment strategies, which can be time-consuming [69]. Furthermore, the need for two suitable learning spaces, whether physical or virtual, can pose logistical constraints in some educational settings [70].

4.3 Team Teaching

Team Teaching is a collaborative co-teaching model in which two educators share equal responsibility for planning, delivering, and assessing instruction within the same classroom and at the same time [71]. It involves both educators engaging with the whole class simultaneously, often interacting dynamically with each other and the students [72]. This approach enables the seamless integration of diverse teaching styles, content expertise, and pedagogical strategies, resulting in a richer, more interactive learning environment [73]. Educators may alternate leading segments of the lesson, interject to add examples or clarifications, model debates or problem-solving dialogues, or co-facilitate discussions [74]. This "two voices in the classroom" dynamic can maintain high levels of student engagement by varying instructional delivery and demonstrating collaborative thinking in action [75].

From a pedagogical standpoint, this model aligns closely with Vygotsky's view of learning as a socially mediated process, where interaction with more knowledgeable others enhances cognitive development [76]. Piaget's constructivist framework also supports *Team Teaching*, as the model provides students with multiple pathways to assimilate and accommodate new information [77]. Bruner's notion of *spiral curriculum* further resonates here, as both educators can revisit key concepts from different disciplinary perspectives, each building on the other's contributions [78].

Despite its strengths, *Team Teaching* requires exceptional communication and trust between educators, as well as significant co-planning time to align instructional goals, strategies, and assessment methods [79]. Without this coordination, there is a risk of redundancy, conflicting messages, or imbalanced participation, which may undermine the intended collaborative dynamic [80]. Additionally, teachers must consciously project equal authority and mutual respect to avoid hierarchical perceptions among students [81].

4.4 Station Teaching

Station Teaching is a co-teaching model in which the classroom is organized into multiple learning stations, with students rotating between them in small groups [82]. Each station focuses on a specific aspect of the lesson or project, and at least one station is typically facilitated by an educator, while others may be teacher-led, student-led, or designed for independent work [83]. This structure allows educators to deliver targeted instruction, differentiate activities according to learner needs, and sustain high levels of student engagement by varying tasks and modalities [84]. By working in small groups, students receive more individualized attention, engage more deeply with content, and develop collaborative skills [85]. The station format also enables educators to address diverse learning styles [86].

From a Piagetian perspective, this model supports the progression of cognitive development by providing concrete, varied experiences that promote the assimilation and accommodation of new knowledge [87]. Theoretically, *Station Teaching* also draws on Vygotsky's sociocultural theory, particularly the use of *scaffolding* in the Zone of Proximal Development [88]. With students working in smaller groups, each educator can provide more tailored support, guiding learners through challenges and gradually releasing responsibility as competence increases [89]. Bruner's constructivist emphasis on discovery learning is also evident in this model, as stations often allow students to explore concepts through inquiry, experimentation, and problem-solving [90].

Nevertheless, *Station Teaching* requires careful planning to ensure that all stations are aligned with the lesson's learning objectives, that resources are adequately prepared, and that the time allocated for each rotation is sufficient [91]. Classroom management can be complex, as movement between stations must be well-coordinated to minimize disruptions [92]. Furthermore, the physical layout of the classroom and availability of materials can limit the scope of activities [93].

4.5 Alternative Teaching

Alternative Teaching is a co-teaching model in which one educator works with the majority of the class while the other provides targeted instruction to a smaller group of students [94]. This smaller group may require additional support to grasp core concepts, need enrichment activities to extend their learning, or benefit from a different instructional approach [95]. By allowing one teacher to focus on the specific needs of a subset of students, *Alternative Teaching* offers a highly flexible means of differentiation and personalized learning [96]. In inclusive classrooms, the smaller group may consist of learners with special educational needs, advanced students seeking further challenge, or those needing targeted intervention in a particular skill area [97]. The smaller group setting can create a supportive environment for risk-taking and experimentation, fostering confidence and engagement [98].

From a Vygotskian perspective, this aligns with the principle of *scaffolding* within the Zone of Proximal Development, as the educator can guide learners through tailored tasks that bridge the gap between their current capabilities and the desired learning outcomes [99]. From Piaget's constructivist standpoint, *Alternative Teaching* supports the active construction of knowledge by enabling the teacher in the smaller group to present content in ways that directly connect to learners' cognitive stage and prior experiences [100]. Bruner's notion of *discovery learning* is also facilitated, as the smaller group format allows for more open-ended exploration, discussion, and problem-solving [101].

Despite its advantages, if the same learners are consistently placed in the smaller group, it may impact their self-esteem or reinforce fixed ability groupings [102]. To mitigate this, the composition of the small group should be flexible and dynamic, changing based on instructional goals, project phases, or specific skills being addressed [103]. Furthermore, the teacher working with the larger group must ensure that learning remains engaging and challenging, even without the additional educator present [104].

4.6 Supplemental Teaching

Supplemental Teaching is a co-teaching model in which one educator delivers the core lesson to the entire class while the other provides additional or differentiated instruction to selected students, either during or immediately after the primary teaching segment [105]. This supplemental instruction can serve various purposes: reinforcing essential concepts for students who require more practice, offering alternative explanations for those struggling with the initial delivery, or extending learning for students who are ready for advanced challenges [106]. A central strength of this model lies in its ability to maintain the momentum of whole-class instruction while simultaneously addressing individual or small-group needs [107]. The supplemental component can be integrated flexibly, occurring in parallel to the main lesson, in a breakout group during independent work, or in follow-up sessions [108]. By targeting instruction to students' immediate learning needs, this model supports the principles of differentiated learning and aligns with inclusive education frameworks that prioritize equitable access to the curriculum [109].

Theoretically, *Supplemental Teaching* is grounded in Vygotsky's concept of the Zone of Proximal Development [110]. The supplemental educator acts as a *more knowledgeable other*, providing scaffolding that helps learners bridge the gap between what they can accomplish independently and what they can achieve with guidance [111]. Piaget's constructivist theory also underpins this approach, as the supplemental teacher can adapt content to the learner's developmental stage, ensuring that new information is assimilated effectively into existing cognitive structures [112]. Bruner's *spiral curriculum* model is equally relevant, as supplemental teaching allows for revisiting key concepts with increasing depth and complexity according to each learner's readiness [113].

However, scheduling and space constraints can make it difficult to deliver supplemental instruction without disrupting the main lesson [114]. There is also a risk that supplemental groups may inadvertently be perceived as remedial or elite, depending on their composition [115]. To avoid such perceptions, group membership should remain flexible and based on specific learning objectives rather than fixed ability levels [116]. Both educators must coordinate closely to ensure alignment between the main and supplemental instruction, maintaining coherence and progression in learning [117].

