

Utilizing cultural-historical activity theory as a theoretical lens in STEM education: A systematic review

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Abstract

This systematic review examines the application of cultural-historical activity theory (CHAT) as a theoretical lens in science, technology, engineering, and mathematics (STEM) education research. Guided by the preferred reporting items for systematic reviews and meta-analyses framework, the study synthesized 30 empirical and theoretical studies drawn from multiple databases, focusing on how CHAT has been conceptualised and applied across diverse STEM contexts. The review analyzed educational levels, methodological approaches, activity system configurations, mediating artefacts, contradictions, and reported learning outcomes. Findings indicate that CHAT is predominantly applied in secondary education settings and is most frequently operationalized through Engeström's (1987) expanded activity system model. Qualitative case study methodologies dominate the field, with increasing use of mixed methods and design-based research in technology-rich contexts. Across studies, digital simulations, robotics, learning management systems, and culturally situated tools emerged as key mediating artefacts shaping STEM learning processes. A central pattern across the literature is the recurrence of systemic contradictions, particularly tool-object, rules-community, and division-of-labor tensions, which function as drivers of pedagogical innovation and expansive learning. Overall, the synthesis demonstrates that CHAT contributes significantly to improved conceptual understanding, learner engagement, collaboration, computational thinking, and teacher professional development in STEM education. However, the review also reveals conceptual fragmentation in how CHAT is interpreted and applied, highlighting the need for greater theoretical coherence and methodological consistency. The study concludes that CHAT provides a robust socio-cultural framework for understanding and transforming STEM education as a complex, mediated, and systemic activity.

Keywords: cultural-historical activity theory, STEM education, Engeström activity system, contradictions, socio-cultural theory, digital learning tools, teacher professional development, inquiry-based learning, educational technology

INTRODUCTION

Science, technology, engineering, and mathematics (STEM) education has become a global priority for equipping learners with the knowledge, skills, and competencies needed to address complex scientific, technological, environmental, and societal challenges. Integrated STEM education promotes scientific literacy, critical thinking, creativity, collaboration, innovation, and problem-solving through authentic, interdisciplinary learning experiences that connect

classroom learning with real-world contexts (Roehrig et al., 2021). As educational systems increasingly adopt integrated STEM approaches, there is a growing need for theoretical frameworks that explain the complex interactions among learners, teachers, technologies, curricula, and learning environments. Despite its growing prominence, STEM education continues to face significant conceptual and pedagogical challenges. The interdisciplinary nature of STEM requires educators to integrate multiple disciplines while responding to diverse learner needs, rapidly evolving technologies,

Contribution to the literature

- This systematic review contributes to the literature by providing a comprehensive synthesis of the use of cultural-historical activity theory (CHAT) as a theoretical lens in STEM education research.
- It consolidates fragmented scholarship across STEM disciplines, educational levels, and contexts; educational levels, and contexts?
- The review further demonstrates the value of CHAT in conceptualizing STEM education as a socially, culturally, and institutionally mediated activity system.

and dynamic classroom contexts. Traditional teacher-centered approaches often fail to capture the collaborative, contextual, and socially mediated nature of STEM learning, highlighting the need for socio-cultural theories that provide a more comprehensive understanding of knowledge construction in authentic educational settings (Amirova, 2025).

Among these frameworks, CHAT has emerged as a powerful lens for examining teaching and learning in STEM education. Originating from the work of Vygotsky and later extended by Leontiev (1978) and Engeström (1987), CHAT conceptualizes learning as a socially situated activity mediated by cultural artefacts, language, community, rules, and division of labor. Rather than focusing solely on individual cognition, CHAT examines learning within interconnected activity systems, enabling researchers to explore how social, cultural, historical, and institutional factors shape educational practice. This systems-oriented perspective is particularly well suited to STEM education, where interdisciplinary collaboration, technology integration, engineering design, inquiry-based learning, and authentic problem-solving are central features.

Over the past two decades, the application of CHAT in STEM education has expanded considerably across diverse educational contexts, including teacher professional development, curriculum implementation, computational thinking, robotics, engineering education, technology integration, makerspaces, and culturally responsive pedagogies. Furthermore, CHAT has been instrumental in identifying systemic contradictions within educational activity systems and explaining how these tensions stimulate innovation, organizational learning, and pedagogical transformation (Qureshi, 2021). However, despite this growing body of scholarship, the literature remains fragmented, with considerable variation in theoretical interpretations, methodological approaches, educational contexts, and analytical focus (Pandey et al. 2026). This fragmentation limits a comprehensive understanding of how CHAT has been conceptualised and applied within STEM education. Although previous reviews have examined STEM education broadly, few have systematically synthesized the application of CHAT as a theoretical lens across the field (Valeri et al., 2025). Consequently, important questions remain regarding the evolution of CHAT-based research, dominant themes,

methodological trends, educational contexts, and emerging research gaps (Munaye et al., 2025). Addressing these issues is essential for strengthening the theoretical foundations of STEM education and informing future research and practice.

This systematic review addresses this gap by synthesizing empirical and theoretical studies that employ CHAT in STEM education. Specifically, the review examines research trends, methodological characteristics, educational contexts, theoretical applications, and key findings to provide a comprehensive understanding of the contributions of CHAT to STEM teaching and learning. By consolidating the existing evidence, this review advances theoretical understanding, identifies future research directions, and offers practical insights for educators, curriculum developers, teacher educators, policymakers, and researchers seeking to design and implement innovative, equitable, and contextually responsive STEM education.

Utilizing Cultural-Historical Activity Theory as a Theoretical Lens in STEM Education

The increasing complexity of STEM education has heightened the need for theoretical frameworks that explain learning as a socially situated, culturally mediated, and context-dependent process. Contemporary STEM education extends beyond disciplinary knowledge to emphasize interdisciplinary collaboration, authentic problem-solving, computational thinking, engineering design, innovation, and digital technologies (Joseph & Nwankwo, 2024). These learning environments involve dynamic interactions among learners, teachers, technological tools, institutional structures, and cultural contexts, making traditional individualistic and primarily cognitive theories insufficient for capturing the systemic nature of STEM learning. Within this context, CHAT has emerged as a powerful sociocultural framework for examining teaching and learning in complex educational settings.

Rooted in the work of Vygotsky and further developed by Leontiev (1978) and Engeström (1987), CHAT conceptualizes learning as participation in collective activity systems mediated by cultural artefacts, language, social interactions, and institutional practices. Engeström's (1987) expanded activity system, comprising the subject, object, mediating artefacts, community, rules, division of labor, and outcomes,

provides a holistic framework for analyzing how learning is shaped by interactions among individuals, technologies, social structures, and historically developed practices. A distinctive theoretical contribution of CHAT lies in its capacity to move beyond an exclusive focus on the individual learner or isolated social interaction towards the activity system as the primary unit of analysis. While other sociocultural perspectives, such as social constructivism and situated learning, foreground social interaction, cultural mediation, and participation, CHAT offers a more explicit systemic account of how multiple elements of an activity system interact and how historically accumulated contradictions within these elements can generate transformation. In comparison with STEM-specific frameworks such as technological pedagogical content knowledge (TPACK), which focuses primarily on the integration of technological, pedagogical, and content knowledge, CHAT provides a broader organizational and sociocultural account of how technologies, institutional rules, communities, roles, and collective goals shape educational activity.

The theoretical value of CHAT can therefore be understood as extending beyond its use as an interpretive lens for explaining existing educational practices. However, it is important to distinguish between what is directly evidenced in the reviewed literature and what constitutes the authors' theoretical interpretation of that evidence. Across the studies included in this review, CHAT is explicitly used to examine activity systems, mediating artefacts, social and institutional relationships, contradictions, and processes of change within STEM education. These applications provide the empirical basis for viewing CHAT as a framework that can direct researchers' attention towards systemic relationships and tensions. Nevertheless, the stronger characterization of CHAT as a research-framing and problem-generating framework is not presented as a uniformly stated claim of the reviewed studies. Rather, it represents a higher-order theoretical interpretation developed through the synthesis of how CHAT concepts were applied across the evidence base.

