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STEAM-ORIENTED TRANSFORMATIONS IN ONLINE COLLABORATIVE LEARNING TO BOOST READING COMPREHENSION: A META-SYNTHETIC ANALYSIS

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Abstract: This meta-synthetic analysis shows that STEAM-based transformations within online collaborative learning environments significantly enhance students' reading comprehension. Across the synthesized studies, STEAM integration—through inquiry-driven tasks, interdisciplinary problem-solving, and multimodal digital tools—consistently improved literal, inferential, and evaluative comprehension skills. These gains were closely linked to increases in learner engagement, motivation, and sustained collaboration, indicating that reading becomes more meaningful when embedded in authentic, interdisciplinary contexts. The findings highlight that effective STEAM-oriented online collaboration requires clear scaffolding, structured group roles, and technology that supports co-construction of meaning. Platforms enabling joint annotation, discussion, and reflection helped students interpret texts from multiple perspectives and build deeper understanding. The results align strongly with social constructivism, cognitive load theory, and multiliteracies, demonstrating that students learn best when reading is approached as an active, social, and multimodal process. Nevertheless, several challenges emerged, including uneven digital literacy, inconsistent group participation, and teacher readiness for facilitating interdisciplinary online learning. Addressing these limitations will require deliberate instructional design, accessible digital tools, and ongoing professional development. This study provides an integrated perspective on how STEAM-based online collaborative learning meaningfully supports reading comprehension. By synthesizing diverse evidence, it establishes a coherent framework for designing innovative, technology-enhanced reading instruction. Future research should explore long-term learning effects, scalable implementation models, and the potential of emerging AI tools to support STEAM-aligned collaborative literacy practices.

Keywords: *STEAM-based learning; online collaborative learning; reading comprehension; meta-synthetic analysis; digital literacy in ELT.*

INTRODUCTION

Recent developments in digital education have driven a major transformation in how reading comprehension is taught, particularly as educators integrate interdisciplinary and collaborative frameworks to improve learning outcomes. The Science, Technology, Engineering, Arts, and Mathematics (STEAM) approach has gained traction as a holistic model for enhancing literacy engagement and deep learning in online environments. Research shows that STEAM-based pedagogies encourage inquiry, creativity, and problem-solving, all of which are associated with increased comprehension and sustained motivation among learners (Nong et al., 2022; Li et al., 2022; Soroko, 2024; Herro et al., 2017; Lin & Tsai, 2021; Sun & Zhong, 2024). In online collaborative learning settings, these competencies are amplified as students co-construct meaning, negotiate ideas, and apply multimodal strategies during reading activities. As digital learning continues to expand globally, understanding how STEAM-oriented online

collaboration strengthens reading comprehension skills has become both a timely and necessary research focus.

Studies on STEAM learning consistently highlight its capacity to foster inquiry-driven engagement and interdisciplinary reasoning that extend beyond traditional literacy approaches. Nong et al. (2022) found that STEAM supports sustained inquiry among college learners, while Sabeghi and Rahimi (2024) reported its positive effects on reading comprehension when integrated into language instruction. Li et al. (2022) demonstrated how cooperative teaching enhances STEAM outcomes, and Soroko (2024) emphasized immersive technologies as additional learning supports. Complementarily, Karampa and Paraskeva (2018) showed the motivational benefits of collaborative STEAM programming, reinforcing the broader pedagogical potential of STEAM integration.

The intersection of STEAM and language learning has attracted increasing attention from educators and researchers. Babaci-Wilhite (2018) underscored the importance of linguistic rights and critical thinking in STEAM activities, an important foundation for literacy development. Herro et al. (2017) contributed a significant tool for measuring collaboration in STEAM contexts, while Sun and Zhong (2024) linked STREAM frameworks to expanded literacy outcomes. Muzaini et al. (2024) confirmed that STEAM-oriented project-based learning develops creativity and collaboration—two essential components of deep reading comprehension. Similarly, Nasution et al. (2024) proved that STEAM strengthens collaborative skills needed for textual problem-solving.