Table 1: Theoretical alignment of co-teaching models

Co-teaching model	Theory of Cognitive Development	Sociocultural Theory	Constructivism
One Teach, One Assist	Prompts assimilation and accommodation during active engagement; connects new ideas to existing schemas	Assisting teacher provides contingent scaffolding within learners' ZPD as a more knowledgeable other	Think-alouds and stepwise scaffolds make strategies and representations explicit for gradual independence
Parallel Teaching	Smaller groups support cognitive conflict and progression toward formal operations through targeted tasks	Close mediation enables tailored support and dialogic interaction within each group's ZPD	Discovery learning is easier to orchestrate; varied representations and hypothesis testing in parallel streams
Team Teaching	Multiple perspectives create productive cognitive conflict that stabilizes new schemes	Joint mediation and co-regulation model collaborative sense-making for the whole class	Spiral revisiting of ideas by two voices; live modelling of disciplinary dialogue and reasoning
Station Teaching	Hands-on, concrete experiences at stations build toward abstraction and generalization	Tailored scaffolds at each station, including peer mediation, widen access within the ZPD	Discovery across stations; progression from enactive and iconic to symbolic representations
Alternative Teaching	Developmentally tuned consolidation or extension for a small group matches learners' readiness	Intensive, targeted scaffolding bridges specific gaps between current and desired performance	Focused discovery with calibrated support; preparation for independent transfer
Supplemental Teaching	Stage-appropriate reinforcement or enrichment supports stable assimilation of new content	Short, focused support episodes function as proximal scaffolds that fade with competence	Spiral revisits of core ideas with increasing complexity and alternative exemplars

5. The Co-Teaching and STEAM Alignment Framework (CTSAF)

5.1 Purpose, scope, and contribution of the CTSAF

The Co-Teaching and STEAM Alignment Framework (CTSAF) aligns established co-teaching models with the transdisciplinary, inquiry-driven, and creative character of STEAM education. Its purpose is threefold. First, it provides a grammar for selecting and blending co-teaching configurations so that inclusivity, collaboration, innovation, and inquiry progress are advanced deliberately rather than incidentally. Second, it translates theory into practical design decisions about roles, task architecture, assessment, time, and space, enabling mixed-attainment classrooms to sustain equitable participation and disciplined exploration. Third, it proposes a lightweight evidence strategy that makes key principles observable in everyday practice and supports iterative improvement. The framework addresses the study's research questions by specifying when and why particular configurations add pedagogical value, how teachers can orchestrate them over an inquiry cycle, and which indicators render improvement tractable. Its scope includes mainstream and special education settings that pursue STEAM education with basic access to maker or digital tools, including AI-enhanced tools, and with the intention to widen participation without reducing conceptual ambition. The framework does not prescribe a single correct model. It offers a structured set of design choices and a rationale for conditional selection that teachers and researchers can appropriate, refine, and test across contexts.

CTSAF's distinctive contribution to co-teaching is to convert familiar models into an evidence-driven switching system with explicit dual-teacher roles. Each model is tied to observable indicators of participation and progress so that a change of configuration is justified by data rather than preference. Brief equity scans, role scripts, and a small library of contingency moves reduce coordination costs and make in-lesson pivots feasible without disrupting inquiry. Co-teaching-sensitive metrics such as distribution of talk, latency of help, and group progress attribute improvement to the quality of teacher coordination rather than to task difficulty alone. In this sense, CTSAF functions as a co-teaching engine that orchestrates roles and models around the dynamics of inquiry.

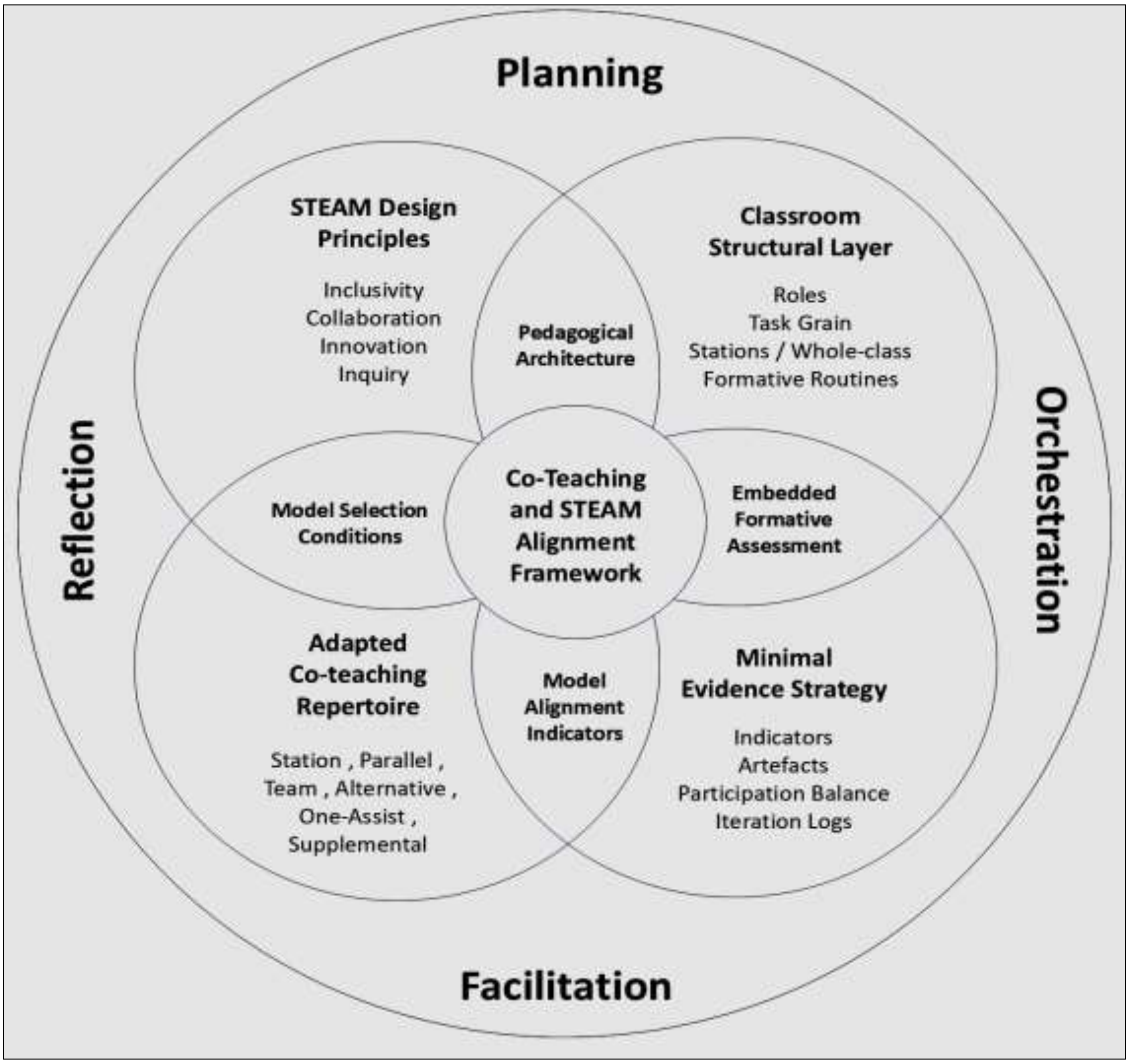

Fig 1: CTSAF as the convergence of four components

5.2 CTSAF: Components and Design Cycle

The CTSAF comprises four interlocking components that organize planning and enactment while avoiding unnecessary workload. The first component is a set of STEAM design principles that define quality as inclusive access and expression, dialogic and interdependent collaboration, tolerance for uncertainty with iterative prototyping and student agency, and inquiry as a cyclic movement of questioning, investigation, modelling, testing, and communication. The second component is a structural layer that translates principles into classroom architecture through coordinated role configurations, appropriate grain size of tasks and products, planned movement between stations and whole-class studios, and formative routines that externalize reasoning and strategy use. The third component is a deliberately small repertoire of adapted co-teaching models whose selection is conditional on moment-to-moment inquiry demands and on observed participation patterns. The fourth component is a minimal evidence strategy with observable indicators that renders the principles visible and improvable in ordinary lessons.

Table 2: CTSAF components at a glance

Component	One-line purpose	Typical choices
STEAM Design Principles	Define quality and inquiry norms	Select 2-3 focal principles; co-authored success criteria
Classroom Structural Layer	Convert principles into lesson architecture	Roles, task grain, stations vs whole-class studio, formative routines
Adapted Co-teaching Repertoire	Blend models conditionally	Station, Parallel, Team, Alternative, One-Assist, Supplemental
Minimal Evidence Strategy	Make principles observable with light workload	2-3 indicators per lesson; brief artifacts for feedback

Enactment follows a concise design cycle. In planning, teachers prioritize a small subset of principles aligned to the current inquiry phase, co-author success criteria with students, and select an initial mix of co-teaching models that fits the task architecture. In orchestration, they script roles, timing, transitions, and contingency moves for fast finishers and common misconceptions. In facilitation, they model disciplinary thinking aloud, deploy targeted scaffolds, and maintain participation equity through simple routines. In reflection, students and teachers appraise processes and products against the stated principles using classroom evidence. In iteration, the team revises roles, tasks, and model choices and records design rationales to build shared professional memory. Artificial Intelligence (AI) functions as an educative medium that mediates access, feedback, and representation under teacher oversight, while co-teaching preserves the human judgment required for ethical use and for calibrating scaffolds.

