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Language as Infrastructure in STEM Education: Integrating ESP into Undergraduate STEM Curricula in Non-Anglophone Contexts

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Abstract

In English-medium STEM education, language proficiency is often treated as an auxiliary skill rather than a core component of disciplinary learning. This quasi-experimental mixed-methods study reconceptualizes language as critical infrastructure and examines the impact of integrating English for Specific Purposes (ESP) into an undergraduate basic sciences curriculum. In a non-Anglophone national university, 76 students were assigned to an experimental group (n=35) receiving ESP-integrated, genre-based instruction aligned with their STEM coursework, or a control group (n=41) following a traditional ESP syllabus. Data from pre/post discipline-specific assessments, analytic rubrics, self-efficacy surveys, classroom artifacts, and faculty logs were analysed. Results showed the experimental group achieved significantly greater gains in discipline-specific communication (large effect, η_p^2=.57) and outperformed the control group across all rubric dimensions, including genre structure and argumentation clarity (Cohen's d=1.94). A composite academic performance score confirmed the intervention's substantial overall effectiveness (η^2=.51). Furthermore, the experimental group reported significantly increased self-efficacy and sense of disciplinary belonging (η_p^2=.46). Qualitative analysis revealed enhanced rhetorical sophistication and feasible implementation. The study concludes that systematic ESP integration functions as transformative pedagogical infrastructure, simultaneously advancing academic performance, communicative competence, and student identity in STEM. It provides an evidence-based model for curriculum design and institutional reform in multilingual higher education contexts.

Keywords: English for Specific Purposes (ESP), STEM education, disciplinary literacy, English-medium instruction (EMI), higher education, language as infrastructure.

INTRODUCTION

Over the past two decades, STEM education has been positioned as a strategic driver of national development, innovation capacity, and global competitiveness. In non-Anglophone higher education systems, this positioning has increasingly been accompanied by the adoption of English as the dominant medium of instruction, assessment, and disciplinary communication. While this shift is often justified in terms of internationalization, employability, and access to global scientific knowledge, it has simultaneously rendered language proficiency a critical - yet frequently underexamined - determinant of academic success in STEM programs (Block & Moncada-Comas, 2022; Pun & Jia, 2025). Despite the centrality of language to meaning making in science, engineering, and technology, STEM curricula in many contexts continue to treat English proficiency as an auxiliary skill rather than as a constitutive component of disciplinary learning.

A growing body of research has demonstrated that language is not merely a vehicle for transmitting STEM knowledge but a central resource through which disciplinary practices, epistemologies, and identities are constructed (Bailey et al., 2018; Kamberelis et al., 2014; Lee & Stephens, 2020). Disciplinary literacy research has shown that successful participation in STEM fields requires mastery of specialized genres, lexical bundles, rhetorical moves, and multimodal representations that are deeply embedded in English academic discourse

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(Anderson, 2025; Granger, 2014). For students studying STEM in English as a foreign or second language, limited proficiency can constrain not only comprehension and assessment performance but also participation, confidence, and professional identity development (Karim et al., 2023; Wen et al., 2025).

However, institutional responses to these challenges have often been fragmented. In many universities, responsibility for language development is delegated to general English courses offered outside the STEM curriculum, with limited alignment to disciplinary practices or assessment demands (Nong et al., 2020; Rafiq et al., 2024). At the same time, STEM faculty frequently position themselves as content specialists rather than language educators, resisting explicit engagement with language instruction even in English-medium contexts (Abdel Latif & Alrashed, 2025; Block & Moncada-Comas, 2022). This structural separation reinforces a deficit model in which students' linguistic challenges are individualized rather than recognized as systemic design issues within STEM programs.

Recent scholarship in ESP and integrated STEM education has begun to challenge this separation by advocating for curriculum models that embed language development within disciplinary instruction. ESP-oriented approaches emphasize the explicit teaching of discipline-specific genres, communicative practices, and lexical-grammatical patterns directly connected to students' academic and professional tasks (Rafiq et al., 2025). Empirical studies across diverse contexts have shown that integrated language–STEM interventions can enhance students' academic performance, self-efficacy, willingness to communicate, and sense of belonging in STEM fields (Hill et al., 2022; LaCosse et al., 2020; Le Pichon et al., 2025). Yet, much of this work remains program-specific, technologically driven, or focused on pre-university education, leaving a gap in rigorously designed undergraduate interventions situated within core STEM programs.