From this synthesis, we interpret CHAT as having the potential to function not only as an explanatory or interpretive framework but also as a mechanism for framing research problems. This interpretation follows from the recurrent use of CHAT to interrogate relationships, tensions, contradictions, and structural conditions within STEM activity systems. For example, the introduction of a new digital technology may generate tensions between established rules, teachers' pedagogical practices, learners' expectations, and institutional resources. Although individual reviewed studies may identify such contradictions primarily as objects of analysis, their recurrence across the literature supports our broader interpretation that CHAT can help researchers formulate questions about the conditions

that produce, sustain, or transform educational practices. These questions may concern power relations, division of labor, institutional constraints, competing objectives, resource inequalities, and tensions between established and emerging practices. Thus, the claim that CHAT can generate research problems should be understood as an interpretive proposition emerging from the cross-study synthesis rather than as a direct empirical finding attributed uniformly to the reviewed studies.

The application of CHAT is particularly relevant to STEM education because it reflects the collaborative, interdisciplinary, technological, and problem-oriented nature of STEM learning. Integrated STEM environments require learners to engage in inquiry, engineering design, teamwork, and authentic problem-solving while using technological and scientific tools (Roehrig et al., 2021). The reviewed studies demonstrate that CHAT can be used to examine how these tools mediate learning, how collaborative practices support knowledge construction, and how interactions among components of activity systems influence educational outcomes (Batiibwe, 2019). Importantly, CHAT also directs attention to tensions and contradictions within STEM activity systems. These include disparities in access to technologies, competing curricular demands, inadequate teacher preparation, unequal participation, tensions between assessment requirements and inquiry-based learning, and mismatches between institutional expectations and classroom realities. In the reviewed literature, such contradictions are often treated not merely as problems to be eliminated but as analytically significant features of activity systems that may create opportunities for learning, innovation, and systemic transformation.

CHAT has been widely employed to investigate diverse aspects of STEM education, including technology integration, robotics, computational thinking, inquiry-based learning, engineering education, makerspaces, curriculum implementation, and teacher professional development (Hardman, 2007; Valeri et al., 2025). It has also informed research on culturally responsive STEM education by recognizing the importance of learners' cultural backgrounds, community knowledge, and indigenous knowledge systems in shaping meaningful learning experiences (Matindike & Ramdhany, 2025). This broader perspective supports efforts to promote equity, inclusivity, and contextual relevance in STEM education. Nevertheless, the literature should not be interpreted uncritically as demonstrating predominantly successful or positive applications of CHAT. A strong prevalence of positive findings may partly reflect publication practices, researchers' selection of successful interventions or innovative contexts, and the tendency of qualitative studies to foreground participants' perceived benefits and transformative experiences. Consequently,

claims about the effectiveness or transformative potential of CHAT should be considered cautiously, particularly where studies do not include negative cases, alternative explanations, longitudinal evidence, or systematic comparison with other theoretical approaches.

Methodologically, the predominance of qualitative case studies in CHAT-informed STEM research presents both strengths and limitations. Qualitative case studies are well suited to CHAT because they enable researchers to investigate activity systems holistically and attend to participants' experiences, contextual conditions, contradictions, and evolving practices. However, heavy reliance on relatively small, context-specific cases limits the transferability and generalizability of findings and may contribute to an overrepresentation of particularly innovative, accessible, or successful settings. The predominance of qualitative evidence also makes it difficult to determine the extent to which reported patterns are widespread across STEM contexts or specific to institutions, technologies, educational levels, or participant groups. Greater methodological diversification—including longitudinal research, mixed-methods designs, comparative case studies, quantitative approaches, and systematic examination of unsuccessful or contradictory outcomes—could strengthen the empirical basis of CHAT research. Such diversification would also enable researchers to examine not only how activity systems function, but whether and under what conditions CHAT-informed interventions produce sustainable changes in STEM teaching and learning.

Despite its growing adoption, the application of CHAT across STEM education remains diverse and fragmented, with variations in theoretical interpretation, methodological approaches, educational contexts, and analytical focus (Avci et al., 2025). These differences make it challenging to develop a coherent understanding of how CHAT has been utilized and what distinctive contributions it has made to STEM education research. There is a need to distinguish studies that use CHAT primarily as a descriptive or interpretive framework from those that engage more deeply with its concepts of activity systems, contradictions, expansive learning, mediation, and transformation. Importantly, the present review does not assume in advance that CHAT functions as a research-framing or problem-generating framework. Rather, it examines the reviewed evidence to determine the extent to which such a role can reasonably be inferred from the ways in which CHAT has been operationalized and applied. A systematic synthesis of the literature is therefore necessary to identify prevailing research trends, theoretical applications, methodological developments, patterns of evidence, and emerging knowledge gaps. Such a synthesis can also assess whether the literature supports a broader interpretation of CHAT as a framework capable of generating research questions by directing

attention towards systemic contradictions, structural tensions, and processes of educational transformation.

Overall, CHAT offers more than a comprehensive theoretical lens for understanding STEM education as a dynamic system of socially mediated activity. Its distinctive value lies in positioning the activity system as a unit of analysis and connecting individual learning with cultural artefacts, communities, institutional rules, divisions of labor, historically developed practices, and collective objects. The reviewed studies provide direct evidence that these concepts have been used to analyze contradictions, mediation, systemic relationships, and processes of change in diverse STEM contexts. Building on this evidence, I interpret CHAT as having the potential to serve as a research-framing and problem-generating framework, because its conceptual apparatus can direct researchers towards questions concerning contradictions, structural tensions, inequities, and possibilities for transformation. This latter characterization is therefore a synthesis-derived theoretical interpretation rather than a claim that all reviewed studies explicitly conceptualize CHAT in these terms. Making this distinction explicit avoids overstating the empirical evidence while retaining the theoretical contribution that emerges from the cross-study synthesis.

At the same time, CHAT's contribution should be assessed critically rather than inferred from the predominance of positive findings. The strong reliance on qualitative case studies provides rich contextual insight but also raises questions concerning transferability, methodological diversity, representativeness, and the robustness of claims about transformation. A more critically reflexive and methodologically diverse application of CHAT, including longitudinal, comparative, mixed-methods, quantitative, and negative-case research, would provide stronger evidence for determining when and under what conditions CHAT contributes to meaningful changes in STEM teaching and learning. As STEM education continues to evolve in response to technological advances and global educational priorities, such an approach can strengthen the empirical and theoretical basis for understanding CHAT's contribution to research, curriculum development, teacher education, and policy.

Research Problem

Despite the rapid global expansion of integrated STEM education, there remains a limited and fragmented theoretical understanding of how learning processes in STEM contexts are systematically conceptualised and analyzed. Much of the existing STEM education research continues to rely on approaches that insufficiently capture the socially mediated, culturally situated, and activity-based nature

of learning in complex, real-world educational environments (Sedebo et al., 2025). Although CHAT has increasingly been adopted as a theoretical lens to examine STEM education practices, particularly in areas such as technology integration, robotics, computational thinking, inquiry-based learning, engineering design, and teacher professional development, its application remains inconsistent and conceptually diverse (Veresov, 2025). Studies vary widely in how CHAT is interpreted, operationalized, and used as an analytical framework, leading to a lack of coherence in the field (Cong-Lem, 2022). In addition, there is no comprehensive synthesis that systematically maps how CHAT has been employed in STEM education research, the contexts in which it has been applied, the methodological approaches used, the nature of activity systems examined, and the types of contradictions and learning outcomes identified. As a result, there is limited consolidated evidence on the contributions of CHAT to advancing STEM education theory, practice, and policy. This fragmentation constrains the ability of researchers, curriculum developers, and teacher educators to fully leverage CHAT for designing transformative, equitable, and contextually responsive STEM learning environments. Therefore, the central research problem addressed in this study is the absence of a systematic, comprehensive synthesis of how CHAT has been utilized as a theoretical lens in STEM education research, and the lack of clarity regarding its conceptual applications, methodological trends, contextual relevance, and emerging research gaps across the field.