5.3 Theoretical Foundations and Rationale

The CTSAF is grounded in constructivist and sociocultural traditions and treats co-teaching as a deliberate mechanism for designing participation and scaffolding in STEAM education. Constructivist perspectives construe learning as active construction through inquiry, iterative problem solving, and metacognitive regulation. These warrants structured exploration, cumulative task complexity, and opportunities for agency in which learners test, refine, and justify ideas with evidence. Sociocultural theory complements this view by positioning learning as mediated participation in communities of practice, with attention to cultural tools, discourse moves, and the zone of proximal development. These commitments imply that scaffolds should be available when needed and gradually withdrawn, and that teacher roles must be coordinated to sustain joint attention to artefacts while enabling progressive independence.

To explain how two teachers can extend learners' reach, the framework draws on distributed cognition. Expertise is treated as distributed across people, tools, and representations, which legitimizes co-present modelling of disciplinary thinking, the externalization of strategies, and the intentional use of heterogeneous tools to widen entry points. Within this sociotechnical view, AI operates as an educative medium. It provides configurable cognitive tools that can generate alternative representations, prompt explanation, support formative feedback, and personalize practice under pedagogical constraints. AI is integrated as a mediational means whose value depends on principled human orchestration and transparent criteria for quality, not as a driver of instruction.

Taken together, these foundations recast co-teaching from a staffing arrangement into a design grammar for equitable participation in STEAM education. Two teachers can distribute expertise, surface and normalize diverse solution paths, and maintain a classroom ecology in which learners gain access to inquiry, representation, critique, and creative risk-taking. The rationale is that aligning co-teaching configurations with inquiry phases and principled assessment routines increases the likelihood that mixed-attainment groups will engage productively with complex problems without narrowing the intellectual horizon of the lesson.

5.4 Architecture, Principles, Structures, and Model Adaptations

The framework links a small set of principles to concrete structures and to conditional adaptations of co-teaching models. The principles specify what counts as quality in STEAM education. The structures translate these principles into classroom organization. The model adaptations operationalize moment-to-moment orchestration across an inquiry cycle. AI is embedded in this architecture under teacher oversight so that access, representation, and feedback are broadened without displacing pedagogical intent or equity safeguards.

The principles are inclusivity, collaboration, innovation, and inquiry. Inclusivity entails multiple means of access, expression, and engagement with systematic differentiation, low thresholds and high ceilings, and accessible materials and tools. Collaboration is defined as interdependence with shared authority, dialogic sense-making, and transparent co-regulation of work. Innovation involves open problem framing, iterative prototyping, tolerance for uncertainty, and legitimized student choice with accountability to constraints. Inquiry is a disciplined cycle of questioning, investigation, modelling, testing, and communication with explicit prompts that externalize reasoning and strategy use. Transparency and sustainability accompany these principles through co-authored success criteria, visible rubrics, public artefacts, and repeatable routines that are realistic in ordinary classrooms.

The structural layer turns principles into architecture. Role configurations specify who leads, who coaches, and who documents at each phase, and include rotation protocols that prevent status hierarchies. Task architecture defines the grain size of activities, expected products, and the ecology of tools across stations, workshops, and whole-class studios, with explicit alignment between tasks and representational forms. Assessment is primarily formative and embedded through brief checks for understanding, structured peer critique, and performances of understanding that align with the principles. AI can support these routines by generating alternative representations, producing low-stakes practice items, or offering draft feedback that teachers moderate. Time and space are planned to support movement between stations and convergence points for conceptual consolidation, while safety, accessibility, and data ethics act as visible constraints on design choices.

Table 3: AI as educative medium with safeguards

Function	Typical use case	Oversight check
Access	Alternative representations for entry points	Accessibility and bias screening; teacher gating
Feedback	Low-stakes hints and formative prompts	Transparency of source; human moderation before uptake
Representation	Draft visuals or simulations for modelling	Alignment with criteria; correctness spot-checks
Practice	Targeted item generation for consolidation	Privacy and data minimization; opt-in settings

Within this architecture, co-teaching models are adapted rather than imported wholesale. Station teaching supports early inquiry by surfacing prior conceptions and widening entry points into a phenomenon. AI-supported prompts at stations can diversify representations while teachers circulate to calibrate support. Parallel teaching supports mid-cycle modelling and testing in smaller discourse communities where teachers can refine scaffolds and monitor participation equity. Team teaching is used at milestones where integration and public justification are needed, with one teacher moderating discourse while the other curates artefacts and evidence. Alternative teaching concentrates responsive intervention and extension for groups that require consolidation or stretch, where AI can provide structured practice or alternative exemplars and teachers safeguard ethics and judgment. One teach, one assist is confined to short windows for tool induction or safety protocols and is rotated to avoid stable asymmetries. Selection remains conditional on the principles prioritized, task demands, and participation patterns, so that the repertoire stays small enough to permit disciplined iteration.

Table 4: Co-teaching model: quick decision rules

Classroom condition	Choose this model	Why it adds value
Talk imbalance or sidelined groups	Station Teaching	Rotations enable equitable access and coaching
Persistent misconceptions in a subset	Alternative Teaching	Short, intensive micro-clinics without stopping the class
Wide dispersion of progress	Parallel Teaching	Targeted pacing and differentiated coaching in halves
Need to synthesise and justify publicly	Team Teaching	Joint modelling and moderated whole-class critique
Tool induction or safety protocol	One Teach-One Assist	Short, focused onboarding with minimal disruption

5.5 Enactment, evaluation, and scope of use

Enactment follows a short cycle that supports improvement without inflating workload. In planning, one teacher typically assumes a lead architect role that aligns tasks, representations, and the initial model mix, while the partner serves as equity and evidence lead who defines indicators and documentation routines; these roles rotate to maintain symmetry. In orchestration, teachers coordinate timing, transitions, and contingency moves, with brief equity scans and pre-positioned materials, tools, and prompts, including AI-generated scaffolds where appropriate and safe. In facilitation, they model disciplinary thinking aloud, deliver targeted scaffolds, and maintain participation equity through simple routines such as structured turn-taking, randomized selection, or accountable talk stems; AI can supply on-the-spot alternative representations or formative hints that teachers gatekeep. In reflection, students and teachers appraise processes and products against the stated principles using interaction evidence, artefacts, and brief formative assessments. In iteration, the team revises roles, tasks, and model choices, records design rationales, and updates reusable resources to build a shared professional memory.

Table 5: Dual-teacher roles by phase

Phase	Lead teacher focus	Partner teacher focus
Planning	Task-representation alignment; initial model mix	Equity and evidence plan; indicators and documentation
Orchestration	Timing, transitions, whole-class cues	Contingency moves; rapid equity scans; materials flow
Facilitation	Think-alouds; whole-group guidance	Targeted scaffolds; monitoring participation balance
Reflection	Criteria framing; discussion synthesis	Evidence curation; brief rubricing and prompts
Iteration	Design rationale and updates	Resource reuse; next-step adjustments

Evaluation targets a compact set of observable indicators that make the principles improvable in daily lessons. Inclusivity is monitored through participation-equity ratios, the distribution of talk moves across subgroups, and the variety and accessibility of representational modes in student artefacts. Collaboration is traced through interaction maps, co-authored logs of key decisions, and rubric-guided judgments of collective reasoning and joint accountability. Innovation is assessed through product rubrics that attend to novelty, elaboration, and constraint satisfaction together with process evidence such as the number and quality of design iterations and the documented use of feedback.