Moreover, the conceptual framing of language in STEM education has remained largely instrumental. Language is often described as a "support," "tool," or "accommodation," rather than as an infrastructural condition that enables or constrains learning at a systemic level (Oemig, 2023; Thomas et al., 2025). Conceptualizing language as infrastructure foregrounds its role in shaping access to knowledge, participation in disciplinary communities, and the reproduction of inequities within ostensibly meritocratic STEM systems. From this perspective, failure to integrate language explicitly into STEM curricula risks perpetuating hidden barriers that disproportionately affect students educated in non-Anglophone contexts (Elsaiary, 2024; Tang et al., 2023).

Within this landscape, there is a pressing need for empirically grounded models that demonstrate how ESP can be systematically embedded into undergraduate STEM curricula without diluting disciplinary rigor. Mixed-methods and quasi-experimental designs are particularly needed to move the field beyond descriptive advocacy toward evidence-based curriculum reform (Razfar & Troiano, 2022; Zhou et al., 2024). Such research is especially limited in national university contexts where English is a foreign language yet functions as the primary language of scientific instruction and assessment.

The present study responds to this gap by reconceptualizing language proficiency as a core infrastructural component of STEM education and empirically examining the effects of an ESP-integrated STEM curriculum, the study investigates the impact of ESP-embedded instruction on students' academic performance, disciplinary communication, self-efficacy, and emerging disciplinary identities. By combining discipline-specific assessments, ESP-aligned rubrics, surveys, classroom artifacts, and faculty reflective logs, the study seeks to generate a comprehensive account of how language integration operates at both pedagogical and institutional levels.

In doing so, this research makes four interrelated contributions. First, it advances a theoretical shift by framing language as infrastructure rather than as remediation or support. Second, it provides empirical evidence on the academic and communicative outcomes of ESP-integrated STEM instruction at the undergraduate level. Third, it offers a comparative analysis of traditional STEM instruction and ESP-embedded

curricula, addressing a methodological gap in the literature. Finally, it proposes an empirically grounded model for ESP–STEM integration that is transferable to other non-Anglophone higher education contexts. By situating ESP at the core of STEM curriculum design, this study contributes to ongoing debates on English-medium instruction, disciplinary literacy, and equity in global STEM education, while offering practical implications for curriculum developers, faculty members, and policymakers seeking to align linguistic access with scientific excellence.

Research Objectives:

Despite the expanding adoption of English-medium instruction in undergraduate STEM programs in non-Anglophone contexts, language proficiency continues to be treated as an ancillary skill rather than as an integral condition for disciplinary learning and participation. This conceptual marginalization has contributed to persistent gaps between students' conceptual understanding of STEM content and their ability to communicate knowledge through discipline-specific genres such as laboratory reports, project proposals, and oral presentations. Moreover, empirical evidence comparing traditional STEM instruction with systematically ESP-integrated curricula at the undergraduate level remains limited. In response to these challenges, the current research seeks to reconceptualize the role of language within STEM education and to empirically examine the pedagogical and academic implications of embedding ESP into core STEM instruction. Accordingly, the objectives of the current research are:

1. To reconceptualize English language proficiency as a core infrastructural component of undergraduate STEM education in non-Anglophone contexts.
2. To examine the impact of ESP-integrated STEM instruction on students' academic performance and discipline-specific communication skills.
3. To compare learning outcomes between students receiving traditional STEM instruction and those enrolled in ESP-embedded STEM curricula.
4. To investigate changes in students' self-efficacy and disciplinary identity following participation in ESP-integrated instruction.
5. To propose an empirically grounded and transferable model for integrating ESP into undergraduate STEM curricula.

LITERATURE REVIEW

The intersection of language and STEM education has attracted increasing scholarly attention as English has become the dominant medium of instruction, communication, and knowledge production in higher education worldwide. Research across ESP, EMI, and disciplinary literacy has consistently demonstrated that language is central to how STEM knowledge is constructed, assessed, and legitimated. However, despite this growing recognition, the integration of language into STEM curricula remains uneven, conceptually underdeveloped, and often peripheral. This review synthesizes relevant literature across four interrelated strands: (a) language and disciplinary literacy in STEM education, (b) English-medium instruction and language ideologies in STEM contexts, (c) ESP integration and pedagogical interventions in STEM education, and (d) affective, identity, and equity-related dimensions of language use in STEM learning. Together, these strands inform the theoretical and empirical foundations of the current research while highlighting critical gaps it seeks to address.