Rationale for Conducting the Systematic Review

The rapid expansion of integrated STEM education has intensified the demand for robust theoretical frameworks capable of explaining learning as a complex, socially mediated, and contextually embedded process. While STEM education is widely recognized as essential for developing 21st century competencies such as critical thinking, collaboration, creativity, and problem-solving, its implementation continues to be challenged by the difficulty of integrating multiple disciplines and accounting for the dynamic interactions among learners, educators, technologies, and institutional environments (Herlinawati et al., 2024). CHAT offers a promising socio-cultural lens for addressing these challenges by conceptualizing learning as participation in collective activity systems mediated by tools, language, community, rules, and division of labor (Engeström, 1987). Its emphasis on systemic interactions and contradictions makes it particularly well suited for analyzing the complexity of STEM education settings, where interdisciplinary collaboration, inquiry-based learning, engineering design, and technology integration are central. Over time, CHAT has been increasingly applied across diverse STEM education contexts, including robotics, computational thinking,

makerspaces, curriculum reform, teacher professional development, and culturally responsive pedagogies (Nedungadi et al., 2026).

However, despite this growing body of research, the application of CHAT in STEM education remains uneven and conceptually fragmented. Studies differ significantly in how CHAT is interpreted, operationalized, and applied as an analytical framework (Debets et al., 2025). There is also wide variation in methodological approaches, levels of analysis (individual, group, or system), and the ways in which contradictions and outcomes are conceptualised (Pandey et al., 2026). As a result, the literature lacks coherence, making it difficult to develop a consolidated understanding of how CHAT contributes to STEM education research and practice. Furthermore, no comprehensive systematic review currently exists that synthesizes how CHAT has been utilized across STEM education studies in terms of its theoretical applications, methodological trends, educational contexts, and reported findings (Abdullahi et al., 2026). This absence of synthesis limits the ability of researchers and practitioners to identify patterns of use, evaluate the strengths and limitations of CHAT-based research, and determine how the theory is advancing or constraining STEM education scholarship.

Conducting a systematic review is therefore necessary to consolidate dispersed evidence, map the evolution of CHAT-informed STEM education research, and critically examine its conceptual and methodological diversity. Such a synthesis will not only clarify how CHAT has been applied but will also identify gaps, inconsistencies, and emerging trends that can guide future research. Ultimately, this review will contribute to strengthening the theoretical foundations of STEM education while providing practical and policy-relevant insights for improving teaching, learning, curriculum design, and educational innovation in complex STEM learning environments.

METHODOLOGY

Research Design

This study adopts a systematic literature review design guided by the preferred reporting items for systematic reviews and meta-analyses (PRISMA) framework. The PRISMA framework is utilized to ensure a transparent, replicable, and methodologically rigorous process for the identification, screening, eligibility assessment, and inclusion of relevant literature. In this study, the review specifically focuses on scholarly works that engage CHAT as either a conceptual or analytical framework within STEM education contexts. Both empirical and theoretical studies are included, provided they explicitly apply CHAT to teaching and learning processes in STEM-

related disciplines. Through this structured approach, the study systematically synthesizes existing knowledge on the application of CHAT in STEM education, thereby enabling a comprehensive and critically informed understanding of its pedagogical and analytical contributions.

Review Protocol and Framework

The review was conducted in accordance with the four key phases of the PRISMA 2020 framework, namely identification, screening, eligibility, and inclusion. Prior to the commencement of the search process, a structured review protocol was developed to guide all stages of the review. This protocol clearly outlined the search strategy, inclusion and exclusion criteria, as well as the procedures for data extraction and synthesis. By adhering to a predefined protocol, the study ensured systematic consistency in the selection of relevant literature and enhanced methodological transparency. Furthermore, the use of a structured protocol contributed to minimizing selection bias and strengthened the overall rigor and trustworthiness of the review process.

Data Sources and Search Strategy

A comprehensive and systematic search strategy was employed to ensure extensive coverage of relevant literature across multiple electronic databases. The databases searched included Scopus, Web of Science, ERIC, Google Scholar, ScienceDirect, SpringerLink, and JSTOR. These databases were selected due to their broad indexing of high-quality scholarly outputs in education, science, and interdisciplinary research fields. The search process utilized a combination of Boolean operators and carefully selected keywords to capture studies relevant to CHAT in STEM education. Key search terms included "Cultural-Historical Activity Theory" OR "CHAT," "Activity Theory" AND STEM, "Engeström" AND STEM education, "Vygotsky" AND STEM learning, "socio-cultural theory" AND STEM, as well as "activity systems" combined with science education, engineering education, technology education, or mathematics education. To ensure methodological consistency and scholarly rigor, the search was limited to peer-reviewed journal articles, book chapters, and conference proceedings published in English. No geographical restrictions were imposed, thereby allowing for a globally inclusive representation of research on the application of CHAT within STEM education contexts.

Inclusion and Exclusion Criteria

Clear inclusion and exclusion criteria were established to guide the selection of studies and ensure methodological rigor and consistency throughout the review process. Studies were included if they explicitly employed CHAT or activity theory as a theoretical or

analytical framework. Furthermore, eligible studies were required to focus on STEM education contexts, encompassing science, technology, engineering, mathematics, or integrated STEM disciplines. Both empirical and conceptual or theoretical studies were considered, provided they were published in peer-reviewed sources and written in English. Conversely, studies were excluded if CHAT was not explicitly applied as a guiding framework, or if it was only superficially referenced without substantive analytical use. Additional exclusion criteria included studies situated outside STEM-related disciplines, as well as non-scholarly output such as editorials, opinion pieces, and other informal reports. Studies lacking sufficient methodological or analytical detail were also excluded to maintain the quality and integrity of the synthesis. Finally, duplicate records identified across multiple databases were removed to ensure accuracy and avoid redundancy in the final dataset.

Study Selection Process (PRISMA Flow Diagram)

The study selection process was guided by the PRISMA 2020 flow framework to ensure transparency, rigor, and reproducibility in the systematic review process. In the identification phase, all records retrieved through comprehensive database searches were exported into a reference management system such as Zotero or Mendeley. Duplicate records were systematically identified and removed to ensure that only unique studies progressed to the next stage. During the screening phase, the remaining records were subjected to an initial review of titles and abstracts. Each record was evaluated against predefined inclusion criteria to determine its relevance to the focus of the study. Records that did not meet the inclusion criteria were excluded at this stage. In the eligibility phase, full-text articles were retrieved and assessed in detail against the established inclusion and exclusion criteria. This ensured that only methodologically sound and contextually relevant studies were retained for further consideration. Finally, in the inclusion phase, studies that satisfied all eligibility criteria were included in the final systematic synthesis and formed the evidence base for analysis and interpretation. The entire study selection process is visually summarized in [Figure 1](#), which presents the PRISMA flow diagram detailing the number of records identified, screened, excluded, and included at each stage of the review process.

Double Screening

To enhance the methodological rigor, transparency, and reliability of the systematic review, a double-screening procedure was employed throughout the study-selection process. Following the removal of duplicate records, two reviewers independently screened the titles and abstracts of all retrieved records against the predefined inclusion and exclusion criteria.