Inquiry progress is documented through short learning journals and checkpoint reflections that externalize hypothesis formation, model revision, and evidence use. Where AI tools contribute data, teachers apply privacy, bias, and transparency checks and treat analytics as provisional until triangulated with human observations and artefacts. These measures remain lightweight, aligned with instruction, and compatible with routine documentation.

Table 6: Lightweight evidence aligned to principles

Principle	Indicator	Evidence artifact
Inclusivity	Participation balance across groups	Tally sheet or heatmap of turns
Collaboration	Quality of joint reasoning	Short interaction excerpts with talk moves
Innovation	Iteration and constraint satisfaction	Versioned prototypes with revision notes
Inquiry	Model revision and evidence use	Checkpoint reflections or learning journals

The scope of use includes mainstream and special education settings that pursue STEAM education with mixed-attainment groups and basic access to maker or digital tools. Time is treated as a hard constraint, so model choices concentrate on phases where they add the greatest value to learning, and curriculum alignment is pursued through principled selection of products and success criteria rather than through reduction of inquiry to procedural compliance. The framework presumes ongoing professional learning in co-planning, discourse facilitation, and the ethical use of AI, and it recognizes boundary conditions such as very large class sizes, severe fragmentation of time, or high-stakes testing cultures that constrain authentic inquiry. Within these constraints, the CTSAF offers a coherent rationale for why co-teaching functions as a lever for STEAM education, a practical grammar for selecting and blending models across inquiry phases, and an evidence strategy that supports reflective improvement over successive cycles.

Table 7: Scope and boundary conditions

Constraint	Pragmatic adaptation	Avoid
Large classes	Limit repertoire to two models per phase	Switching across many models in one lesson
Limited tools	Paper-based stations with shared devices	Tool-centric tasks that block participation
Tight time	One evidence indicator per lesson	Full-scale assessments that inflate workload
High-stakes culture	Products mapped to curriculum criteria	Reducing inquiry to procedural compliance

6. Discussion

The findings of this study, which synthesize established pedagogical theories, a range of co-teaching models, and the demands of STEAM education, provide an expanded perspective on the relationship between instructional design and disciplinary context. The international literature on co-teaching outside STEAM has built a robust evidence base on the value of collaborative teaching for differentiation, inclusion, and targeted intervention [52, 79]. In mainstream and special education settings, co-teaching models such as One Teach One Assist, Parallel Teaching, Team Teaching, Station Teaching, Alternative Teaching and Supplemental Teaching have been documented as effective in addressing heterogeneous learning needs and increasing engagement within a single-subject framework [84, 93, 105].

The present analysis confirms that these functional benefits are not lost when the models are transferred into STEAM contexts. However, it also shows that their scope, demands and intended outcomes are altered in significant ways [46, 48]. In a non-STEAM environment, co-teaching may remain firmly within the boundaries of a single discipline, with both educators drawing on similar content expertise and pedagogical repertoires [61, 62]. In STEAM education, the collaboration must extend beyond reinforcement of content to the intentional merging of epistemologies, methods and creative processes from different fields. This shift requires educators to negotiate meaning across disciplinary cultures and to design tasks that require such negotiation from students as well [46, 48].

The adaptation of familiar co-teaching strategies to STEAM therefore cannot be viewed as a simple matter of applying an existing template to a new subject area [79]. For example, Alternative Teaching in a language arts classroom might be used for remedial literacy instruction, while in a STEAM setting the smaller group could require high-level coding skills, advanced statistical reasoning, or aesthetic design techniques, depending on the project [84, 100]. The pedagogical relationship between the two groups is also different: in STEAM, the outputs of both groups often need to be integrated into a single product or solution, creating interdependencies that are not typical in many non-STEAM applications of the same model [46, 48].

The comparison also reveals differences in the pairing of teacher expertise. In much of the non-STEAM literature, co-teaching pairs frequently consist of two educators from the same or closely related specializations, which allows for interchangeable roles and parallel reinforcement of content [72, 74]. In STEAM, the pairing often involves complementary specializations, such as a technologist with a visual artist or a scientist with an engineer. This arrangement changes the dynamic from shared coverage of the same material to deliberate integration of distinct disciplinary contributions [46, 48]. The success of the model in this context depends on both educators being willing and able to collaborate across epistemic boundaries, which introduces a layer of complexity rarely addressed in the broader co-teaching literature [78, 79].

Assessment practices are another area where STEAM-specific adaptations are necessary. In traditional co-teaching research, success is often measured through gains in subject-specific test scores or standardized assessments [57, 62]. In STEAM, however, evaluation must take into account additional indicators such as the quality of interdisciplinary integration, originality of solutions, aesthetic coherence, teamwork processes and adaptability in the face of evolving project requirements [80, 81]. These expanded assessment criteria influence how co-teaching is planned and implemented, as instructional choices must support the development of both disciplinary mastery and transdisciplinary competencies [48, 80].

The evidence also challenges the assumption, implicit in some of the non-STEAM literature, that the primary function of co-teaching is to facilitate differentiation within a pre-existing instructional design. In STEAM, the design itself is often co-constructed, with both educators contributing to the conception of the learning experience from the outset [78, 79]. This shifts co-teaching from a model of delivery to a model of joint curriculum design, where planning, assessment and facilitation are integrated processes rather than discrete stages [79].

Overall, the comparative analysis underscores that while the structural forms of co-teaching are indeed transferable, their operational logic shifts in STEAM environments. Educators who wish to carry over a familiar co-teaching method from a non-STEAM context must consider how transdisciplinary content, complementary expertise and broader learning outcomes will reshape the demands placed on both teachers and students [46, 48]. This recognition is critical for making informed pedagogical decisions that preserve the strengths of established models while fully exploiting the opportunities presented by the STEAM framework.

7. Applications

The practical applications of the findings from this study extend directly to curriculum design, instructional planning, and professional development in STEAM education. For curriculum designers, the analysis offers a framework for selecting co-teaching models that align with the scope and sequencing of transdisciplinary projects. For example, Station Teaching can be embedded in units that require students to rotate through scientific experimentation, engineering prototyping, and artistic design, while Team Teaching may be strategically applied during phases that demand live integration of disciplinary perspectives. By mapping specific models to project phases and intended competencies, educators can ensure that the collaborative structure supports both the content and the processes of learning.

In terms of classroom practice, the research provides guidance for adapting co-teaching strategies already familiar to educators from non-STEAM contexts. Teachers who have successfully implemented Alternative Teaching in mathematics or literacy, for instance, can modify the approach to deliver targeted instruction in specialized STEAM skills such as programming, data visualization, or 3D modelling. Likewise, One Teach, One Assist can be reconfigured for complex laboratory or design studio settings, where one educator oversees the flow of the activity and the other supports troubleshooting, material management, and individual coaching. These applications emphasize the need for deliberate role definition, continuous communication, and flexibility to respond to emergent project demands.

Professional development is another key area of application. The study's findings underscore the value of pairing educators with complementary disciplinary expertise to achieve authentic transdisciplinary integration. Training programmes can use the comparative insights from this research to help teachers anticipate how a chosen co-teaching model will function differently in STEAM environments, identify the additional coordination and planning required, and design assessment tools that capture both disciplinary depth and integrated project outcomes. By embedding these practices into institutional routines, schools and educational organizations can cultivate co-teaching partnerships that consistently enhance the quality, inclusivity, and real-world relevance of STEAM learning experiences.