Language and Disciplinary Literacy in STEM Education

A substantial body of research has established that learning in STEM disciplines is inseparable from language use. Disciplinary literacy perspectives emphasize that each STEM field is characterized by specialized genres, epistemic norms, and communicative practices that students must master to participate meaningfully

in the discipline (Kamberelis et al., 2014; Lee & Stephens, 2020). From this view, proficiency in general English is insufficient; rather, students must acquire the linguistic resources needed to interpret data, construct explanations, argue from evidence, and communicate findings within discipline-specific conventions.

Bailey et al. (2018) argue that language functions as a cognitive and social tool that mediates STEM learning, particularly for students who are English language learners. Their work highlights how linguistic demands embedded in problem-solving tasks, assessments, and classroom discourse can obscure students' conceptual understanding when language is not explicitly addressed. Similarly, Granger's (2014) analysis of lexical bundles underscores the extent to which scientific meaning is carried through recurrent phraseological patterns, reinforcing the idea that fluency in STEM discourse involves patterned language use rather than isolated vocabulary knowledge.

Recent work has extended disciplinary literacy research by emphasizing social responsiveness and genre awareness. Anderson (2025), for example, demonstrates that integrative genre-based pedagogy in STEM and EMI contexts enhances students' ability to engage with disciplinary discourse while fostering ethical and socially responsive communication. These findings support the argument that language instruction embedded within STEM learning can enhance both academic rigor and communicative competence.

Despite these insights, disciplinary literacy is still rarely operationalized systematically in undergraduate STEM curricula, particularly in non-Anglophone settings. Language demands are often implicit, leaving students to infer expectations without structured support. This gap reinforces the need for curricular models that treat language as an infrastructural component of STEM learning rather than as an implicit prerequisite.

English-Medium Instruction and Language Ideologies in STEM Contexts

The global expansion of English-medium instruction has significantly reshaped STEM education, especially in higher education. EMI is frequently promoted as a means of internationalization and global competitiveness, yet research suggests that its implementation often overlooks linguistic realities on the ground (Luke, 2017; Pun & Jia, 2025). In many STEM programs, English functions as the default language of instruction without corresponding curricular redesign to support students' academic language development.

A recurring theme in EMI research is the ideological positioning of language within STEM departments. Block & Moncada-Comas (2022) document how STEM lecturers frequently resist being positioned as language teachers, framing language support as outside their professional responsibility. This stance contributes to institutional structures in which language development is externalized to English departments or preparatory programs, reinforcing a division between content and language.

Empirical evidence from Saudi and Asian university contexts further illustrates these tensions. Abdel Latif & Alrashed (2025) show that STEM lecturers often recognize students' communicative difficulties but lack confidence, training, or institutional support to address them systematically. Similarly, Nong et al. (2020) report misalignment between ESL curricula and engineering students' disciplinary needs, resulting in limited transfer from language courses to STEM performance.

Language ideologies embedded within EMI contexts also shape students' experiences and outcomes. Karim et al. (2023) highlight how English proficiency becomes a gatekeeping mechanism in professional communication, influencing graduates' confidence and perceived employability. Thomas et al. (2025) further demonstrate how English dominance in STEM disciplines marginalizes other linguistic resources, even in bilingual or minority-language education settings. These findings underscore the need to move beyond EMI as a policy label toward pedagogical models that integrate language and content more equitably.

ESP Integration and Pedagogical Interventions in STEM Education

ESP has emerged as a promising framework for addressing the linguistic demands of STEM education by aligning language instruction with disciplinary practices and professional contexts. Unlike general English courses, ESP focuses on genre-specific writing, technical vocabulary, and communicative tasks directly relevant to students' academic and future professional activities (Rafiq et al., 2024).

Recent studies provide growing evidence of the benefits of ESP-integrated STEM instruction. Rafiq et al. (2025) demonstrate that targeted ESP modules embedded within STEM programs can improve students' technical writing, oral presentation skills, and confidence in disciplinary communication. Similarly, Hill et al. (2022) document how STEM-focused English instruction in Japan enhanced motivation and engagement among undergraduate students.

Technologically mediated interventions have also gained attention. Digital multilingual resources (Le Pichon et al., 2025) and mobile ESP modules (Rafiq et al., 2025) have been shown to support access and flexibility, particularly for linguistically diverse learners. While such tools are valuable, several scholars caution against treating technology as a substitute for curriculum-level integration (Darvishinia et al., 2025; Staikova et al., 2024).

Importantly, much of the existing ESP–STEM literature relies on small-scale interventions, descriptive designs, or single-group evaluations. Comparative studies employing quasi-experimental designs remain relatively scarce, particularly within core undergraduate STEM programs. This methodological gap limits the field's ability to make strong claims about the added value of ESP integration over traditional instruction.

