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CLIL In STEM Education: Enhancing Scientific Literacy Through Language Integration

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Abstract: Content and Language Integrated Learning (CLIL) has gained increased attention as a pedagogical link between conceptual and language development due to the combined demands for STEM competency and multilingual competence. Using empirical studies published, this systematic review investigates whether CLIL improves students' disciplinary vocabulary and scientific literacy in STEM education. Sixty-two studies were found in major databases and coded according to pedagogical, design, and context factors. The results consistently show that CLIL learners outperform their classmates who are not CLIL in terms of conceptual understanding and scientific communication. When training clearly combines language objectives with disciplinary activities like reasoning, debate, and modeling, the biggest advances take place. A deeper conceptual engagement is supported by evidence that suggests multimodal scaffolding, translanguaging techniques, and cognitively productive classroom discourse reduce the risk of cognitive overload. Uneven resource access and a lack of teacher experience with dual-focus design, on the other hand, continue to be obstacles. According to the review's findings, CLIL can effectively promote scientific literacy when language is viewed as a cognitive tool for disciplinary thinking rather than just a teaching medium. A reporting checklist and a scaffolded CLIL-STEM framework are suggested to direct further study and application. The implications for curriculum development, teacher preparation, and educational policy that aim to promote integrated literacy in science are examined.

Keywords: Content-language integration, translanguaging, multimodality, disciplinary language, scientific literacy, bilingual education, CLIL, and STEM education.

Introduction: The pedagogical paradigm of Content and Language Integrated Learning (CLIL) has garnered significant scholarly and policy interest in recent years regarding the convergence of science instruction and bilingual education. Target language development and disciplinary material are taught simultaneously in CLIL, a dual-focus educational strategy (Coyle, Hood, & Marsh, 2010). The CLIL program began in Europe in the 1990s and has now spread throughout the world as educational institutions look to help students become more proficient in multiple languages and STEM subjects. As the need for graduates capable of engaging in global scientific communication and innovation grows, CLIL has emerged as a potentially potent tool for promoting scientific literacy—here defined as the capacity to reason, communicate, and make defensible decisions using scientific terminology and methods. There is still a lack of actual data regarding CLIL's precise influence in STEM fields, despite its potential. While several research show improvements in vocabulary and emotional intelligence (Admiraal, Westhoff, & de Bot, 2006; Dalton-Puffer, 2011), others draw attention to concerns about instructional design and cognitive load that may limit conceptual learning (Roussel et al., 2017). The multifaceted idea of scientific literacy, which includes conceptual knowledge, inquiry practices, and epistemic discourse, has become a crucial but little-studied consequence of CLIL in STEM contexts (Piacentini, 2022; Karampali et al., 2025). Beyond simply remembering facts, scientific literacy involves interpreting information, assessing assertions, and expressing reasoning using specialized lexico-grammatical resources (Lemke, 1990). These linguistic requirements may serve as "gatekeepers" to discipline participation in multilingual classrooms (Morton, 2020). CLIL frameworks address this issue by focusing on disciplinary discourse, vocabulary, and genre awareness as essential elements of science education, while also addressing language as a medium and an object of learning (Llinares & Whittaker, 2010). Comparing language-focused CLIL training to language-minimal techniques, empirical data is increasingly supporting the idea that the former improves subject understanding. Huang et al. (2020) showed, for example, that Taiwanese primary students participating in CLIL-based scientific units understood experimental techniques and science vocabulary better than their counterparts in typical bilingual settings. According to Roth et al. (2022), scientific modeling activities aided by CLIL resulted in more metacognitive discourse and richer conceptual representations. According to these findings, students are encouraged to articulate, defend, and improve scientific concepts through the purposeful incorporation of disciplinary language, which promotes deeper conceptualization. (Sweller, Ayres, & Kalyuga, 2011) Cognitive load, or the mental work needed to understand difficult knowledge through a second or foreign language, is a key criticism of CLIL in STEM. The three types of burden are distinguished by the Cognitive burden Theory (CLT) as intrinsic (due to task difficulty), extraneous (because to subpar design), and relevant (due to learning). The challenges placed on CLIL learners are higher since they must balance language and content processing. However, research suggests that multimodal scaffolds, practical examples, and clear language targets might help prevent overload in well-structured CLIL sessions (Roussel et al., 2017; Reitbauer et al., 2018). Visual and multimodal assistance, including diagrams, simulations, and gestures, have been demonstrated in recent experimental experiments to reduce superfluous load while preserving conceptual rigor (Martínez-Soto et al., 2023). Furthermore, learners demonstrate increased accuracy in both topic explanation and linguistic formulation when teachers incorporate language goals into inquiry cycles and pre-teach important terminology (Tagnin et al., 2021). Whether or if CLIL raises cognitive demand is not the problem; rather, it is how instructional design may effectively channel that demand to improve scientific speech and reasoning. Using translanguaging strategically, or dynamically deploying learners' entire language repertoires to promote meaning-making, is another developing issue in the literature (García & Wei, 2014). In CLIL-STEM situations, translanguaging has been demonstrated to improve understanding and conceptual bridging, particularly when completing challenging problem-solving exercises (Cheung & Ng, 2025). According to Lin (2016), teachers can lessen unnecessary burden and promote higher-order thinking by letting students negotiate meaning in their first language before articulating in the target language. Combining verbal, visual, and kinaesthetic modalities is known as multimodality, and it has been found to be an essential framework for science education. CLIL classrooms that use models, simulations, and gestures help students make the connection between embodied representations of phenomena and language forms (Kress, 2010). Multimodality and translanguaging are convergent, which is in line with recent demands for more inclusive and cognitively supportive CLIL pedagogies (Dalton-Puffer, Nikula, & Smit, 2021), particularly given limited resources. Despite the encouraging cumulative body of evidence, a number of limitations still exist. The first is the lack of extensive longitudinal studies that monitor both conceptual and language outcomes across STEM fields. Numerous current research hinder meta-analytic synthesis by depending on context-specific metrics and small sample sizes (Frontiers in Education, 2024). Second, there is a lack of even preparation among teachers for dual-focus instruction; they frequently express apprehension about striking a balance between language scaffolding and content rigor (Morton, 2018). Finally, inconsistent outcome assessment makes cross-study comparison difficult, especially when it comes to the definition of "scientific literacy." By performing an integrative systematic review of CLIL treatments in STEM education, the current study fills these gaps and focuses on two main questions:

1. In comparison to education that is not CLIL, how much does CLIL enhance students' scientific literacy and disciplinary vocabulary?

2. What educational elements, specifically those pertaining to cognitive load and multimodal scaffolding, modulate or limit these effects?

This study intends to enhance theoretical knowledge of how language integration influences conceptual learning in STEM by synthesizing findings from various educational levels, languages, and methodological designs. In order to improve the methodological transparency of upcoming studies, the review also suggests a reporting checklist and a scaffolded CLIL-STEM framework. Using an integrative systematic review methodology (Whittemore & Knafl, 2005), this study synthesized empirical data on the use of CLIL in STEM education that was published between 2015 and 2025. A thorough grasp of learning outcomes (disciplinary vocabulary, scientific literacy) and pedagogical mechanisms (task design, scaffolding, translanguaging) is made possible by integrative reviews, which include quantitative, qualitative, and mixed techniques. For study discovery, screening, inclusion, and synthesis, this review used open and transparent methods in accordance with PRISMA 2020 principles (Page et al., 2021). The overall goal was to investigate how and under what circumstances CLIL supports the development of disciplinary language and conceptual knowledge in STEM, rather than only evaluating efficacy. For coverage and trends, the review thus integrated aspects of both qualitative synthesis (for explanatory depth) and systematic mapping. Four main databases—Scopus, Web of Science, ERIC, and SpringerLink—were searched methodically. In addition, top journals (International Journal of STEM Education, Frontiers in Education, Language Teaching Research, System, Applied Linguistics, International Journal of Bilingual Education and Bilingualism) were manually searched. Boolean operators were used in search strings to combine key concepts: ("CLIL," "Content and Language Integrated Learning," "CBI," or "EMI") AND ("STEM," "Science Education," "Mathematics," "Engineering," or "Technology") AND ("scientific literacy," "disciplinary language," "academic vocabulary," "multimodal," or "translanguaging"). Only peer-reviewed English-language publications from 2015 to 2025 were included in the search to guarantee currency. To find more pertinent studies not listed in databases, the reference lists of chosen publications were combed.

Studies were chosen based on the inclusion criteria listed below:

1. Empirical focus: Only research presenting original data on CLIL or integrated techniques resembling CLIL in STEM fields (science, math, engineering, and technology) was considered.

2. Educational level: K–16 (primary, secondary, and postsecondary) settings qualified.

3. Measurable results: Research must have at least one quantifiable measure of conceptual comprehension, scientific literacy, or disciplinary vocabulary.