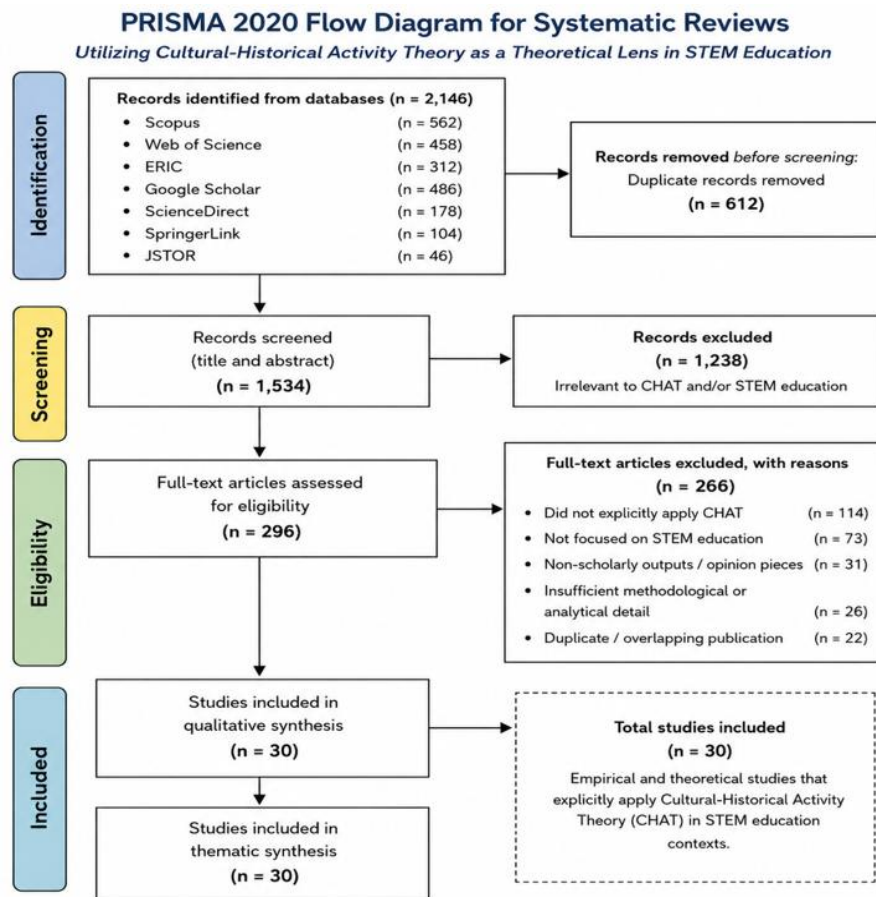


Figure 1. PRISMA flow diagram (adapted from Page et al., 2021)

Records considered potentially relevant by either reviewer were retained for full-text assessment. The same two reviewers then independently evaluated the full texts to determine final eligibility. Disagreements at either screening stage were resolved through discussion and consensus; whereas consensus could not be reached, a third reviewer was consulted to make the final determination. This process was undertaken to minimize selection bias and reduce the possibility of relevant studies being inadvertently excluded.

Data Extraction Procedure

A structured data-extraction form was developed and pilot-tested before the formal extraction process to ensure a consistent, systematic, and transparent approach to capturing relevant information from each included study. The form comprised key bibliographic, methodological, and conceptual fields, including author(s) and year of publication; country and educational context; level of education (primary, secondary, tertiary, or teacher education); STEM discipline; research design and methodology; participants and sample size; data-collection and analytical methods; and the stated purpose of the study. Particular attention was given to the theoretical framing and application of CHAT, including the conceptualization of CHAT and the specific CHAT

model employed in each study. Where reported, data were also extracted on the principal components of the activity system, namely the subject, object, mediating tools, rules, community, division of labor, and outcomes. Key findings, including reported contradictions within or between activity-system components, were documented, together with the implications of each study for STEM teaching and learning. These fields facilitated a more nuanced examination of how CHAT was applied across diverse STEM education contexts. Two reviewers independently extracted data from all studies that met the inclusion criteria. Following independent extraction, the reviewers compared their records to assess consistency and identify discrepancies. Any discrepancies were resolved through discussion and reference to the original publication. Where consensus could not be reached, a third reviewer was consulted to adjudicate. This process helped minimize extraction errors and strengthened the reliability of the final dataset. All verified extraction data were systematically organized using spreadsheet software to facilitate comparison, thematic analysis, and synthesis across the included studies. The combination of a standardized and pilot-tested extraction instrument, independent duplicate extraction, and consensus-based resolution of discrepancies enhanced the reliability, transparency, reproducibility, and analytical coherence of the review process.

Methodological Quality Appraisal and Risk of Bias

To enhance the credibility, dependability, and overall trustworthiness of the evidence base, a systematic methodological quality appraisal was undertaken for all included studies. Given the methodological diversity of research applying CHAT in STEM education, appraisal was guided by established critical evaluation frameworks appropriate to the design of each study. For qualitative studies, the critical appraisal skills program checklist was used to assess key dimensions of methodological rigor, including clarity of the research aims, appropriateness of the methodology and research design, adequacy of data-collection procedures, ethical considerations, analytical rigor, and the credibility and robustness of the findings. For mixed-methods studies, the mixed methods appraisal tool was employed to evaluate the quality of the respective qualitative and quantitative components, as well as the appropriateness and extent of integration between the methodological strands. Where appropriate, the Joanna Briggs Institute critical appraisal tools were also used to provide design-specific assessment of methodological quality.

In addition to these design-specific criteria, the appraisal considered broader dimensions of methodological quality and potential risk of bias, including the clarity of research objectives, appropriateness and coherence of the research design, adequacy of the sampling strategy, transparency of data-collection procedures, appropriateness of data analysis, support for the reported findings, consideration of study limitations, and alignment among the research questions, methodology, analysis, and conclusions. This comprehensive approach enabled the reviewers to assess both methodological rigor and the credibility of the evidence generated across diverse STEM education contexts.

Two reviewers independently appraised each included study using the appropriate quality appraisal instrument. Their assessments were subsequently compared, and any discrepancies were resolved through discussion and consensus. Where agreement could not be reached, a third reviewer was consulted to adjudicate. This independent double-appraisal procedure reduced the potential for individual reviewer bias and enhanced the consistency and reliability of the quality assessment. Methodological quality was not used as an automatic basis for excluding studies that otherwise satisfied the eligibility criteria. Instead, appraisal results were explicitly incorporated into the subsequent evidence synthesis and interpretation. The quality assessments were considered when comparing findings across studies, identifying patterns and areas of convergence or divergence, and determining the strength and reliability of the evidence underpinning the review's conclusions. Studies demonstrating stronger methodological rigor were given greater interpretive weight when drawing

conclusions, whereas findings from studies with identified methodological limitations were treated more cautiously and were not considered equivalent in evidential strength to findings supported by more rigorous designs. Where recurring findings were derived predominantly from studies with methodological limitations, these findings were interpreted as indicative rather than definitive and were used to identify areas requiring further empirical investigation.

The appraisal findings also informed the identification of methodological gaps within the CHAT-in-STEM literature. Limitations relating to study design, sampling, data collection, analytical procedures, and the predominance of qualitative case-based research were considered when evaluating the consistency and transferability of reported outcomes. Consequently, conclusions regarding the effectiveness, applicability, and broader educational implications of CHAT were framed in relation to the quality and methodological characteristics of the underlying evidence rather than solely on the frequency of reported positive findings. This ensured that the synthesis distinguished between well-supported conclusions and findings for which the available evidence remained limited or methodologically constrained.

Overall, the systematic application of design-appropriate appraisal tools, independent double appraisal, consensus-based resolution of discrepancies, and third-reviewer adjudication where necessary strengthened the transparency, methodological rigor, and credibility of the systematic review. More importantly, integrating appraisal outcomes into the synthesis and interpretation ensured that methodological quality directly informed the evidential weight assigned to individual findings and the degree of confidence placed in the review's conclusions, while allowing relevant empirical contributions to remain within the evidence base.

Data Analysis and Synthesis

A thematic synthesis approach was employed to analyze the extracted data, enabling a structured yet interpretive integration of findings across the included studies. The synthesis combined descriptive, thematic, and theoretical analytical layers to ensure both breadth and depth while maintaining a clear distinction between insights directly supported by the reviewed studies and higher-order interpretations developed by the authors.

Firstly, a descriptive analysis was conducted to provide an overview of the studies included. This involved quantitative mapping of publication trends, geographical distribution, educational levels, and methodological approaches. This stage offered a contextualized understanding of the scope and characteristics of the existing body of literature and

established the empirical basis for subsequent thematic and theoretical interpretation.

Secondly, a thematic analysis was undertaken to identify recurring patterns and conceptual categories across the dataset. The analysis focused on several key dimensions, including applications of CHAT in STEM education; the types of activity systems examined; mediating artefacts and tools such as technology, robotics, and digital learning platforms; and the nature of contradictions identified within activity systems, including primary, secondary, tertiary, and quaternary contradictions. Pedagogical implications and reported learning outcomes were also systematically examined to capture the educational significance of the findings. At this stage, the synthesis remained grounded in concepts, relationships, and interpretations explicitly reported or evidenced in the reviewed studies.