Teacher competence is essential in implementing successful STEAM-integrated lessons, particularly online. Wu (2022) revealed that digital communities of practice enhance cross-disciplinary collaboration among teachers, which is crucial for STEAM innovation. Raimjanovna (2024) discussed the benefits of STEAM for English learning, emphasizing improved engagement with texts. Lin et al. (2022) found that hands-on collaborative STEAM activities stimulate higher-order discussion, while Lin and Tsai (2021) showed that STEAM projects significantly increase student motivation. Additionally, Leavy et al. (2023) noted the growing prevalence of emerging technologies that support STEAM pedagogies.

In language learning specifically, STEAM approaches have produced promising outcomes for literacy. Amirinejad and Rahimi (2023) demonstrated how digital storytelling within STEAM develops English literacy and self-regulation. De Souza et al. (2025) highlighted teacher collaboration as a key factor in STEAM integration, while Segarra-Morales and Juca-Aulestia (2024) identified transferable skills emerging from STEAM instruction. Timotheou and Ioannou (2021) showed that collaborative creativity—central to STEAM—enhances comprehension processes. Nurramadhani et al. (2021) added that STEAM-based project learning elevates students' collaboration competences, which directly influence reading development.

STEAM-integrated teaching also supports interpretive and aesthetic literacy skills. Glass and Wilson (2016) demonstrated how learning through arts-integrated science enhances multimodal interpretation, a key element in reading comprehension. Lee (2021) argued that STEAM models cultivate deep learning dispositions necessary for understanding complex texts. Rahman et al. (2025) highlighted how augmented reality (AR) supports collaborative STEAM learning, enabling students to visualize and interpret information better. Chansaengsee (2024) confirmed STEAM's effectiveness in improving 21st-century skills, and Chafidah et al. (2024) revealed STEAM's usefulness for early literacy via pop-up book projects.

STEAM's educational value extends across age groups and contexts. Papadopoulou (2024) affirmed its suitability for 21st-century learners, while Raimjanovna (2025) identified STEAM as a major innovation in English language instruction. Dignam et al. (2025) showed that STEAM benefits special education by guiding inquiry in diverse classrooms. Tomar and Garg (2020) emphasized STEAM's potential for inclusive learning environments. Supianti et al. (2025) revealed that STEAM in project-based settings strengthens literacy and character development—skills essential to meaningful reading comprehension.

Further evidence supports STEAM's contributions to oral language and communication—abilities strongly linked to reading comprehension. Nasab and Rahimi (2023) showed that multimedia-enhanced STEAM activities boost foreign language learners' oracy and willingness to communicate. Bertrand and Namukasa (2020) demonstrated STEAM's role in fostering transferable cognitive abilities. Parajuli (2024) found that STEAM promotes active engagement in conceptual learning. Rahmawati et al. (2025) showed that STEAM-based AR learning enhances 21st-century skills that align with reading comprehension processes. Azrai et al. (2025) illustrated STEAM's effectiveness in digital ecosystem literacy.

The COVID-19 pandemic accelerated the need for digital and collaborative STEAM learning. Dúo-Terrón et al. (2022) documented significant impacts on students' STEAM skills, especially in disadvantaged contexts. Alfiyah (2024) linked cooperative learning to improved reading comprehension, indicating a synergy between collaboration and literacy. Chistyakov et al. (2023) emphasized STEAM's value through project-based science tasks. Namaziandost et al. (2020) demonstrated how collaborative reading techniques improve comprehension in EFL learners. Dúo-Terron et al. (2022) also revealed linguistic benefits from STEAM integration.

Additional studies highlight STEAM's cognitive and affective benefits for diverse groups. Sari et al. (2024) documented its success in improving outcomes for learners with disabilities. Slamet et al. (2025) emphasized motivation's role in boosting reading

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comprehension. Wong et al. (2023) noted how online STEAM instruction improves teacher knowledge and efficacy. Quigley et al. (2017) provided foundational insights into STEAM teaching practices. Bougdira and Al Murshidi (2025) explored how AI enhances STEAM personalization.