Table 8: Co-Teaching Models Mapped to Typical STEAM Applications

Co-teaching Model	Example STEAM Application	Role of Each Educator	Pedagogical Focus / Outcomes
One Teach, One Assist	Physics lab on motion with sensor-based data	Lead models procedure and safety; partner circulates for calibration, troubleshooting, and immediate checks; roles rotate in the next segment.	Accurate data capture; just-in-time scaffolding without stopping whole-class flow; time-boxed use to avoid stable hierarchy.
Parallel Teaching	Robotics project: mechanical build and programming	One leads mechanical build, the other programming; shared objectives and synchronised checkpoints; swap groups mid-lesson.	Lower student-teacher ratio; differentiated pacing; rapid misconception repair; smooth reintegration of skills.
Team Teaching	Sustainable architecture charrette	Co-present instruction; one moderates discourse and questioning while the other curates artefacts, models techniques, and annotates ideas; roles switch during synthesis.	Public reasoning with two expert voices; interdisciplinary integration; visible modelling of collaborative problem-solving.
Station Teaching	Renewable energy rotations (solar, wind, hydro)	Each teacher anchors a station; third station runs as independent or peer-led with scaffold cards or AI-prompted tasks; timed rotations and equity passes.	Multimodal, hands-on inquiry; equitable circulation and feedback; iterative prototyping across representations.
Alternative Teaching	Environmental data analysis clinic	Lead continues the main investigation; partner runs an 8-10 minute small-group intervention or extension; membership remains flexible.	Targeted support or stretch without pausing the class; protects student identity; accelerates data literacy.
Supplemental Teaching	Coding + digital art integration	Whole-class on animation principles; partner offers brief supplemental session during independent work or immediately after for advanced scripting or consolidation.	Maintains lesson momentum while extending or reinforcing learning; coherence between core and supplemental strands.

8. Conclusion

This study synthesized developmental, sociocultural and constructivist foundations with established co-teaching configurations to propose the Co-Teaching and STEAM Alignment Framework (CTSAF). The framework reframes co-teaching from a staffing arrangement into an evidence-driven design grammar that aligns models with the transdisciplinary and inquiry-oriented character of STEAM. Its distinctive contribution is to couple explicit dual-teacher roles with minimal decision rules and indicators sensitive to co-teaching, so that switches between One Teach, One Assist, Parallel, Station, Team, Alternative and

Supplemental teaching are justified by participation and progress data rather than preference.

Three practice-level implications follow. First, principles are operationalized as classroom structures that specify role configurations, task and product grain, movement between stations and whole-class studios, and formative routines that externalize strategy use. Second, model adaptations are conditional on inquiry phase and observed participation patterns, which reduces coordination costs and makes in-lesson pivots feasible without disrupting learning. Third, AI functions as an educative medium that broadens access, feedback and representation under teacher oversight, while co-teaching preserves human judgement for ethical use and the calibration of scaffolds.

Implementation is most effective when teams plan for a small set of focal principles, script roles and contingency moves, and evaluate with lightweight indicators that are sensitive to collaboration and equity. Talk distribution, latency to assistance and group progress provide actionable feedback within ordinary lessons and help attribute gains to how teachers coordinate, not only to task difficulty or tooling. In mixed-attainment contexts, this alignment enables equitable participation without narrowing conceptual ambition and supports students in modelling, testing and justifying ideas across disciplinary lenses.

The study has limits. Findings are bounded by typical constraints of school timetables, large class sizes and uneven access to maker or digital tools. The framework presumes basic professional learning in co-planning and discourse facilitation, and AI-supported routines require transparency, bias checks and data minimization. Transferability beyond the documented conditions remains a working hypothesis that calls for systematic examination.

Future work should combine design-based research with comparative studies that test CTSAF against business-as-usual co-teaching with respect to equity and inquiry outcomes. Fine-grained analyses of talk distribution, latency to assistance and the timing of model switches can clarify causal links between coordination and learning. Fidelity of implementation tools are needed to document how roles, structures and indicators are enacted across subjects and age groups, together with workload and cost-benefit analyses that keep the framework tractable for teachers.

References

1. Cook L, Friend M. Co-teaching: Guidelines for creating effective practices. Focus on Exceptional Children. 1995;28(3):1-16. doi:10.17161/foec.v28i3.6852.
2. Friend M. The coteaching partnership. Educational Leadership. 2007;64(5):48-51.
3. Friend M, Reising M, Cook L. Co-teaching: An overview of the past, a glimpse at the present, and considerations for the future. Preventing School Failure: Alternative Education for Children and Youth. 1993;37(4):6-10. doi:10.1080/1045988X.1993.9944611.
4. Vaughn S, Schumm JS, Arguelles ME. The ABCDEs of co-teaching. Teaching Exceptional Children. 1997;30(2):4-10. doi:10.1177/004005999703000201.
5. Eckardt PN, Giouroukakis V. The impact of co-teaching on pedagogical approaches and student conceptual understanding in a graduate, adolescent literacy course. Journal for Leadership and Instruction. 2018;17(2):40-43.
6. Murphy C, Martin SN. Coteaching in teacher education: Research and practice. Asia-Pacific Journal of Teacher Education. 2015;43(4):277-280. doi:10.1080/1359866X.2015.1060927.
7. Cross JC. Academic achievement in traditional classrooms versus co-teaching classrooms [dissertation]. Phoenix: Grand Canyon University; 2023.
8. van Velzen C, Volman M, Brekelmans M. There is no need to sit on my hands anymore! Modelling and scaffolding as mentoring tools during co-teaching. In: Murray J, Swennen A, Kosnik C, editors. International research, policy and practice in teacher education: Insider perspectives. Cham: Springer International Publishing; 2019. p. 155-170. doi:10.1007/978-3-030-01612-8_11.
9. Sagredo-Lillo E, Salamanca-Garay I, Sagredo-Concha I, Espinoza J, Soto-Fuentes A. Collaborative work and co-teaching as 21st century skills for educating from an inclusive perspective in face-to-face and virtual contexts. In: Rocha Á, Ferrás C, Hochstetter Diez J, Diéguez Rebolledo M, editors. Information technology and systems: ICITS 2024, Volume 2. Cham: Springer Nature Switzerland; 2024. p. 327-338. doi:10.1007/978-3-031-54256-5_31.
10. Rafti M, Milakis ED, Argyrakou CC, Vangeli DG, Katsarou MC. Hands-On STEAM programming: Microteaching with micro:bit for enhanced learning. Journal of Hypermedia & Technology-Enhanced Learning. 2025;3(2):1-20. doi:10.58536/j-hytel.172.
11. Li J, Luo H, Zhao L, Zhu M, Ma L, Liao X. Promoting STEAM education in primary school through cooperative teaching: A design-based research study. Sustainability. 2022;14(16):10333. doi:10.3390/su141610333.
12. Fluijt D, Bakker C, Struyf E. Team-reflection: The missing link in co-teaching teams. European Journal of Special Needs Education. 2016;31(2):187-201. doi:10.1080/08856257.2015.1125690.
13. Sochacka NW, Guyotte KW, Walther J. Learning together: A collaborative autoethnographic exploration of STEAM (STEM + the Arts) education. Journal of Engineering Education. 2016;105(1):15-42. doi:10.1002/jee.20112.
14. Wu Y, Cheng J, Koszalka TA. Transdisciplinary approach in middle school: A case study of co-teaching practices in STEAM teams. International Journal of Education in Mathematics, Science and Technology. 2021;9(1):138-162. doi:10.46328/ijemst.1017.
15. Schwartz-Barcott D, Kim HS. An expansion and elaboration of the hybrid model of concept development. In: Rodgers BL, Knafl KA, editors. Concept development in nursing: Foundations, techniques, and applications. 2nd ed. Philadelphia: W. B. Saunders; 2000. p. 129-159.
16. Farrell A, Lawlor B, Jordan A, Strawbridge J, Brabazon D, Casey K. Full STEAM ahead! Guiding principles for the design of interdisciplinary approaches to the development of communication skills and enquiry based collaborative learning in STEM and Arts subjects. In: Science and Mathematics Education Conference (SMEC 2014) Proceedings. Dublin: Dublin City University; 2014. p. 82-85.