Finally, a theoretical synthesis was conducted to integrate the emergent themes into a coherent conceptual understanding of how CHAT has been applied to interpret STEM learning processes. The identification of activity systems, mediating tools, contradictions, and their relationships was grounded in the empirical and conceptual accounts provided by the reviewed studies. However, the characterization of CHAT as extending beyond an interpretive lens to function as a research-framing and problem-generating framework represents the authors' higher-order theoretical interpretation of the synthesized evidence rather than a claim that all reviewed studies explicitly characterized CHAT in these terms. This distinction is important because the reviewed literature primarily demonstrates how CHAT was used to frame research contexts, analyze systemic relationships, and identify contradictions and tensions within STEM activity systems, while the broader conceptualization of CHAT as a framework for generating research problems emerged through the authors' synthesis across these applications.

Accordingly, the theoretical synthesis involved two related but analytically distinct processes: first, identifying theoretical and methodological uses of

CHAT that were explicitly evident in the reviewed studies; and second, developing higher-order interpretations from the convergence of these findings. The latter included the interpretation that CHAT can serve not only as an explanatory or interpretive lens but also as a framework for framing research problems by directing attention towards activity-system structures, mediating relations, contradictions, and possibilities for transformation. This interpretation is therefore presented as a synthesis-derived theoretical proposition rather than as a uniformly stated position of the studies included in the review.

This layered approach ensured that the synthesis remained empirically grounded while also allowing theoretically meaningful insights to emerge from cross-study comparison. It is consequently distinguished between what the reviewed studies explicitly reported, patterns identified across the evidence base, and the authors' theoretical interpretation of those patterns, thereby strengthening the transparency and credibility of the synthesis.

Ethical Considerations

As this study involved secondary analysis of published literature, no human participants were directly engaged in the research process. Consequently, ethical clearance relating to human subject participation was not required. Nevertheless, strict adherence to ethical scholarly practice was maintained throughout the study. This included ensuring accurate and consistent citation of all sources, maintaining fidelity to the original meaning of the included studies, and avoiding any form of misrepresentation or selective distortion of findings. In addition, the review was conducted in accordance with established academic integrity standards, ensuring transparency, honesty, and responsibility in the synthesis and reporting of evidence.

RESULTS: CHARACTERISTICS OF THE INCLUDED STUDIES

Table 1 presents a summary of the characteristics of the 30 studies included in this systematic review.

Table 1. Summary of Included Studies on CHAT in STEM education

No	Study	Level of education	STEM focus	Research design	CHAT conceptualization	Activity system focus	Mediating tools	Key contradictions identified	Key findings/outcomes
1	Lichtenberger et al. (2025)	Secondary	Physics	Qualitative case study	Engeström model	Classroom learning system	Simulation	Subject-rules contradiction	Improved conceptual understanding
2	Mahlo and Waghid (2025)	Teacher education	STEM integration	Mixed methods	Activity systems analysis	Teacher professional learning	Digital tool	Tool-object tension	Enhanced TPACK integration
3	Varela et al. (2022)	Tertiary	Engineering	Ethnography	CHAT expanded model	Engineering design system	CAD software	Division of labor conflict	Improved collaborative design
4	Zidny et al. (2021)	Secondary	Chemistry	Qualitative	Engeström triangle	Laboratory learning system	Indigenous tool	Rules-community contradiction	Contextualized learning improved

Table 1 (Continued).

No	Study	Level of education	STEM focus	Research design	CHAT conceptualization	Activity system focus	Mediating tools	Key contradictions identified	Key findings/outcomes
5	Maboya et al. (2020)	Primary	Mathematics	Case study	Activity theory lens	Classroom activity system	Manipulative	Subject-object misalignment	Improved engagement
6	Yeung et al. (2026)	Secondary	Robotics	Design-based research	CHAT framework	Robotics learning system	Robotics kits	Tool mediation gap	Enhanced problem-solving
7	Huang et al. (2022)	Teacher education	STEM pedagogy	Mixed methods	Engeström model	Professional learning system	LMS platforms	Community-rules tension	Improved pedagogical design
8	Smith (2026)	Tertiary	Engineering	Qualitative	Activity theory	Studio learning system	Digital modelling tools	Division of labor issues	Better teamwork outcomes
9	Yang et al. (2025)	Secondary	ICT/STEM	Quasi-experimental	CHAT-informed framework	Classroom system	Tablets	Object contradiction	Increased achievement
10	Pozuelo-Muñoz et al. (2025)	Secondary	Science	Ethnography	Activity system model	Inquiry-based system	Lab instruments	Rules contradiction	Improved inquiry skills
11	Pangestu et al. (2025)	Teacher education	STEM integration	Qualitative	CHAT lens	Teacher learning system	Simulation tools	Tool-subject mismatch	Improved TPACK
12	Shambare and Simuja (2024)	Secondary	Physics	Mixed methods	Engeström model	Classroom system	Virtual labs	Secondary contradictions	Improved conceptual change
13	Berselli et al. (2020)	Tertiary	Engineering	Case study	Activity theory	Project-based system	CAD tools	Division of labor	Stronger collaboration
14	Tytler et al. (2023)	Secondary	STEM integration	Qualitative	CHAT framework	Integrated STEM system	Digital platforms	Object contradictions	Improved engagement
15	Liu et al. (2024)	Teacher education	STEM pedagogy	Survey + qualitative	Activity theory	Professional learning system	Online tools	Rules-community	Enhanced collaboration
16	Iyamuremyem et al. (2022)	Secondary	Computer science	DBR	CHAT lens	Coding learning system	Scratch platform	Tool mediation	Improved computational thinking
17	Saucedo Gonzales et al. (2025)	Primary	STEM literacy	Qualitative	Engeström model	Classroom system	Games-based tools	Subject-object tension	Improved motivation
18	Mutende (2025)	Secondary	Science	Case study	CHAT framework	Classroom system	PhET simulations	Rules contradiction	Improved conceptual understanding
19	Erichsen et al. (2019)	Tertiary	Engineering	Qualitative	Activity theory	Design studio	Prototyping tools	Division of labor	Innovation improved
20	Li et al. (2025)	Teacher education	STEM integration	Mixed methods	CHAT lens	Professional system	LMS tools	Community contradictions	Improved teacher collaboration
21	Hillmayr et al. (2020)	Secondary	Mathematics	Qualitative	Activity systems model	Classroom system	Digital tools	Object contradiction	Higher achievement
22	Xu and Ouyang (2025)	Secondary	Robotics	DBR	CHAT framework	Robotics system	Robotics kits	Tool mediation gap	Enhanced engagement
23	Pullenayegem et al. (2021)	Secondary	Physics	Case study	Engeström model	Inquiry system	Virtual labs	Rules-object tension	Improved inquiry learning
24	Stevenson et al. (2026)	Teacher education	STEM pedagogy	Mixed methods	Activity theory	Professional learning	Online platforms	Community-rules	Better integration
25	Photo and McKnight (2024)	Secondary	STEM integration	Qualitative	CHAT lens	Classroom system	Indigenous tools	Cultural contradictions	Contextualized STEM improved
26	Soomro et al. (2023)	Secondary	Engineering	DBR	Activity theory	Design learning system	Makerspaces	Division of labor	Creativity enhanced
27	Vasconcelos and dos Santos (2023)	Tertiary	ICT/STEM	Case study	CHAT model	Learning ecosystem	Digital platforms	Tool-object contradictions	Improved learning outcomes
28	Morselli and Sannino (2021)	Secondary	Science	Qualitative	Engeström framework	Classroom system	Simulations	Rules contradiction	Conceptual gains
29	Avci et al. (2025)	Teacher education	STEM integration	Mixed methods	CHAT lens	Professional system	AI tools	Community tensions	Improved instructional design
30	Qamila et al. (2026)	Secondary /tertiary	STEM integration	Systematic study	Activity theory synthesis	Multi-activity systems	Digital ecosystems	Multi-level contradictions	Systemic transformation observed

The studies demonstrate considerable diversity in educational contexts, STEM disciplines, research methodologies, and applications of CHAT, reflecting the increasing adoption of CHAT as a theoretical and

analytical framework for understanding complex teaching and learning processes in STEM education.