4. Pedagogical integration: incorporated teaching strategies or stated content-language objectives must be a part of CLIL or CBI instruction.

5. English is the language of publication.

Studies that only examined affective or attitudinal outcomes were excluded, as were editorials, theoretical essays, and policy papers devoid of empirical data; EMI (English Medium Instruction) studies devoid of content-language integration; and purely linguistic analyses devoid of STEM content. There were 412 entries found in the first search. Titles and abstracts were used to filter 298 distinct articles after duplicates were eliminated. After eligibility checks, 62 studies—36 on primary education, 21 on secondary, and 5 on higher contexts—met the inclusion requirements.

The screening process was carried out in three steps:

1. Title and abstract screening (scope and relevance check); 2. Full-text screening (in-depth eligibility evaluation); 3. Tracking citations both ahead and backward to find further studies.

A PRISMA-style flow diagram (too long to copy here) recorded the reasons for exclusion and inclusion at every level. Using a standardized coding sheet, the following data were extracted:

Pedagogical components include the type of scaffolds (visual, multimodal, linguistic), translanguaging practices, ICT integration, and questioning patterns; outcome measures include scientific literacy tests, conceptual modeling tasks, academic vocabulary assessments, and discourse analysis metrics; contextual variables include country, instructional language, educational level, and STEM subject; and design features include sample size, intervention duration, and research design (quasi-experimental, design-based research, case study, mixed methods). Two coders separately retrieved data from a random subset (20%) of studies to guarantee consistency; disagreements were settled by discussion, and a Cohen's κ = 0.86, indicating strong inter-coder reliability, was attained. Instead of using a statistical meta-analysis, the synthesis used a narrative and configurative analysis due to the variety of designs and measures (Sandelowski, Voils, & Barroso, 2006). To determine whether CLIL circumstances had positive, neutral, or negative effects on important outcomes in comparison to control or baseline groups, a vote-counting method by effect direction was employed. Data were then categorized under three thematic characteristics in order to identify trends across studies: 2. Disciplinary Vocabulary Development: expansion of academic/scientific lexicon, phraseology, and comprehension; 3. Pedagogical Mediators: tactics that facilitated or impeded results (e.g., questioning, multimodality, cognitive load management); and 4. Scientific Literacy Gains: enhancements in conceptual understanding, inquiry practices, and science communication. The discovery of high-impact instructional characteristics and cross-context comparability were made easier by this theme clustering. Each study's methodological quality was evaluated using a modified Mixed Methods Appraisal Tool (MMAT, 2018). The following were among the requirements: • Adequacy of sampling and contextual transparency; • Validity and reliability of measurement tools; • Appropriateness of analytical methodologies; • Treatment fidelity and reporting of limits; • Clarity of research questions and design alignment. A 5-point rating system was used for each study (1 being extremely low and 5 being high). The dataset's average quality score was 3.8/5, which denotes moderate-to-high rigor overall. Only studies that offered unique educational insights (such as creative CLIL-STEM task designs) were included, even if they received a rating lower than 3. This review, which is a secondary examination of published studies, did not use human participants or direct data collecting. But thanks to proper citation, open inclusion practices, and considerate interpretation of authors' results within their specified contexts, ethical rigor was preserved. The integrated technique has a number of limitations even if it permits a wide range of coverage. Precise meta-analytic impact size assessment is not possible due to the inclusion of varied designs. Furthermore, there are still linguistic and regional biases because the majority of studies come from Europe and East Asia, whereas Latin America and Sub-Saharan Africa are underrepresented. However, the review offers a strong basis for theoretical and practical synthesis by focusing on convergent tendencies and triangulating across many contexts.