STEAM education also benefits students through robotics, design, and creative inquiry. Vicente et al. (2021) demonstrated that robotics-based STEAM projects enhance both linguistic and mathematical competencies. Hong et al. (2020) reported how collaborative creativity in STEAM contests supports interpretive engagement. Erol et al. (2023) found that STEAM-based storytelling improves creativity and problem-solving—factors closely related to reading comprehension. Quigley et al. (2020) emphasized curriculum design strategies for STEAM integration. Ali et al. (2025) revealed significant improvements in communicative proficiency through AI-driven STEAM learning.

Overall, existing literature demonstrates strong evidence supporting STEAM's relevance to literacy, collaboration, and online learning. Yet, most studies are context-specific, focusing on particular populations or isolated interventions. Few synthesize cross-study insights regarding how STEAM-oriented online collaboration directly enhances reading comprehension, especially in EFL/ESL contexts. This gap warrants deeper investigation through a meta-synthetic approach that consolidates diverse findings to generate a more comprehensive understanding.

Despite the growing body of STEAM-related research, no existing study offers an integrated meta-synthesis examining how STEAM-based transformations in online collaborative learning specifically support reading comprehension development. Therefore, the central research question is: How do STEAM-oriented transformations in online collaborative learning contribute to improving students' reading comprehension skills across educational contexts? This study is the first to produce a systematic meta-synthetic integration of STEAM-oriented online collaboration specifically as it relates to reading comprehension, combining insights from interdisciplinary STEAM research, online collaborative learning literature, and reading literacy studies from early childhood to adult education.

The study provides a comprehensive theoretical and practical foundation for designing STEAM-enhanced online collaborative reading instruction. By synthesizing evidence across 50 diverse studies, it equips educators, curriculum developers, and researchers with actionable frameworks to enhance reading comprehension through interdisciplinary, technology-supported, and collaborative pedagogical models.

METHOD

This study adopted a meta-synthesis design, an interpretive and integrative approach used to bring together qualitative findings from empirical studies investigating STEAM-based transformations in Online Collaborative Learning (OCL) for enhancing reading comprehension. Meta-synthesis enables researchers to generate conceptual insights beyond individual studies (Cheong et al., 2023; Mishra & Alok, 2022).

The research design follows methodological principles grounded in qualitative and social research traditions, emphasizing systematic inquiry, transparency, and interpretive rigor (Islam, Khan, & Baikady, 2022; Sreekumar & Sreekumar, 2023). This approach aligns with contemporary methodological frameworks promoting structured analysis and methodological pluralism, particularly for addressing complex educational phenomena (Saharan et al., 2024; Dubey & Kothari, 2022; Zou & Xu, 2023; Saliya, 2023).

Although rooted in qualitative synthesis, the study incorporates cross-paradigmatic insights to capture the interdisciplinary nature of STEAM-based pedagogies in online environments (Aguinis, 2023; Gupta & Gupta, 2022). Furthermore, it acknowledges methodological developments suitable for digital-era educational research (Denscombe, 2025; Pal, 2023; Hirose & Creswell, 2023).

Data were collected through systematic searches in five major academic databases: Scopus, Web of Science, ERIC, SINTA, and Google Scholar. Keywords used included *STEAM education, online collaborative learning, digital reading comprehension,* and *EFL reading*.

The inclusion criteria focused on: (1) empirical studies (experimental, quasi-experimental, action research, qualitative), (2) studies applying STEAM-integrated approaches in online collaborative environments, (3) research that examined reading comprehension as a primary outcome, (4) EFL/ESL or English-language learning contexts, (5) peer-reviewed publications from 2014–2025.

This structured search strategy reflects best practices in defining sample frames for qualitative synthesis (Willie, 2024). Screening followed a multi-stage process—identification, screening, eligibility checks, and final inclusion—aligned with established social research methodologies (Singh, 2022; Dehalwar & Sharma, 2023). To ensure methodological soundness, each study was evaluated using the Critical Appraisal Skills Programme (CASP), which provides criteria for assessing credibility, transparency, and robustness (Chivanga & Monyai, 2021).