With respect to the level of education, most of the studies ($n = 15$; 50%) were conducted in secondary school settings, indicating that CHAT has been most frequently applied to investigate STEM teaching and learning within compulsory education. Teacher education constituted the second largest category ($n = 7$; 23.3%), highlighting the importance of CHAT in examining teacher professional learning, pedagogical development, and instructional practices. Tertiary education accounted for five studies (16.7%), while only two studies (6.7%) focused on primary education. One study (3.3%) spans both secondary and tertiary education contexts, illustrating the applicability of CHAT across multiple educational levels.

Regarding STEM discipline focus, the reviewed studies covered a broad range of disciplinary and interdisciplinary contexts. Integrated STEM education emerged as the most common focus ($n = 8$), followed by engineering education ($n = 5$), science education ($n = 3$), physics ($n = 3$), robotics ($n = 2$), mathematics ($n = 2$), STEM pedagogy ($n = 3$), and ICT/computer science ($n = 3$). Other specialized areas included chemistry and STEM literacy. This diversity demonstrates the versatility of CHAT for investigating learning processes across different STEM domains while supporting interdisciplinary approaches to teaching and learning.

The research designs employed across the studies were predominantly qualitative. Qualitative case studies and qualitative research designs together represented the largest methodological category, complemented by ethnographic investigations and activity-based case analyses. Several studies adopted mixed-methods approaches to integrate qualitative and quantitative evidence, while design-based research featured prominently in studies involving robotics, computational thinking, and engineering design. A smaller number of studies employed quasi-experimental designs, surveys combined with qualitative methods, or systematic synthesis approaches. Collectively, these findings indicate a strong preference for methodologies capable of capturing the complexity and contextual nature of activity systems.

Analysis of CHAT conceptualization revealed that Engeström's (1987) expanded activity system model was the dominant theoretical framework across the reviewed studies. Variations included the Engeström (1987) triangle, activity theory, CHAT frameworks, activity systems analysis, and broader CHAT-informed analytical models. Despite differences in terminology, virtually all studies conceptualised learning as participation within socially mediated activity systems involving interactions among subjects, objects, mediating artefacts, communities, rules, and divisions of labor. This finding confirms the central role of

Engeström's (1987) third-generation CHAT in contemporary STEM education research.

The activity systems examined reflected the diversity of STEM learning environments. Most studies focused on classroom learning systems, while others investigated teacher professional learning systems, engineering design systems, robotics learning environments, project-based learning systems, coding environments, laboratory learning systems, learning ecosystems, and multi-activity systems. These findings demonstrate that CHAT has been successfully applied across a wide range of educational settings, from formal classrooms to collaborative design studios and technology-enhanced learning environments.

Through the reviewed studies, mediating artefacts played a central role in shaping teaching and learning processes. Frequently reported tools included digital learning platforms, virtual laboratories, computer simulations, robotics kits, Scratch programming environments, computer-aided design (CAD) software, learning management systems (LMS), AI-supported instructional tools, PhET simulations, prototyping technologies, and Indigenous knowledge-based resources. The widespread use of technological and cultural mediating tools underscores the importance of artefact-mediated learning within CHAT-informed STEM education.

A recurring finding across the studies was the identification of systemic contradictions within educational activity systems. The most frequently reported tensions involved subject-object, subject-rules, rules-community, tool-object, tool-subject, and division of labor contradictions. Several studies also reported secondary, cultural, and multi-level contradictions, illustrating the complexity of interactions among components of the activity system. Rather than being viewed as obstacles, these contradictions were consistently interpreted as drivers of reflection, organizational learning, pedagogical innovation, and educational transformation.

The educational outcomes reported across the reviewed studies were overwhelmingly positive. The application of CHAT contributed to improved conceptual understanding, higher learner engagement, enhanced inquiry skills, increased academic achievement, stronger computational thinking, improved problem-solving abilities, greater collaboration, enhanced TPACK, more effective instructional design, increased creativity, and more contextually relevant STEM learning experiences. Several studies further demonstrated that resolving contradictions within activity systems facilitated sustainable pedagogical change and supported more equitable, collaborative, and learner-centered STEM education.

Overall, the findings indicate that CHAT has become an increasingly influential theoretical lens for understanding the complexity of STEM education. By conceptualizing learning as a socially situated and culturally mediated activity, CHAT provides researchers and practitioners with a comprehensive framework for analyzing interactions among learners, teachers, technologies, institutional structures, and educational practices. The collective evidence suggests that CHAT offers significant theoretical and practical value for advancing innovative, contextually responsive, and transformative STEM teaching and learning across diverse educational settings.

Critical Theoretical Synthesis

Across the 30 studies, the evidence does not simply demonstrate a consistent positive contribution of CHAT to STEM education; rather, it reveals a complex and contingent relationship between activity-system structures, mediating artefacts, contradictions, educational levels, research methodologies, and learning outcomes. CHAT is most analytically valuable when it is used not merely to describe the components of STEM learning environments, but to explain how historically developed relations among subjects, objects, tools, rules, communities, and divisions of labor create both opportunities and constraints for transformation. The synthesis identifies four interconnected theoretical concerns: contradictions as historically situated mechanisms of transformation; mediation as a relational rather than inherently beneficial process; educational outcomes as contingent and uneven; and STEM transformation as a multi-level reconfiguration of interacting activity systems. However, the evidence base also exposes important limitations concerning educational-level coverage, methodological diversity, and the tendency toward optimistic reporting, which constrain the explanatory reach of current CHAT scholarship.

A particularly important finding is the uneven distribution of research across educational levels. Half of the reviewed studies (50%) focus on secondary education, whereas only 6.7% address primary education. This concentration raises an important theoretical question about the visibility and applicability of CHAT during the early stages of STEM learning. The limited representation of primary education means that current scholarship provides insufficient evidence about how activity systems develop during the formative years of learners' STEM participation and how contradictions encountered at primary level may subsequently shape learning trajectories in secondary and tertiary education. From a CHAT perspective, this is significant because activity systems are historically constituted and continuously transformed; therefore, studying STEM learning predominantly at one educational stage risks treating activity systems as relatively static rather than

examining how subjects, tools, rules, and divisions of labor evolve over time. The underrepresentation of primary education consequently limits understanding of longitudinal STEM learning trajectories, including how early experiences with inquiry, technology, collaboration, and disciplinary practices may establish or constrain later forms of STEM engagement. Future research should therefore examine CHAT across educational transitions rather than treating primary, secondary, and tertiary contexts as analytically disconnected sites.

A central theoretical insight concerns the role of contradictions as generative mechanisms rather than simply recurring problems. Across the studies, tensions occur between and within activity-system components, including subject-object misalignments (Hillmayr et al., 2020; Maboya et al., 2020), rules-community tensions (Liu et al., 2024; Stevenson et al., 2026), and divisions of labor in collaborative and design-oriented environments (Berselli et al., 2020; Erichsen et al., 2019; Soomro et al., 2023). Tool-mediated contradictions are particularly visible in robotics- and ICT-rich settings, where technological artefacts may not align with pedagogical purposes, teacher competence, learner readiness, or institutional expectations (Xu & Ouyang, 2025; Yeung et al., 2026). From a CHAT perspective, these tensions should not be interpreted simply as isolated implementation deficiencies. They represent manifestations of historically accumulated and structurally embedded relationships within activity systems.

Nevertheless, an important limitation of the reviewed literature is that contradictions are frequently identified rather than theoretically traced. Many studies document the existence of tensions but provide limited longitudinal evidence of how contradictions emerge, intensify, are negotiated, or become transformed through expansive learning cycles. Identifying a contradiction between, for example, rules and community is theoretically less consequential than demonstrating how participants question existing practices, analyze the contradiction, construct alternative models, implement new forms of activity, and subsequently consolidate or revise those models. The synthesis therefore indicates a need to move from a descriptive identification of contradictions towards process-oriented theorization of contradiction development and resolution. Future studies should explicitly trace the movement from questioning and analysis through modelling, implementation, reflection, and consolidation, thereby providing stronger empirical evidence for claims about expansive learning. Such an approach would enable CHAT research to explain not only *where* tensions occur but *how and under what conditions* they become transformative.