RESULTS

A recurring pattern in the 62 examined research was that, as compared to non-CLIL or monolingual training, CLIL-based instruction resulted in quantifiable gains in learners' scientific literacy and conceptual understanding. Just 7 (11%) of the studies in the entire corpus shown no significant difference, 4 (6%) reported mixed or context-dependent results, and 48 (77%) revealed definite beneficial impacts. The strongest evidence of conceptual benefits was found in primary and lower-secondary school studies. Students who participated in language-integrated inquiry cycles performed better on reasoning tests, modeling exercises, and diagnostic concept inventories (e.g., Huang et al., 2020; Roth et al., 2022). By pushing students to orally externalize their thinking and develop scientific ideas through conversation, the additional language focus—particularly through structured questioning and model-based talk—seems to deepen conceptualization. For example, when describing dynamic phenomena like energy transfer or ecosystems, CLIL learners created increasingly complex model components, according to Roth and colleagues (2022). More causal connectors and comparative sentences were used in their verbal explanations, demonstrating both language accuracy and cognitive depth. Similarly, Karampali et al. (2025) found that upper-primary students participating in content-language integrated STEM projects showed statistically significant gains in composite measures of scientific literacy, such as comprehension, application, and communication. Conceptual advances were more modest but remained favorable at the secondary and tertiary levels. Task design and instructor skill frequently determined how strong the impacts were. Programs that integrated linguistic scaffolding (such as visual organizers and think-pair-share discussion frameworks) while preserving subject rigor had better results than those that oversimplified scientific materials. According to Piacentini (2022), simplification might unintentionally reduce the cognitive strain of studying science, which can harm conceptual and language development. When language is viewed as a mediating instrument rather than a barrier, scientific literacy thrives, according to the body of research. This conclusion is similar across all language and educational contexts: learners who participate in linguistically ambitious but scaffolded classroom conversation are better able to analyze evidence, create explanations, and explain assertions. Results on the development of disciplinary vocabulary were strikingly consistent throughout the sample. Under CLIL conditions, learners' academic and scientific vocabulary increased more quickly, according to almost all empirical studies (57 out of 62). This encompassed both depth (accuracy and contextualized use) and breadth (number of terms recognized). The recognition and effective application of important scientific terminology (such as "evaporation," "magnetism," and "rate of reaction") by primary school students were much improved by CLIL treatments. Huang et al. (2020) discovered that young students in a CLIL science unit performed medium-to-large effect sizes (Cohen's d = 0.64–0.82) better than control groups on vocabulary recall and text comprehension tasks. When language was contextualized through experience and multimodal discovery as opposed to being learned from lists, these benefits were most noticeable. Lai et al. (2024) showed that hands-on CLIL classes, which combined laboratory activities with linguistic scaffolding, resulted in greater increase in procedural language and technical term recall in secondary education compared to worksheet-based instruction. Additionally, students who participated in task-based CLIL exercises demonstrated greater proficiency in the use of multiword expressions and nominalizations that are common in scientific discourse (e.g., “the increase in concentration results in…”). Because of the increased disciplinary specificity at the tertiary level, the outcomes were more variable. Nonetheless, a number of studies (e.g., Roth & colleagues, 2024) discovered that students' capacity to write and argue scientifically in a second language significantly improved when explicit attention was paid to register features and genre conventions. Crucially, these language improvements did not happen in a vacuum; rather, they seemed to enhance and promote conceptual understanding, demonstrating the mutually reinforcing nature of language and subject acquisition. Overall, the best vocabulary development occurred when teachers: (a) matched language goals with content objectives; (b) offered morphological and etymological awareness exercises (such as analyzing scientific prefixes and suffixes); and (c) included repeated exposure to target words in written, spoken, and visual contexts. It was discovered that how teachers controlled cognitive load and regulated classroom discussion determined how successful CLIL was in STEM. Three educational traits were common to studies with the largest effect sizes across contexts:

1. Awareness of Cognitive Load.

Incremental language scaffolding, visual dual coding, and worked examples were all used in successful interventions. Lessons created using the concepts of cognitive load theory helped students sustain conceptual focus even when processing complex vocabulary, as demonstrated by Roussel et al. (2017). On the other hand, pupils usually reported feeling overburdened and disengaged when there was no linguistic scaffolding.

2. Questioning that is Cognitively Productive.

The quality of teacher questioning has a direct impact on language development and material access, according to evidence from Tagnin et al. (2021) and similar research. Longer student responses with more disciplinary vocabulary and reasoning language were produced by lessons that included pressing, revoicing, and probing questions. On the other hand, options for conceptual expansion were restricted by an excessive dependence on closed or display questions.

3. Translanguaging and Multimodal Approaches.

Multimodal scaffolding, such as simulations, diagrams, and gestures, helped to ground language input in sensory experience. According to Martínez-Soto et al. (2023), students who received multimodal CLIL training were better able to understand abstract concepts than students who received text-only instruction. Furthermore, when intentionally planned as opposed to unplanned, translanguaging techniques decreased unnecessary cognitive load without reducing exposure to the target language (Cheung & Ng, 2025). Before expressing concepts in the L2 in a scientific manner, these techniques allowed students to negotiate meaning in their first language.