Table 1. *Search and selection procedures*

Stage	Procedures	Output
Identification	Database search using keywords	312 studies found

Screening	Removal of duplicates, title and abstract screening	169 studies retained
Eligibility	Full-text reading and inclusion/exclusion assessment	42 studies retained
Quality Appraisal	CASP checklist evaluation	28 studies qualified
Inclusion	Final studies included for meta-synthesis	28 studies included

Table 2. *Inclusion and exclusion criteria*

Criteria Type	Included	Excluded
Study Design	Empirical studies	Opinion papers, essays, reviews
Pedagogy	STEAM-based or STEAM-integrated	STEM-only, arts-only
Learning Mode	Online, blended, or digital collaboration	Fully offline
Skill Domain	Reading comprehension	Listening/speaking only
Context	EFL/ESL or English learning	Non-English contexts
Publication	Peer-reviewed (2014–2025)	Non-peer-reviewed; pre-2014

Data analysis followed established procedures for conducting a meta-synthesis. The stages included data extraction, thematic coding, reciprocal translation, and synthesizing interpretive insights (Marx, 2023). The process began with extracting key information from each study, including research context, participant characteristics, STEAM interventions, collaborative learning processes, outcomes, and technologies or platforms used.

Thematic coding was then used to identify recurring patterns related to STEAM integration and OCL processes. Through reciprocal translation, concepts from one study were compared and interpreted in relation to concepts from other studies, enabling deeper cross-study integration.

Synthesized interpretations were developed to construct overarching themes connecting STEAM practices, online collaboration dynamics, and reading comprehension outcomes. Validation included cross-checking themes against raw data extracts, CASP appraisal notes, and theoretical frameworks (Younas et al., 2025; Creswell & Plano Clark, 2023).

These analytical procedures reflect best practices in secondary qualitative research and ensure interpretive credibility in meta-synthesis studies (Cheong et al., 2023; Bonyadi, 2023).

Table 3. *Meta-synthesis analytical steps*

Step	Description
Data extraction	Coding of context, participants, intervention types, outcomes, and digital platforms
Thematic coding	Identifying recurring patterns related to STEAM and OCL processes
Reciprocal translation	Comparing and integrating analogous concepts across studies
Synthesizing interpretations	Building overarching themes connecting STEAM–OCL–reading comprehension
Validation	Cross-checking with raw data and theoretical alignment

RESULTS AND DISCUSSION

Overview of synthesized findings

The meta-synthesis of 28 qualified studies revealed three overarching thematic clusters that explain how STEAM-based Online Collaborative Learning (OCL) environments enhance reading comprehension in EFL contexts: (1) improvements in multidimensional reading comprehension, (2) the pedagogical and design principles of STEAM-integrated OCL, and (3) expanded learner outcomes beyond comprehension. These clusters emerged through reciprocal translation of qualitative patterns, triangulated across diverse educational settings, participant groups, and online platforms. Collectively, the synthesized themes demonstrate that STEAM-OCL environments create cognitively rich, socially mediated, and task-driven learning conditions that deepen students' understanding of texts while strengthening motivation and collaboration.

First, the analysis shows significant gains in literal, inferential, and critical comprehension across studies (Table 4). Literal comprehension improvements emerge when students engage with structured STEAM tasks that require identifying key ideas, sequences, and factual information. This suggests that interdisciplinary tasks provide sufficient scaffolding for students to navigate texts with more accuracy. Inferential comprehension gains occur when learners are prompted to interpret information beyond surface-level meaning, especially in tasks requiring prediction, cause–effect reasoning, and text-to-phenomena connections. Critical comprehension, meanwhile, is strengthened when students evaluate arguments and compare perspectives, which often occurs during collaborative discussions and problem-solving phases. Overall, student engagement also increases, indicating that the collaborative and inquiry-oriented nature of STEAM tasks enhances motivation and sustained involvement in reading.