17. Nicolopoulou A. Play, cognitive development, and the social world: Piaget, Vygotsky, and beyond. Human Development. 1993;36(1):1-23. doi:10.1159/000277285.
18. Pakpahan FH, Saragih M. Theory of cognitive development by Jean Piaget. Journal of Applied Linguistics. 2022;2(2):55-60. doi:10.52622/joal.v2i2.79.
19. Barrouillet P. Theories of cognitive development: From Piaget to today. Developmental Review. 2015;38:1-12. doi:10.1016/j.dr.2015.07.004.
20. Babakr ZH, Mohamedamin P, Kakamad K. Piaget's cognitive developmental theory: Critical review. Education Quarterly Reviews. 2019;2(3):517-524.
21. Kazi S, Galanaki E. Piagetian theory of cognitive development. In: Hupp S, Jewell JD, editors. The Encyclopedia of Child and Adolescent Development. Hoboken: Wiley-Blackwell; 2020. doi:10.1002/9781119171492.wecad364.
22. Ewing JC, Foster DD, Whittington MS. Explaining student cognition during class sessions in the context of Piaget's theory of cognitive development. NACTA Journal. 2011;55(1):68-75.
23. Ryan RM, Deci EL. Toward a social psychology of assimilation: Self-determination theory in cognitive development and education. In: Sokol BW, Grouzet FME, Müller U, editors. Self-regulation and autonomy: Social and developmental dimensions of human conduct. Cambridge: Cambridge University Press; 2013. p. 191-207. doi:10.1017/CBO9781139152198.014.
24. Bormanaki HB, Khoshhal Y. The role of equilibration in Piaget's theory of cognitive development and its implication for receptive skills: A theoretical study. Journal of Language Teaching and Research. 2017;8(5):996-1005. doi:10.17507/jltr.0805.22.
25. Mahn H. Vygotsky's methodological contribution to sociocultural theory. Remedial and Special Education. 1999;20(6):341-350. doi:10.1177/074193259902000607.
26. Kashani EA. Applying Lev Vygotsky's sociocultural theory of development to teaching responsibility in elementary schools. Journal of Research in Curriculum Studies. 2025;15(1):1-18. doi:10.48310/jcdr.2024.16083.1098.
27. Karimi-Aghdam S. Zone of proximal development as an emergent system: A dynamic systems theory perspective. Integrative Psychological and Behavioral Science. 2017;51(1):76-93. doi:10.1007/s12124-016-9359-1.
28. Fani T, Ghaemi F. Implications of Vygotsky's zone of proximal development in teacher education: ZPTD and self-scaffolding. Procedia - Social and Behavioral Sciences. 2011;29:1549-1554. doi:10.1016/j.sbspro.2011.11.396.
29. Wass R, Harland T, Mercer A. Scaffolding critical thinking in the zone of proximal development. Higher Education Research & Development. 2011;30(3):317-328. doi:10.1080/07294360.2010.489237.
30. Basile G. Experience, cognition, and language in Lev S. Vygotsky: A socio-cognitive approach to meaning and understanding. Reti, saperi, linguaggi. 2023;10(1):85-106. doi:10.12832/107715.
31. Leontiev D, Lebedeva A, Kostenko V. Pathways of personality development: following Lev Vygotsky's guidelines. Voprosy Obrazovaniya / Educational Studies Moscow. 2017;(2):98-112. doi:10.17323/1814-9545-2017-2-98-112.
32. MacBlain S. Jerome Bruner and constructivism. In: Learning Theories for Early Years Practice. 2nd ed. London: Sage; 2021. p. 87-100.
33. Chand SP. Constructivism in education: Exploring the contributions of Piaget, Vygotsky, and Bruner. International Journal of Science and Research. 2023;12(7):274-278. doi:10.21275/SR23630021800.
34. Stapleton L, Stefaniak J. Cognitive constructivism: Revisiting Jerome Bruner's influence on instructional design practices. TechTrends. 2019;63(1):4-5. doi:10.1007/s11528-018-0356-8.
35. Metsämuuronen J, Räsänen P. Cognitive-linguistic and constructivist mnemonic triggers in teaching based on Jerome Bruner's thinking. Frontiers in Psychology. 2018;9:2543. doi:10.3389/fpsyg.2018.02543.
36. Ozdem-Yilmaz Y, Bilican K. Discovery learning - Jerome Bruner. In: Akpan B, Kennedy TJ, editors. Science Education in Theory and Practice. Cham: Springer Nature Switzerland; 2025. p. 173-187. doi:10.1007/978-3-031-81351-1_11.
37. Suhendi A, Purwarno. Constructivist learning theory: The contribution to foreign language learning and teaching. KnE Social Sciences. 2018;3(4):87-95. doi:10.18502/kss.v3i4.1921.
38. Segarra VA, Natalizio B, Falkenberg CV, Pulford S, Holmes RM. STEAM: Using the arts to train well-rounded and creative scientists. Journal of Microbiology & Biology Education. 2018;19(1):19.1.53. doi:10.1128/jmbe.v19i1.1360.
39. Roussou AM, Argyrakou CC, Milakis ED. Integrating STEAM and theatrical methods in early childhood environmental education: A framework for holistic learning. International Journal of Geography, Geology and Environment. 2025;7(2):19-42. doi:10.22271/27067483.2025.v7.i2a.336.
40. Argyrakou CC, Milakis DE, Vasilara A, Lalou A. From text analysis to environmental action: An interdisciplinary learning scenario for primary education. International Journal of Research Publication and Reviews. 2023;4(10):1005-1014. doi:10.5281/zenodo.8421396.
41. Milakis ED. Collaborative project-based learning as a pedagogical strategy for inclusion in gifted STEAM education: Teachers' perspectives from mixed-ability classrooms. International Journal of Multidisciplinary Trends. 2025;7(5):92-105. doi:10.22271/multi.2025.v7.i5b.690.
42. Milakis ED, Argyrakou CC, Melidis A, Vrettaros J, Katsarou MC, Lalou A. ChatGPT and AI chatbots in education: An umbrella review of systematic reviews, scoping reviews, and meta-analyses. International Journal of Education and Information Technologies. 2025;19:100-119. doi:10.46300/9109.2025.19.11.
43. Milakis ED. The role of educational games in developing cognitive, social, and creative skills in gifted STEAM education. International Journal of Communication and Information Technology. 2025;6(1):88-97. doi:10.33545/2707661X.2025.v6.i1b.118.