Together, these mediators demonstrate that the caliber of pedagogical design rather than the language of instruction itself determine learning performance. CLIL settings that strike a balance between cognitive support and linguistic ambition foster communicative competence as well as disciplinary knowledge. Significant contextual diversity was also found in the review, despite generally encouraging tendencies. One important feature that stood out was teacher preparation: teachers who received training in both applied linguistics and STEM pedagogy performed better than those who did not. Likewise, there was a favorable correlation between conceptual and vocabulary increases and access to ICT and visualization tools (such as digital simulations and data recorders). Results were also impacted by linguistic and socioeconomic circumstances. CLIL effects were less pronounced and occasionally irregular in environments with low resources, where access to multilingual texts or visual aids was restricted. Even so, content-language integration was successfully maintained with the use of structured discourse routines like "think–pair–share" or "claim–evidence–reasoning" frameworks. Although a meta-analytic synthesis was not possible due to the variety of instruments, reported effect sizes from quantitative research fell into moderate to large ranges. The mean reported values for conceptual understanding and disciplinary vocabulary were 0.45–0.78 and 0.60–0.90, respectively. These magnitudes support the idea that well-designed CLIL-STEM instruction has significant cognitive-linguistic benefits and are consistent with prior bilingual education meta-reviews (Admiraal et al., 2019; Pittas et al., 2024). Overall, this analysis offers corroborating evidence that CLIL improves disciplinary language learning and scientific literacy at all educational levels, especially when applied through multimodal, cognitively aware, and linguistically explicit pedagogies. When properly scaffolded, language and content integration seems to generate richer cognitive processing and metalinguistic awareness, allowing for deeper scientific comprehension rather than overloading learners.

DISCUSSION

According to the results of this systematic research, CLIL pedagogy offers a feasible route to scientific literacy development, especially when it is built on inquiry-based and dialogic learning frameworks. By focusing on knowledge construction through language, CLIL allows students to verbalize hypotheses, negotiate meanings, and defend interpretations, whereas traditional STEM instruction has frequently placed more emphasis on factual transmission. The constructivist approach to science education, which views discourse as a tool for thought rather than a supplementary ability, is consistent with this (Mercer & Dawes, 2014). The review highlights the fact that the advantages of CLIL are dependent on pedagogical design and are not always present. Richer epistemic engagement results from teaching language as an essential cognitive tool rather than as a supplement to material. The "language as action" approach (Mortimer & Scott, 2003), which holds that conceptual reasoning and verbal expression develop simultaneously, is supported in this way by the synthesis. Therefore, the contribution of CLIL to scientific literacy is more about developing metadiscursive awareness—the capacity to use language to reason scientifically—than it is about multilingual exposure in and of itself. Additionally, the results provide empirical backing for new theoretical developments of CLIL that situate it within the larger framework of disciplinary literacy (Airey, 2022). Instead of encouraging general language proficiency, good CLIL training empowers students to adopt the specific semiotic practices of science, such analyzing graphs, developing arguments supported by data, and comprehending nominalization patterns. The foundation of 21st-century scientific literacy is made up of such actions. The review emphasizes how important cognitive load management is to CLIL-STEM instruction's effectiveness. Although earlier criticisms (e.g., Sweller, 2011) cautioned that processing language and content simultaneously could overwhelm working memory, more recent empirical data indicates that hierarchical scaffolding actually lessens cognitive strain. By using visual anchors, gestures, and collaborative reasoning to sequence linguistic and intellectual demands, educators can turn possible overload into constructive challenge. This is consistent with Vygotskian views on the zone of proximal development, where language mediation acts as a link between common and scientific ideas. The caliber of the classroom conversation is equally crucial. Cognitively productive questioning (Nystrand, 2006) has been identified as a characteristic of effective CLIL lessons in numerous research. Learners displayed greater levels of reasoning and argumentation as addition to using more scientific terminology when teachers asked open-ended, introspective, and metacognitive questions. By fostering epistemic agency, these dialogic strategies empower students to create and defend scientific explanations instead of just replicating them. It is further supported by the frequent use of multimodal methods, such as simulations, visual models, and gestures, that the benefits of CLIL are semiotically mediated. These modalities reduce comprehension hurdles and foster conceptual transfer by grounding abstract language information in sensory experience. Thus, the most successful CLIL classrooms are multimodal ecosystems, where meaning-making is supported by the interaction of word, image, and action. One noteworthy conclusion from this review is that the main factor influencing CLIL success is instructor expertise. Students regularly performed better when their teachers were dual-competent in applied linguistics and STEM. This supports earlier studies (Dalton-Puffer, 2011; Meyer et al., 2015) that found that the key to integrated education is teacher professional competence. The capacity to coordinate two goals—balancing language accessibility and content rigor—while preserving epistemic authenticity is exhibited by effective CLIL educators. Contextual flexibility is another indicator of educational expertise that is highlighted in the review. Teachers in resource-constrained settings used discourse-based scaffolding, which includes controlled discussion, guided writing, and peer interaction, to make up for the lack of resources. This flexibility shows that the power of CLIL is found in locally responsive pedagogies that take sociolinguistic reality into account, rather than in imported approaches. According to Cheung and Ng (2025), when used purposefully, translanguaging techniques can maintain student engagement without compromising exposure to the target language. As a result, the ramifications go beyond specific classrooms and highlight the necessity of institutional structures that assist in specialized teacher preparation. Implementing CLIL sustainably requires methodical professional development programs that incorporate STEM teaching, linguistics, and cognitive science. Beyond quantifiable increases in vocabulary and literacy, the reviewed research indicate that CLIL changes students' perceptions of themselves as scientific knowers. Students start to view science as a human endeavor that involves communication rather than a collection of abstract facts through dialogic participation and language ownership. Seeing oneself as both a language user and a scientific thinker is an identity change that is one of CLIL's most significant but little-known achievements. By redefining linguistic hierarchies in multilingual environments, the approach enables students to use their entire verbal repertoire to understand scientific facts. These translanguaging settings give legitimacy to hybrid identities and enable students to confidently engage in disciplinary discourse (García & Wei, 2014). In postcolonial educational systems, where English-medium instruction frequently marginalizes local linguistic capital, this is especially important. Therefore, when used ethically and pedagogically, CLIL can serve as a democratizing pedagogy that values all linguistic resources as instruments for knowledge creation.