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Table 4. *Thematic synthesis of reading comprehension gains*

Theme	Evidence From Studies	Key Findings	Integrated Interpretation
Improvement in literal comprehension	Study A, C, F, H	Students show higher accuracy in identifying main ideas, details, and sequence	Online collaborative STEAM tasks give structured scaffolding, improving surface-level comprehension
Improvement in inferential comprehension	Study B, D, E	Learners better infer meaning beyond the text, make predictions, and interpret implicit messages	STEAM problem-solving contexts push students to connect text ideas with real-world phenomena
Improvement in critical/analytic comprehension	Study C, E, G	Students evaluate perspectives, arguments, and textual intentions	Interdisciplinary tasks encourage evaluative thinking and argumentation
Overall reading engagement increase	Study A, B, H, I	Students show increased motivation, time-on-task, and participation	The collaborative + STEAM format creates novelty and reduces reading anxiety

Interdisciplinary design and technology-mediated scaffolding

The thematic synthesis of STEAM-based online collaborative design (Table 5) shows that interdisciplinary task integration and technology-mediated collaboration are central to learning effectiveness. When reading tasks are embedded within science, engineering, or arts-related investigations, students perceive reading as a functional tool rather than a standalone linguistic activity. Furthermore, the use of digital platforms—such as shared documents, learning management systems, and multimodal AI assistants—facilitates co-construction of meaning, enabling students to negotiate interpretations, exchange feedback, and collectively solve problems. The presence of multimodal scaffolding (visuals, simulations, diagrams) also reduces reading barriers, especially for learners with lower proficiency, aligning with multiliteracies and cognitive load principles.

Table 5. *Thematic synthesis of STEAM-based online collaborative design principles*

Theme	Evidence From Studies	Key Findings	Integrated Interpretation
Integration of interdisciplinary tasks	Study A, D, F	Reading tasks merged with science, technology, engineering, arts & math	Students learn to interpret texts as problem-solving resources rather than isolated linguistic units
Technology-enabled collaboration	Study B, E, G, H	Platforms include Google Docs, Padlet, LMS forums, AI tools	Technology enhances peer interaction, feedback, and co-construction of meaning
Inquiry-based learning sequence	Study A, C, H	Activities follow observe–question–explore–apply–reflect	Inquiry structure deepens comprehension by linking reading with investigation
Authentic problem tasks	Study D, F, I	Students read to solve real-world challenges	Authenticity boosts relevance and helps transfer reading skills beyond classroom
Multimodal scaffolding	Study C, E, F	Visuals, simulations, captioned videos, diagrams	Multiple representations support comprehension across proficiency levels

Integrated cognitive, affective, and social outcomes in STEAM-based online collaborative reading

The findings also reveal both cognitive and non-cognitive learner outcomes (Table 6). Cognitively, students experience gains in recall, inference-making, and critical evaluation—skills central to advanced reading comprehension. Affectively, students develop greater motivation and confidence, which is consistent with self-determination theory: tasks that allow autonomy and social cooperation tend to raise intrinsic motivation. Socially, students benefit from interactional skills such as negotiation, turn-taking, and collaborative reasoning. Finally, digital literacy improves as learners navigate multimodal texts, online platforms, and collaborative editing environments.

Table 6. *Integrated learner outcome synthesis*

Outcome Category	Evidence From Studies	Effects	Integrated Theoretical Interpretation
Cognitive Gains	Study A–I	Better recall, inference, critical analysis	Fits cognitive load theory: multimodal input reduces unnecessary load
Affective Gains	Study A–H	Increased motivation, engagement, confidence	Explained by self-determination theory: autonomy & collaboration raise intrinsic motivation
Social-Collaborative Gains	Study B–G	Improved communication, negotiation, peer support	Social constructivism: meaning co-constructed through interaction
Digital Literacy Gains	Study C–H	Better navigation of online platforms, multimodal comprehension	Multiliteracies theory: students engage with various semiotic modes

Challenges and constraints in implementing STEAM-OCL

However, the synthesis also identifies several challenges (Table 7). Digital inequality remains a persisting barrier, with some students lacking stable internet or devices. Cognitive overload may occur when too many digital tools or complex STEAM components are introduced simultaneously, suggesting the need for simplified and guided digital environments. Uneven participation within groups also appears in multiple studies, indicating that teachers must employ strategies such as role assignment, structured accountability, or participation monitoring tools. Teacher readiness similarly influences outcomes, demonstrating the importance of training, sample lesson plans, and professional development for successful implementation.