The synthesis further challenges the assumption that mediating tools are inherently transformative. Digital

simulations, virtual laboratories, robotics kits, CAD/CAE environments, AI-enabled platforms, learning-management systems, and indigenous knowledge artefacts mediate relationships between learners, teachers, and STEM objects of learning. Studies such as Shambare and Simuja (2024) and Mutende (2025) associate simulation-based environments with enhanced conceptual engagement, while Yeung et al. (2026) and Xu and Ouyang (2025) identify contributions of robotics to problem-solving and computational thinking. Similarly, digital platforms in teacher education can support collaboration and technological pedagogical knowledge development (Huang et al., 2022; Pangestu et al., 2025). However, viewed through CHAT, these findings should not be reduced to a technology-effects narrative. The educational significance of an artefact emerges through its relationship with the object of activity, subjects' competencies, institutional rules, community expectations, and divisions of labor. Thus, the same technological tool may expand one activity system while constraining another. The more theoretically productive question is therefore not simply whether a technology "works", but how, for whom, under what conditions, and in relation to which activity-system object it becomes consequential.

The reported positive outcomes also require a more critical interpretation because the review reveals evidence of optimistic reporting. Although numerous studies identify improvements in conceptual understanding, inquiry, engagement, creativity, computational thinking, pedagogical design, STEM integration, and professional collaboration (Avci et al., 2025; Li et al., 2025; Lichtenberger et al., 2025; Mahlo & Waghid, 2025; Pullenayegem et al., 2021; Soomro et al., 2023), relatively limited attention is given to unintended consequences, failed implementations, resistance, sustainability problems, resource constraints, or outcomes that remain unchanged despite intervention. This creates a potential asymmetry in the evidence base in which successful transformations are more visible than unsuccessful or incomplete ones. Such reporting may inadvertently reinforce the assumption that CHAT-informed interventions are inherently productive.

A more critical reading suggests that failure and non-transformation are theoretically important outcomes rather than methodological inconveniences. Where pedagogical intentions, technological tools, teacher capabilities, institutional rules, and learner needs remain poorly aligned, innovative interventions may reproduce existing contradictions rather than resolve them. Teachers may resist new divisions of labor, learners may appropriate tools in unintended ways, institutional rules may constrain experimentation, or resource inequalities may prevent the consolidation of newly modelled practices. These possibilities should form part of the CHAT analysis rather than being treated as peripheral implementation issues. Consequently, future studies

should deliberately report negative cases, unintended consequences, resistance, abandoned innovations, and failed expansive-learning attempts. Such evidence would provide a more balanced account of the conditions under which activity-system transformation succeeds, stalls, or reverses.

The methodological profile of the literature introduces a further limitation. The predominance of qualitative case studies provides rich contextual accounts of activity systems but limits the capacity of the field to establish the durability, generalizability, and temporal consequences of identified transformations. Qualitative studies are particularly valuable for revealing contradictions and participants' interpretations; however, they are less suited to determining whether observed changes persist over extended periods or whether similar patterns occur across larger and more diverse populations. The evidence base would therefore benefit from longitudinal and large-scale mixed-methods research that combines the explanatory depth of qualitative CHAT analysis with quantitative evidence of changes in learning, teaching, participation, or professional practice. Longitudinal studies could trace how activity systems evolve across educational transitions, while large-scale mixed-methods studies could test whether patterns identified in individual cases are observable across schools, districts, disciplines, and educational levels. Such designs would also strengthen the field's ability to distinguish between short-term intervention effects and sustained activity-system transformation.

The multi-level and interconnected nature of STEM activity systems constitute another important theoretical insight. The reviewed studies extend beyond conventional classroom activity systems to teacher education programs, professional learning communities, engineering studios, makerspaces, design environments, and digitally mediated learning spaces. This expansion strengthens CHAT's explanatory potential but simultaneously exposes a theoretical challenge: contemporary STEM education involves interacting and partially overlapping activity systems rather than bounded systems with clearly identifiable subjects and objects. The more recent studies, including Mahlo and Waghid (2025), suggest that contradictions may span institutional, technological, pedagogical, and disciplinary boundaries. Transformation therefore cannot always be adequately explained through a single activity triangle. A more sophisticated interpretation requires attention to networked and historically interconnected activity systems, particularly where teachers, learners, institutions, technologies, communities, and external stakeholders pursue partially aligned or competing objects.

Taken together, the 30 studies position CHAT less as a framework for categorizing STEM education practices and more as a critical explanatory and transformative

Table 2. Aggregated patterns across studies

Dimension	Dominant pattern
Education level	Majority secondary education contexts
Dominant CHAT model	Engeström's (1987) six-component activity system
Most used methodology	Qualitative case studies
Most analyzed tools	Digital simulations, robotics, LMS platforms
Most frequent contradiction	Tool-object and rules-community contradictions
Key outcome trend	Improved engagement, collaboration, conceptual understanding

lens, while simultaneously revealing important limitations in its current empirical application. Its distinctive contribution lies in making visible the historically and socially mediated relations through which STEM practices are reproduced, contested, and potentially transformed. However, the review demonstrates that the field needs to move beyond predominantly secondary-school, qualitative, and positively framed accounts towards a more developmentally comprehensive, methodologically diverse, and theoretically process-oriented evidence base.

Accordingly, four research priorities emerge. First, primary education and educational transitions require substantially greater attention to establish how STEM activity systems develop across learners' trajectories. Second, longitudinal and large-scale mixed-methods designs are needed to examine the durability and broader applicability of reported transformations. Third, researchers should systematically document failures, unintended consequences, resistance, and implementation barriers to counterbalance optimistic reporting. Fourth, future CHAT research should trace the evolution of contradictions through expansive learning cycles, rather than merely identifying tensions within activity-system components. These directions would strengthen the theoretical explanatory power of CHAT by connecting activity-system configurations with processes of change over time.

Overall, the evidence suggests that meaningful STEM transformation cannot be reduced to the introduction of innovative technologies, pedagogies, or interventions. Rather, transformation involves the historically situated and collectively negotiated reconfiguration of activity systems, including their objects, mediating tools, rules, communities, and divisions of labor. The critical contribution of CHAT therefore lies not in demonstrating that interventions produce positive outcomes, but in explaining why transformation occurs in some activity systems, why it fails or remains partial in others, and how contradictions are transformed—or remain unresolved—over time. This more critical interpretation strengthens the theoretical contribution of the review and positions CHAT as a framework for interrogating both the possibilities and the limits of STEM educational transformation.

Aggregated Patterns Across Studies

As illustrated in **Table 2**, the aggregated analysis of the 30 reviewed studies reveals several consistent macro-level patterns characterizing the application of CHAT in STEM education research. These patterns reflect recurring methodological preferences, theoretical orientations, and dominant pedagogical trends across diverse educational contexts. A first key observation in **Table 2** is that secondary education contexts dominate the reviewed literature, indicating that CHAT-informed STEM research is most frequently situated within school-based teaching and learning environments. This emphasis highlights a strong focus on foundational STEM concept development, particularly within science, mathematics, and technology classrooms. Secondly, the figure shows that Engeström's (1987) six-component activity system model is the most widely used CHAT framework. Across the studies, this model is consistently applied to examine interactions among subject, object, tools, rules, community, and division of labor. Its prominence underscores its analytical strength in capturing the complexity of STEM learning environments and its adaptability across classroom, laboratory, and professional learning contexts.

In terms of methodology, **Table 2** further indicates that qualitative case study designs are the dominant research approach. This trend reflects the field's emphasis on in-depth, context-sensitive inquiry into learning processes, where the focus is on understanding how contradictions and mediating tools shape educational practice within specific settings rather than producing broad generalizations. Regarding mediating artefacts, the figure highlights that digital simulations, robotics kits, and LMS are the most frequently analyzed tools. This pattern signals the increasing integration of digital technologies in STEM education and their central role in mediating learner engagement, conceptual development, and instructional design. A particularly important insight from **Figure 1** is the recurrence of tool-object and rules-community contradictions as the most frequently identified systemic tensions. These contradictions reflect misalignments between technological affordances and learning goals, as well as between institutional expectations and classroom practices. Importantly, these tensions are consistently interpreted as productive drivers of innovation and expansive learning.