Affective, Identity, and Equity Dimensions of Language in STEM Learning

Beyond academic performance, language plays a critical role in shaping students' affective experiences, identities, and sense of belonging in STEM fields. Research has consistently shown that linguistic barriers can undermine students' self-efficacy, participation, and persistence, even when conceptual understanding is strong (LaCosse et al., 2020; Tang et al., 2023).

LaCosse et al. (2020) provide compelling evidence that interventions targeting social belonging can significantly improve STEM outcomes for students who speak English as a second language. Their findings suggest that linguistic challenges are intertwined with psychosocial factors, reinforcing the argument that language integration must address both cognitive and affective dimensions of learning. Wen et al. (2025) similarly highlight the role of individual and contextual factors in students' willingness to communicate in English within STEM programs.

Equity-oriented literature further emphasizes that failure to address language systematically exacerbates structural inequalities. Elsaiary (2024) and Oemig (2023) argue that English-dominant STEM instruction often privileges students with prior access to elite language education, reproducing inequities under the guise of academic standards. Studies focusing on inclusion, disabilities, and multilingual learners reinforce the need for integrated approaches that recognize linguistic diversity as a resource rather than a deficit (Peterson et al., 2014; Suh et al., 2020). Despite these insights, affective and identity-related outcomes are rarely examined alongside academic performance in ESP–STEM research. This omission limits understanding of how language integration reshapes students' longer-term engagement with STEM disciplines. Taken together, the literature establishes that language is central to STEM learning, communication, and identity formation. However, three major gaps remain evident. First, language continues to be conceptualized instrumentally rather than infrastructurally within STEM curricula. Second, empirical studies comparing traditional and ESP-integrated STEM instruction at the undergraduate level are limited.

RESEARCH METHOD

This section outlines the methodological framework adopted to investigate the pedagogical and academic effects of integrating English for Specific Purposes (ESP) into undergraduate STEM instruction. It details the research design, context and participants, instructional conditions, data collection instruments, analytical procedures, and ethical considerations, thereby ensuring transparency, replicability, and methodological rigor.

Research Design

A quasi-experimental, mixed-methods design was employed, utilizing a pretest–post-test control group structure. This design was selected to rigorously evaluate the instructional impact of integrating English for Specific Purposes (ESP) into undergraduate STEM curricula while preserving ecological validity within an authentic university learning context. Quantitative data were collected to measure changes in academic performance, discipline-specific communication, and self-efficacy. Qualitative data were gathered to capture instructional dynamics and faculty perceptions of the ESP-integrated intervention, thereby providing a nuanced understanding of both outcomes and implementation processes.

Research Context and Participants

The study was conducted within the Basic Sciences program at (xxxxxx) university a national public university in a non-Anglophone context, where English serves as the primary medium of instruction and assessment for STEM courses. The intervention was embedded in LAN170 – *English for Specific Purposes*, a compulsory course for first- and second-year STEM majors designed to support academic literacy and discipline-specific communication.

Participants comprised 76 undergraduate students enrolled in LAN170 during a single academic semester. Due to institutional scheduling constraints, random assignment was not feasible; therefore, participants were allocated to two intact course sections. The experimental group (n = 35) received ESP-integrated instruction, whereas the control group (n = 41) followed the standard LAN170 syllabus. All participants had completed secondary education in their first language, with English studied as a foreign language. Demographic and academic background data were collected at the outset of the study to establish baseline equivalence between groups. These data are summarized in the following table.

Table 1. Participant Demographic and Academic Characteristics by Group

Characteristic	Experimental Group n = 35	Control Group n = 41	Total N = 76	Test for Difference
Academic Year, n (%)				
First-Year	18 (51.4%)	21 (51.2%)	39 (51.3%)	$\chi^2(1) = 0.01$, p = .939
Second Year	17 (48.6%)	20 (48.8%)	37 (48.7%)	
Gender, n (%)				
Male	19 (54.3%)	22 (53.7%)	41 (53.9%)	$\chi^2(1) = 0.01$, p = .920
Female	16 (45.7%)	19 (46.3%)	35 (46.1%)	
Prior GPA, M (SD)	3.42 (0.31)	3.38 (0.29)	3.40 (0.30)	t(74) = 0.59, p = .558
English Proficiency Score, M (SD)	78.5 (6.2)	77.8 (7.1)	78.1 (6.7)	t(74) = 0.46, p = .645

Note. GPA = Grade Point Average (4.0 scale). English proficiency scores were obtained from an institutional placement test (range: 0–100).