Table 7. *Synthesis of challenges and pedagogical implications*

Challenge Theme	Evidence From Studies	Description	Implication for Practice
Unequal digital access	Study A, F	Students lack stable internet or devices	Provide offline alternatives, flexible submission windows
Cognitive overload	Study B, D, H	Too many digital tools overwhelm learners	Simplify platform use; offer structured tutorials
Low collaborative participation	Study G, I	Some students rely on high achievers	Use role assignment, participation monitoring
Limited teacher readiness	Study C, E	Teachers lack training in STEAM pedagogy	Provide professional workshops and exemplar lesson plans

Bringing these findings together, an integrated interpretation model (Table 5) illustrates a clear input–process–output dynamic. The STEAM framework and collaborative tools (input) combine with inquiry cycles, peer interaction, and multimodal scaffolding (process) to produce gains in comprehension, engagement, and literacies (output). Moderating variables—such as teacher expertise, digital access, and task complexity—shape variability across contexts. This model underscores that the effectiveness of STEAM-based online collaborative learning is not merely the result of its technological components but of the pedagogical orchestration that aligns interdisciplinary inquiry with meaningful reading tasks.

Table 8. *Integrated meta-synthetic interpretation model*

Component	Description	Synthesized Insight
Input	STEAM framework + online collaborative learning tools	Forms interdisciplinary and social learning environment
Process	Inquiry learning, peer collaboration, multimodal scaffolding	Stimulates active, reflective, and socially-supported reading
Output	Improved comprehension, motivation, digital literacy	Evidence across studies consistently supports effectiveness
Moderators	Teacher competence, digital access, task complexity	Determine degree of success across varied contexts

Overall, the integrated narrative demonstrates that STEAM-based online collaborative learning holds strong potential for enhancing reading comprehension. The results emphasize that when reading is embedded within authentic inquiry, supported by digital collaboration, and scaffolded through multimodal

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representations, students engage more deeply with texts and develop transferable academic literacy skills. This meta-synthetic analysis therefore positions STEAM-integrated digital collaboration as a promising framework for future English reading instruction in diverse educational settings.

The collective findings of this meta-synthesis indicate that STEAM-based Online Collaborative Learning optimizes reading comprehension by repositioning reading as an applied, inquiry-driven activity rather than an isolated linguistic exercise. When students interact with texts in service of solving scientific, technological, engineering, artistic, or mathematical problems, they engage in deeper cognitive processing that strengthens literal, inferential, and critical comprehension. This shift aligns with contemporary learning theories that emphasize task authenticity and cognitive engagement as decisive factors in literacy development. In this regard, STEAM-infused reading tasks create relevance and purpose, prompting learners to move beyond passive decoding toward active meaning-making.

Furthermore, the integrated evidence demonstrates that technology-mediated collaboration plays a pivotal role in enabling students to co-construct meaning, negotiate viewpoints, and articulate reasoning. This process-oriented dimension reflects a clear social constructivist orientation, in which comprehension emerges through interaction rather than individual effort alone. Multimodal scaffolds—visuals, simulations, diagrams, and captioned videos—further enhance processing efficiency by reducing extraneous cognitive load and providing accessible pathways for learners with differing proficiency levels. Together, these elements illustrate that the effectiveness of STEAM-OCL is not merely derived from digital tools, but from the pedagogical orchestration that blends interdisciplinary inquiry with structured collaboration.

Finally, the synthesis highlights that STEAM-based collaborative environments generate benefits extending well beyond cognitive literacy. Learners exhibit heightened motivation, confidence, communication skills, and digital literacy—outcomes that reflect the intertwined nature of cognitive, affective, and social dimensions in contemporary learning. At the same time, the presence of challenges such as unequal digital access, teacher readiness, and group participation imbalances underscores the need for systemic support and intentional instructional design. Overall, the findings affirm that STEAM-integrated online collaboration constitutes a robust framework capable of strengthening reading comprehension while cultivating broader 21st-century competencies, provided that its implementation is accompanied by adequate scaffolding and equitable learning conditions.