44. Milakis ED. Teachers' insights on intercultural inclusion in gifted STEAM education. International Journal of Humanities and Education Research. 2025;7(1):432-443. doi:10.33545/26649799.2025.v7.i1e.172.
45. Argyrakou CC, Milakis ED. STEAM in intercultural education: Teaching popular culture to Filipino immigrants. Physics News. 2018;7(9):28-30. doi:10.5281/zenodo.6464923.
46. Quigley CF, Herro D, Jamil FM. Developing a conceptual model of STEAM teaching practices. School Science and Mathematics. 2017;117(1-2):1-12. doi:10.1111/ssm.12201.
47. Milakis ED, Argyrakou CC, Loukisas T, Vangeli DG, Katsarou MC, Lalou A. Comparative analysis of large language models as AI assistants for educational assessment: A case study in STEAM education. International Journal of Computing and Artificial Intelligence. 2024;5(2):51-55. doi:10.33545/27076571.2024.v5.i2a.97.
48. Quigley CF, Herro D. "Finding the joy in the unknown": Implementation of STEAM teaching practices in middle school science and math classrooms. Journal of Science Education and Technology. 2016;25(3):410-426. doi:10.1007/s10956-016-9602-z.
49. Herro D, Quigley C. Exploring teachers' perceptions of STEAM teaching through professional development: Implications for teacher educators. Professional Development in Education. 2017;43(3):416-438. doi:10.1080/19415257.2016.1205507.
50. Johnson NH, Brumback L. Guest editorial: Co-teaching in the science classroom: The one teach/one assist model. Science Scope. 2013;36(6):6-9. doi:10.2505/4/ss13_036_06_6.
51. Burks-Keeley RG, Brown MR. Student and teacher perceptions of the five co-teaching models: a pilot study. Journal of the American Academy of Special Education Professionals. 2014;9(3):149-185. doi:10.64546/jaasep.256.
52. Cook SC, McDuffie-Landrum KA, Oshita L, Cook BG. Co-teaching for students with disabilities: a critical and updated analysis of the empirical literature. In: Kauffman JM, Hallahan DP, editors. Handbook of Special Education. 2nd ed. New York: Routledge; 2017. p. 233-248. doi:10.4324/9781315517698-20.
53. Murphy C, Martin SN. Coteaching in teacher education: research and practice. Asia-Pacific Journal of Teacher Education. 2015;43(4):277-280. doi:10.1080/1359866X.2015.1060927.
54. Takavarasha E, Uwamariya M. Towards strengthening the mentoring of Teacher Training College tutors through the co-teaching approach in the Eastern Province, Rwanda. Rwandan Journal of Education. 2024;7(2):4-16.
55. McCullagh J, Doherty A. A coteaching model for developing pre-service teachers' practice and confidence in teaching primary science through inquiry. In: Bansal G, Ramnarain U, editors. Inquiry-Based Science in the Primary Classroom. Abingdon: Routledge; 2023. p. 99-112. doi:10.4324/9781003380351-9.
56. Mohammad Hassani Soudmand F, Ahour T. The effect of one teach-one assist model of co-teaching on Iranian EFL learners' reading comprehension. Journal of English Language Pedagogy and Practice. 2020;13(26):24-48. doi:10.30495/JAL.2020.676716.
57. Carty A, Farrell AM. Co-teaching in a mainstream post-primary mathematics classroom: an evaluation of models of co-teaching from the perspective of the teachers. Support for Learning. 2018;33(2):101-121. doi:10.1111/1467-9604.12198.
58. Stobaugh R, Gichuru M. Co-teaching practices during student teaching. Educational (Re)naissance. 2016;5(1):53-73. doi:10.33499/edren.v5i1.100.
59. Aliakbari M, Bazyar A. Exploring the impact of parallel teaching on general language proficiency of EFL learners. Journal of Pan-Pacific Association of Applied Linguistics. 2012;16(1):55-71.
60. Simons M, Baeten M, Vanhees C. Team teaching during field experiences in teacher education: investigating student teachers' experiences with parallel and sequential teaching. Journal of Teacher Education. 2020;71(1):24-40. doi:10.1177/0022487118789064.
61. Zhou J, Wang K, Zhang X, Wang C. The comparison between series and parallel: integrated experimental teaching model for pharmaceutical engineering students based on criteria for accrediting engineering programs in China. J Clean Prod. 2018;172:4421-4434. doi:10.1016/j.jclepro.2017.03.039.
62. Viola D, Sabina LL, Smith A. Exploring the effectiveness of parallel teaching in a high school mathematics classroom. J Res Educ. 2023;32(1):71-88.
63. Zhou G, Yunus MM, Mansor AZ. Influence of series parallel teaching methods on critical and creative thinking in STEM, art, and music courses in China. *Rev Electron LEEME*. 2025;(55). doi:10.58262/LEEME.55.0010.
64. Simons M, Baeten M. Innovative field experiences in teacher education: An evaluation of sequential and parallel teaching by student teachers, mentors and pupils. In: Mena J, García-Valcárcel A, García-Peñalvo FJ, Martín del Pozo M, editors. *Search and research: teacher education for contemporary contexts*. Salamanca: Ediciones Universidad de Salamanca; 2017. p. 781-790.
65. Ezenwafor JI, Onokpaunu MO, Oghenekaro M. Business educators' knowledge and competence level in pedagogical strategies for implementing inclusive business education programs in Nigeria. J Plus Educ. 2019;24(Special issue):100-106.
66. Murray F. The development of successful bilingual, biliterate and bicultural pedagogy: place for Tiwi teachers and Tiwi language in learning. In: Devlin BC, Disbray S, Devlin NR, editors. *History of bilingual education in the Northern Territory: people, programs and policies*. Singapore: Springer; 2017. p. 113-126. doi:10.1007/978-981-10-2078-0_10.
67. Hyry-Beihammer EK, Hascher T. Multigrade teaching in primary education as a promising pedagogy for teacher education in Austria and Finland. In: Craig CJ, Orland-Barak L, editors. *International teacher education: promising pedagogies (Part C)*. Bingley: Emerald; 2015. p. 89-113. doi:10.1108/S1479-368720150000022005.
68. Stobaugh R, Everson K. Student teacher engagement in co-teaching strategies. *Educational (Re)naissance*. 2020;8(1):30-47. doi:10.33499/edren.v8i1.137.