Finally, **Table 2** shows a clear dominant outcome trend of improved learner engagement, collaboration, and conceptual understanding across the reviewed studies. Despite systemic contradictions, the overall evidence suggests that CHAT-informed interventions positively influence both cognitive and social dimensions of STEM learning. Collectively, the patterns presented in **Table 2** reinforce the explanatory and transformative value of CHAT in STEM education research, particularly in revealing how systemic tensions can be leveraged to improve teaching and learning outcomes.

Gaps in the Existing Literature

Based on the synthesis of the 30 reviewed studies, several important gaps emerge in the application of CHAT in STEM education research.

A first notable gap is the over-concentration on secondary education contexts, with relatively limited representation of primary and tertiary levels. As shown in the dataset, most studies focus on secondary classrooms, while early foundational STEM learning (primary level) and advanced disciplinary learning (post-secondary/tertiary) remain underexplored. This limits the generalizability of CHAT-informed findings across the full education continuum and constrains understanding of developmental trajectories in STEM learning.

Secondly, there is a methodological dominance of qualitative case studies, with fewer mixed-methods, quasi-experimental, and longitudinal designs. While qualitative approaches provide rich contextual insights into activity systems, the lack of large-scale and longitudinal evidence limits the ability to establish causal relationships or examine long-term effects of CHAT-informed interventions. The strong predominance of qualitative case studies also suggests the need for greater methodological diversity, particularly longitudinal and mixed-methods research. Future research would benefit from more robust mixed-method and design-based longitudinal studies to strengthen empirical validation.

A third gap concerns the narrow focus on recurring mediating tools, particularly digital simulations, robotics kits, LMS platforms, and similar technologies. Although these tools are important, the literature shows limited exploration of emerging technologies such as artificial intelligence-driven systems, immersive extended reality, adaptive learning analytics, and hybrid physical-digital makerspaces. This suggests a need to broaden the scope of mediating artefacts studied within CHAT frameworks.

In addition, while contradictions are consistently identified (e.g., tool-object, rules-community, and division of labor tensions), they are often described rather than deeply theorized or systematically resolved.

Many studies stop identifying contradictions without fully tracing how they evolve over time or how expansive learning cycles resolve them. This indicates a conceptual gap in the longitudinal analysis of contradiction transformation processes within activity systems.

Another gap lies in the limited integration of socio-cultural diversity and indigenous epistemologies within CHAT analyses. Only a small number of studies (e.g., Photo & McKnight, 2024; Zidny et al., 2021) explicitly incorporate culturally responsive or indigenous knowledge systems. This suggests underutilization of CHAT's potential for addressing epistemic diversity and decolonizing STEM education.

Furthermore, there is relatively limited attention to multi-activity system interactions, despite some recent work (e.g., Roehrig et al., 2021). Most studies focus on single classroom or institutional activity systems, overlooking broader ecological interactions across schools, universities, communities, and digital platforms. This restricts understanding of systemic transformation in STEM education at macro levels.

Finally, although most studies report positive learning outcomes (engagement, conceptual understanding, collaboration), there is a tendency toward optimistic reporting with limited critical examination of unintended consequences, implementation barriers, or inequitable access to mediating tools.

Overall, these gaps indicate the need for more diversified contexts, stronger methodological designs, deeper theoretical engagement with contradictions, and broader socio-cultural and technological inclusivity in future CHAT-informed STEM education research.

Implications for Meaningful Teaching and Learning

The synthesis of the reviewed studies suggests several important implications for enhancing meaningful teaching and learning in STEM education through a CHAT lens. A primary implication is that meaningful learning is strengthened when teaching is designed around activity systems rather than isolated content delivery. Across the studies, learning becomes more impactful when teachers intentionally align the subject, tools, rules, community, and division of labor to support coherent learning activity. This shift moves instruction away from fragmented knowledge transmission toward structured, goal-directed learning experiences that promote deeper conceptual understanding. A second implication is that pedagogical practices should actively surface and work with contradictions rather than suppress them. Recurrent tensions, such as tool-object misalignments, rules-community conflicts, and division-of-labor challenges, function as catalysts for learning when they are explicitly addressed. Meaningful teaching therefore involves

designing learning environments where learners and teachers can identify, reflect on, and resolve these contradictions through guided inquiry and collaborative problem-solving.

Thirdly, the findings highlight that mediating tools play a central role in shaping meaningful engagement and understanding. Digital simulations, robotics, virtual laboratories, LMS platforms, and indigenous knowledge artefacts enhance learning when they are purposefully integrated into instructional design. However, their effectiveness depends on pedagogical alignment; tools alone do not guarantee meaningful learning unless they are embedded within coherent activity structures. A further implication is the importance of collaborative and socially mediated learning environments. Many studies show that improved outcomes are associated with stronger interaction among learners, teachers, and broader communities. This suggests that meaningful teaching should prioritize dialogue, shared problem-solving, and distributed expertise rather than individualized learning alone.

In addition, the synthesis underscores the need for teacher professional development that supports CHAT-informed instructional design. Teachers require sustained opportunities to develop pedagogical capacity for analysing activity systems, identifying contradictions, and redesigning learning environments. Without this capacity, the transformative potential of CHAT remains under-realized in classroom practice. Finally, the evidence suggests that meaningful teaching and learning is enhanced when STEM education is contextualized and culturally responsive. Integrating indigenous knowledge systems, real-world contexts, and authentic problem-solving scenarios increases learner motivation and relevance, thereby strengthening conceptual understanding and engagement.

Overall, these implications indicate that meaningful teaching and learning in STEM education is not achieved through content coverage alone, but through the deliberate orchestration of socially, culturally, and technologically mediated activity systems that support expansive learning.

CONCLUSION

This systematic review set out to examine how CHAT has been utilized as a theoretical lens in STEM education research. By synthesizing 30 empirical and theoretical studies across primary, secondary, tertiary, and teacher education contexts, the study provides a comprehensive account of how CHAT has been conceptualised, operationalized, and applied to understand the complexity of STEM teaching and learning. Overall, the findings demonstrate that CHAT, particularly Engeström's (1987) expanded activity system model, has become a robust and widely adopted framework for analyzing STEM education as a socially situated,

culturally mediated, and tool-dependent process. Across the reviewed studies, learning is consistently understood as emerging through interactions among learners, educators, mediating artefacts, institutional rules, communities, and divisions of labour, rather than as an isolated cognitive activity.

A key conclusion is that systemic contradictions are central to educational change within CHAT-informed STEM contexts. Rather than being treated as barriers, contradictions such as tool-object, rules-community, and division-of-labour tensions are consistently shown to function as drivers of reflection, innovation, and expansive learning. These contradictions enable the transformation of teaching practices, curriculum implementation, and learner engagement across diverse STEM domains. The review also concludes that mediating tools play a decisive role in shaping STEM learning outcomes, particularly digital simulations, robotics kits, virtual laboratories, LMS platforms, CAD tools, and emerging AI-supported technologies. When appropriately aligned with pedagogical intentions, these tools enhance conceptual understanding, engagement, collaboration, and problem-solving skills. However, the effectiveness of these tools is strongly dependent on their integration within coherent activity systems.

In addition, the evidence indicates that CHAT contributes significantly to improved learner and teacher outcomes, including enhanced conceptual understanding, computational thinking, inquiry skills, TPACK development, and collaborative practices. These gains are most evident when teaching strategies deliberately engage with systemic tensions and support reflective redesign of learning environments. Importantly, the review highlights that CHAT has been applied across multiple educational levels and STEM disciplines, though with a strong concentration in secondary education and qualitative case study methodologies. This suggests both the strength of CHAT in rich contextual analysis and the need for broader methodological diversification and expanded coverage across underrepresented educational levels. Despite its strengths, the review identifies ongoing fragmentation in how CHAT is conceptualised and applied, underscoring the need for greater theoretical coherence, longitudinal research designs, and deeper exploration of multi-activity systems and emerging technologies.

In conclusion, CHAT offers a powerful and comprehensive lens for understanding and transforming STEM education. Its emphasis on systemic relationships, mediated action, and productive contradictions positions it as a critical framework for advancing innovative, equitable, and context-responsive STEM teaching and learning. Future research should build on this foundation by expanding methodological diversity, strengthening theoretical integration, and exploring CHAT in increasingly complex, technology-rich, and culturally diverse educational environments.

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