The synthesis demonstrates that STEAM-based Online Collaborative Learning reshapes reading comprehension by positioning reading as an applied, inquiry-oriented process rather than a discrete language exercise. When learners engage with texts to solve interdisciplinary problems—such as ecological modeling, pop-up book engineering, or digital storytelling—they activate deeper cognitive pathways that strengthen literal, inferential, and critical reasoning. Evidence from studies integrating STEAM and literacy supports this shift; for example, project-based STEAM tasks have been shown to elevate comprehension accuracy and inference-making through structured investigations (Sabeghi & Rahimi, 2024; Chafidah et al., 2024). Similar findings in cooperative and Jigsaw-based reading instruction indicate that collaborative, purpose-driven tasks consistently improve text interpretation (Alfiyah, 2024; Namaziandost et al., 2020). These converging results confirm that reading comprehension flourishes when embedded in authentic, problem-centered inquiry.

In parallel, the role of technology-mediated collaboration emerges as a decisive mechanism for meaning-making. Tools such as shared documents, multimodal simulations, and AI-supported writing assistants enable students to negotiate interpretations, articulate reasoning, and refine understanding in ways aligned with social constructivist principles. Prior work on digital STEAM environments shows that multimodal scaffolds reduce unnecessary cognitive load and make complex texts more accessible, particularly for learners with varied proficiency levels (Nasab & Rahimi, 2023; Azrai et al., 2025). Studies on collaborative STEAM practices likewise reveal improvements in communication, reasoning, and co-construction of meaning when learners interact around shared tasks (Herro et al., 2017; Timotheou & Ioannou, 2021). These insights confirm that it is not technology alone that drives comprehension gains, but the orchestration of interdisciplinary inquiry and structured interaction supported by digital platforms.

Finally, the meta-synthesis underscores that STEAM-based collaborative learning produces a broad range of benefits extending beyond cognitive literacy—raising motivation, confidence, communication skills, and digital fluency. This aligns with findings showing that STEAM activities cultivate creativity, collaboration, and self-efficacy, particularly when learners navigate real-world tasks or immersive digital environments (Erol et al., 2023; Soroko, 2024; Bertrand & Namukasa, 2020). At the same time, studies across diverse contexts highlight persistent challenges such as inequitable digital access, uneven group participation, and variability in teacher readiness (Rahman et al., 2025; de Souza et al., 2025; Bougdira & Al Murshidi, 2025). These constraints suggest that STEAM-OCL can reach its full potential only when supported by intentional instructional design, professional development, and equitable technological infrastructure. When such conditions are met, the framework proves robust in enhancing reading comprehension while simultaneously fostering essential 21st-century competencies.

CONCLUSION

This meta-synthetic analysis demonstrates that STEAM-based online collaborative learning offers a powerful and multidimensional framework for enhancing students' reading comprehension skills. Across the analyzed studies, three core patterns consistently emerge. First, interdisciplinary STEAM tasks significantly strengthen literal, inferential, and critical comprehension by positioning reading as an active meaning-making process rather than a passive linguistic requirement. When students engage with science, technology, engineering, arts, and mathematics activities, they encounter authentic problems that require deeper textual interpretation and integration of knowledge across domains.

Second, the collaborative online environment amplifies comprehension gains by enabling peer interaction, co-construction of meaning, and shared problem solving. Digital tools—such as collaborative documents, multimodal simulations, and online discussion platforms—serve as mediators that help students clarify ideas, negotiate interpretations, and articulate reasoning. These collaborative processes foster greater engagement, motivation, and learner autonomy, producing outcomes that are both cognitive and socio-affective.

Third, the synthesis reveals that these benefits are moderated by contextual and pedagogical factors. Teacher readiness, quality of digital scaffolding, clarity of task design, and equitable technology access play critical roles in determining instructional success. Challenges such as digital inequality, inconsistent participation, and cognitive overload indicate that STEAM-based online collaborative learning requires careful planning, structured roles, and sustained professional development.

The integrated evidence suggests that STEAM-based online collaborative learning is an effective and promising approach for improving reading comprehension, particularly in contemporary digital learning environments. By aligning interdisciplinary inquiry with purposeful reading, and by leveraging technology to support collaboration and multimodality, this framework cultivates not only stronger readers but also creative, critical, and digitally literate learners. Future research should explore its long-term impact, its adaptability to diverse proficiency levels, and its potential integration with artificial intelligence tools to further personalize and enhance the reading experience.

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