69. Gerakopoulou O. Scaffolding oral interaction in a CLIL context: a qualitative study. *Sel Pap Theor Appl Linguist*. 2016;21:602-613. doi:10.26262/istal.v21i0.5257.
70. Carrillo López C, Boldú Rodríguez S. A real experience in a high complexity school: modelling small group conversations through coteaching in CLIL. CLIL J. 2024;1(1):50-73. doi:10.60940/cjv1n1id430057.
71. Buckley FJ. *Team teaching: what, why, and how?* Thousand Oaks: Sage Publications; 2000.
72. Baeten M, Simons M. Student teachers' team teaching: models, effects, and conditions for implementation. *Teach Teach Educ*. 2014;41:92-110. doi:10.1016/j.tate.2014.03.010.
73. Jang SJ. Research on the effects of team teaching upon two secondary school teachers. *Educ Res*. 2006;48(2):177-194. doi:10.1080/00131880600732272.
74. Carpenter DM, Crawford L, Walden R. Testing the efficacy of team teaching. *Learn Environ Res*. 2007;10(1):53-65. doi:10.1007/s10984-007-9019-y.
75. Game A, Metcalfe A. Dialogue and team teaching. *High Educ Res Dev*. 2009;28(1):45-57. doi:10.1080/07294360802444354.
76. Chen CWY, Cheng YS. Learning from team teaching and beyond: a case study on EFL teachers' professional development. J Pan-Pac Assoc Appl Linguist. 2014;18(1):33-47.
77. Shing ML, Shing CC, Chen KL, Lee H. Issues in information security curriculum: collaborative learning and team teaching. Int J Innov Learn. 2007;4(5):516-529. doi:10.1504/IJIL.2007.012961.
78. Plank KM, editor. *Team teaching: across the disciplines, across the academy*. New York: Routledge; 2023. doi:10.4324/9781003447504.
79. Friend M, Cook L, Hurley-Chamberlain D, Shamberger C. Co-teaching: an illustration of the complexity of collaboration in special education. J Educ Psychol Consult. 2010;20(1):9-27. doi:10.1080/10474410903535380.
80. Lozano R, Merrill MY, Sammalisto K, Ceulemans K, Lozano FJ. Connecting competences and pedagogical approaches for sustainable development in higher education: a literature review and framework proposal. *Sustainability*. 2017;9(10):1889. doi:10.3390/su9101889.
81. Chu SKW, Reynolds RB, Tavares NJ, Notari M, Lee CWY. *21st century skills development through inquiry-based learning: from theory to practice*. Singapore: Springer; 2017. doi:10.1007/978-981-10-2481-8.
82. Gurgur H, Uzuner Y. Examining the implementation of two co-teaching models: team teaching and station teaching. Int J Incl Educ. 2011;15(6):589-610. doi:10.1080/13603110903265032.
83. Haghighi JK, Abdollahi K. On the efficacy of team teaching and station teaching in the enhancement of students' reading comprehension in an EAP situation. *Procedia Soc Behav Sci*. 2014;98:882-890. doi:10.1016/j.sbspro.2014.03.496.
84. Lyon C, Hogan EK, Kearns DM. Individualizing literacy instruction in co-taught classrooms through a station teaching model. *Interv Sch Clin*. 2021;56(4):224-232. doi:10.1177/1053451220944376.
85. Pho DH, Nguyen HT, Nguyen HM, Nguyen TTN. The use of learning station method according to competency development for elementary students in Vietnam. *Cogent Educ*. 2021;8(1):1870799. doi:10.1080/2331186X.2020.1870799.
86. Aydoğmuş M, Şentürk C. The effects of learning stations technique on academic achievement: a meta-analytic study. *Res Pedagog*. 2019;9(1):1-15. doi:10.17810/2015.87.
87. Tekin E, Taşpınar ŞE. Painting with learning stations: effect on creativity in visual arts class. *Cogent Educ*. 2025;12(1):2429370. doi:10.1080/2331186X.2024.2429370.
88. Boothe KA, Frazier T, Clements TP. Collaborating to meet the diverse needs of students in higher education. In: Watkins HE, Williams RF, editors. *Academic coaching in modern online education*. Hershey (PA): IGI Global; 2025. p. 109-132. doi:10.4018/979-8-3373-2582-8.ch005.
89. Howlett KM, Nguyen HL. Autoethnographic reflections of an international graduate teaching assistant's co-teaching experiences. J Int Students. 2020;10(2):401-419. doi:10.32674/jis.v10i2.774.
90. Kamran PK, Palta MN. Teaching strategies in inclusive education. In: Kauts DS, editor. *Inclusive education: practices and challenges*. New Delhi: K.K. Publications; 2021. p. 232-239.
91. Chien GCW. Challenges of implementing station teaching between ELL teachers and general education teachers and its implication on classroom practice. In: Perren JM, Losey KM, Perren DO, Piippo A, editors. *Transforming learning: Teaching & advocacy and ESL at the crossroads. Selected proceedings of the 2009 and 2010 Michigan Teachers of English to Speakers of Other Languages conferences*. Ypsilanti (MI): Michigan TESOL; 2011. p. 7-18.
92. Bolat Y. Student and teacher perspectives on interdisciplinary station technique. J Adv Educ Stud. 2023;5:1-30. doi:10.48166/ejaes.1330326.
93. Sharma BU. The role of co-teaching in enhancing instructional strategies in inclusive classrooms. Int J Res Sci Innov. 2025;12(5):1248-1253. doi:10.51244/IJRSI.2025.120500120.
94. Brendle J, Lock R, Piazza K. A study of co-teaching identifying effective implementation strategies. Int J Spec Educ. 2017;32(3):538-550.
95. Nurutdinova AR, Perchatkina VG, Zinatullina LM, Zubkova GI, Galeeva FT. Innovative teaching practice: traditional and alternative methods (challenges and implications). Int J Environ Sci Educ. 2016;11(10):3807-3819.
96. Suell JL, Piotrowski C. Alternative teacher education programs: a review of the literature and outcome studies. J Instr Psychol. 2007;34(1):54-58.
97. Putnam JW. Cooperative learning in inclusive classrooms. In: Kourkoutas E, Hart A, editors. *Innovative practice and interventions for children and adolescents with psychosocial difficulties and disabilities*. Newcastle upon Tyne: Cambridge Scholars Publishing; 2015. p. 184-206.
98. Kershner R. Learning in inclusive classrooms. In: Hick P, Kershner R, Farrell PT, editors. *Psychology for inclusive education: new directions in theory and practice*. Abingdon: Routledge; 2009. p. 52-65.
99. Morcom VE, MacCallum JA. Getting personal about values: scaffolding student participation towards an

inclusive classroom community. Int J Incl Educ. 2012;16(12):1323-1334. doi:10.1080/13603116.2011.572189.

100. Bisiri E. Intercultural story-based framework in young language learners' classrooms: from alternative teaching to alternative assessment. *Lang Teach Res Q*. 2020;17:55-69. doi:10.32038/ltrq.2020.17.05.
101. Ishartono N, Nurcahyo A, Setyono ID. Guided discovery: an alternative teaching method to reduce students' rote learning behavior in studying geometric transformation. J Phys Conf Ser. 2019;1265(1):012019. doi:10.1088/1742-6596/1265/1/012019.
102. Gagnon JC, Barber BR. Research-based academic and behavioral practices in alternative education settings: best evidence, challenges, and recommendations. In: Cook BG, Tankersley M, Landrum TJ, editors. *Transition of youth and young adults*. Bingley: Emerald; 2015. p. 225-271. doi:10.1108/S0735-004X20150000028010.
103. Turabovna KC. Exploring the benefits and challenges of alternative education. Int J Soc Sci Interdiscip Res. 2025;14(6):218-231.
104. Best M. Teaching within the 'margins': capturing the challenges, tensions, and rewards of alternative education. *Teach Teach*. 2025;31(7):1114-1133. doi:10.1080/13540602.2024.2439564.
105. Ning HK, Downing K. The impact of supplemental instruction on learning competence and academic performance. *Stud High Educ*. 2010;35(8):921-939. doi:10.1080/03075070903390786.
106. Naidoo J, Paideya V. Exploring the possibility of introducing supplemental instruction at secondary school level. S Afr J Educ. 2015;35(2): Article #1022. doi:10.15700/saje.v35n2a1022.
107. Flaris V. Improving student outcomes with supplemental instruction. In: *Strategies promoting success of two-year college students*. Washington (DC): American Chemical Society; 2018. p. 49-58. (ACS Symposium Series; 1280). doi:10.1021/bk-2018-1280.ch003.
108. Buchanan EM, Valentine KD, Frizell ML. Supplemental instruction: understanding academic assistance in underrepresented groups. J Exp Educ. 2019;87(2):288-298. doi:10.1080/00220973.2017.1421517.
109. Preszler RW. Student- and teacher-centered learning in a supplemental learning biology course. Bioscene J Coll Biol Teach. 2006;32(2):21-25.
110. Sebald A, Myers A, Frederiksen H, Pike E. Collaborative co-teaching during student teaching pilot project: what difference does context make? J Educ. 2023;203(1):18-31. doi:10.1177/00220574211016403.
111. Merk H, Betz M, O'Mara C. Teacher candidates' learning gains: the tale of two co-teachers. Networks Online J Teach Res. 2015;17(2):Article 3. doi:10.4148/2470-6353.1028.
112. Khan M, McGeown S, Bell S. Can an outdoor learning environment improve children's academic attainment? A quasi-experimental mixed methods study in Bangladesh. *Environ Behav*. 2020;52(10):1079-1104. doi:10.1177/0013916519860868.
113. Nwoko OO, Atteng CJ, Wonu N. Discovery learning model and the remediation of developmental dyscalculia in number and numeration. *Fac Nat Appl Sci J Sci Innov*. 2023;4(1):8-15.
114. Moleko MM, Hlalele D, Mahlomaholo M. Challenges experienced with the implementation of supplemental instruction at institutions of higher education. Mediterr J Soc Sci. 2014;5(27):740-751. doi:10.5901/mjss.2014.v5n27p740.
115. Burman E, Miles S. Deconstructing supplementary education: from the pedagogy of the supplement to the unsettling of the mainstream. *Educ Rev*. 2020;72(1):3-22. doi:10.1080/00131911.2018.1480475.
116. Chatterji M, Kwon YA, Sng C. Gathering evidence on an after-school supplemental instruction program: design challenges and early findings in light of NCLB. *Educ Policy Anal Arch*. 2006;14(12):1-47.
117. Channing J, Okada NC. Supplemental instruction and embedded tutoring program assessment: problems and opportunities. Community Coll J Res Pract. 2020;44(4):241-247. doi:10.1080/10668926.2019.1575777.