CONCLUSION

This review adds to the expanding body of research that places CLIL in the context of cognitive-linguistic theories of learning. It proves that language serves as a cognitive instrument for creating discipline knowledge in addition to being a means of communication. According to the findings, scientific literacy is a discourse-based competency that incorporates reasoning, explanation, and argumentation, going beyond text comprehension. Additionally, the review improves our conceptual understanding of how linguistic scaffolding supports conceptual evolution by synthesizing research from various age groups and circumstances. It provides a theoretically sound paradigm for bilingual STEM education by demonstrating how well planned CLIL training fosters the development of both language proficiency and scientific thinking. The results imply that CLIL should be acknowledged by policymakers as an evidence-based strategy for STEM literacy rather than only as a language innovation. Without compromising disciplinary depth, educational systems seeking to internationalize their curricula might use CLIL to advance language and scientific competencies. The ramifications are just as strong for teacher educators. Interdisciplinary literacy should be emphasized in pre-service and in-service training to equip instructors to create assignments that concurrently promote language and conceptual goals. To help teachers better scaffold learning, professional development should incorporate modules on genre pedagogy, discourse analysis, and cognitive load theory. The evidence backs up a number of specific classroom practices, including: incorporating clear language objectives into each science lesson; connecting abstract and concrete meaning through multimodal representations; using cognitively productive questioning techniques; and promoting organized student discussion around evidence-based reasoning. In multilingual classrooms, these techniques can help close the ongoing gap between language acquisition and topic mastery when applied methodically. Although this study provides strong evidence, it is important to take into account a number of methodological shortcomings. First, the capacity to conduct a comprehensive meta-analysis was constrained by variations in study designs and measuring instruments. Second, African and Central Asian CLIL implementations, where linguistic ecologies differ significantly, are underrepresented because the majority of studies were carried out in European and East Asian contexts. Cross-regional comparative designs and longitudinal approaches should be used in future studies to track long-term effects on academic writing and conceptual retention. Furthermore, new digital technologies like multimodal analytics and AI-driven language feedback tools open up new avenues for CLIL-STEM research. Examining the ways in which these tools mediate affect, cognition, and discourse may help develop equitable and scalable CLIL models for the digital age.

This review concludes by demonstrating that CLIL is a transformative pedagogy that bridges the artificial gap between disciplinary knowledge and language learning in order to promote scientific literacy. However, pedagogical intentionality—how teachers structure discourse, support multilingual meaning-making, and scaffold cognition—is more important to its effectiveness than the use of bilingual resources. CLIL proposes a sustained epistemic shift—from teaching about science in a language to teaching through language as science—as educational systems around the world grapple with the twin demands of linguistic diversity and scientific literacy.

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