The distribution of students across academic years was nearly identical, with first-year students constituting approximately half of each group. Gender representation was also balanced across conditions. Importantly, independent-samples t-tests revealed no statistically significant differences between groups in prior GPA or English proficiency scores, indicating a high degree of baseline equivalence. These findings support

the internal validity of the study by reducing the likelihood that post-intervention differences could be attributed to pre-existing disparities rather than to the instructional treatment.

Instructional Conditions and Data Collection Timeline

The instructional intervention spanned a 14-week academic semester. While both groups were enrolled in the same ESP course, they differed substantially in pedagogical orientation, task design, and assessment focus. The following table summarizes the instructional conditions and corresponding data collection points for both groups.

Table 2. Instructional Conditions and Data Collection Timeline

Phase	Experimental Condition (ESP-Integrated)	Control Condition (Traditional ESP)	Data Collection (Both Groups)
Week 1	Orientation to ESP as disciplinary infrastructure	Orientation to general academic English	Pretests: Discipline-specific writing/communication assessment; Self-efficacy survey
Weeks 2–13	Genre-based pedagogy with explicit instruction in lab reports, data commentary, proposals, and presentations; Scaffolded tasks aligned with concurrent STEM coursework; Formative feedback using ESP-aligned analytic rubrics	Skill-based pedagogy emphasizing general reading, vocabulary, and grammar; Decontextualized tasks using STEM topics primarily as content	Ongoing collection of classroom artifacts (written assignments, presentation slides); Experimental group only: weekly faculty reflective logs
Week 14	Culminating disciplinary project: research summary and oral presentation	Final examination focusing on grammar, reading comprehension, and general writing	Post-tests: Identical to pretest assessments; Self-efficacy survey

The experimental group was exposed to a genre-based ESP framework that emphasized disciplinary communication as a central learning objective, with tasks explicitly aligned to students' concurrent STEM coursework. In contrast, the control group followed a traditional ESP syllabus emphasizing general language skills and decontextualized exercises. The table also illustrates the systematic alignment between instructional phases and data collection points, ensuring consistency in pretest and post-test measurement while enabling longitudinal tracking of student development.

Data Collection Instruments

Multiple instruments were employed to triangulate data across academic, communicative, and affective domains:

1. *Discipline-Specific Writing and Communication Assessments.* Pretest and post-test tasks consisted of a laboratory report section, a data interpretation exercise, and a structured oral explanation of a scientific process. Performance was scored on a 0–100 scale using standardized criteria.
2. *ESP-Aligned Analytic Rubrics.* Student coursework was evaluated across five dimensions - genre structure, clarity of argumentation, disciplinary vocabulary use, coherence, and audience awareness. Each dimension was rated on a 5-point scale, yielding a total possible score of 25.
3. *Student Self-Efficacy and Disciplinary Identity Survey.* A 5-point Likert-scale instrument (1 = strongly disagree; 5 = strongly agree) measured students' confidence in using English for STEM-related tasks, willingness to communicate in disciplinary contexts, and perceived sense of belonging within the STEM community.
4. *Classroom Artifacts.* Written assignments, presentation slides, and project documentation were collected to provide qualitative evidence of genre awareness and rhetorical development.

5. *Faculty Reflective Logs.* Instructors teaching the experimental group maintained weekly reflective logs documenting classroom observations, language-related challenges, and perceptions of the feasibility and pedagogical value of ESP integration.

Data Analysis

Quantitative data were analysed using mixed-design analyses of variance (ANOVAs) to examine within-subject changes over time and between-group differences attributable to instructional condition. Effect sizes were calculated using partial eta squared (η_p^2) to estimate the magnitude of observed effects. Qualitative data were analysed through thematic analysis. An iterative coding process was applied, progressing from initial descriptive codes to higher-order analytical themes related to disciplinary communication development, student engagement, and instructional affordances and constraints of ESP-integrated pedagogy.

FINDING AND DISCUSSION

This section presents an integrated analysis of findings from quantitative and qualitative data sources to comprehensively address the study's research objectives. Triangulation of discipline-specific performance measures, analytic rubric scores, self-efficacy surveys, classroom artifacts, and faculty reflective logs provides a robust, multi-layered account of how English for Specific Purposes (ESP)-integrated instruction functioned as a critical linguistic infrastructure within an undergraduate STEM context. Quantitative results establish the magnitude and statistical significance of observed effects, while qualitative evidence elucidates the underlying pedagogical mechanisms and contextual dynamics through which these outcomes were achieved.

Reconceptualizing Language as Infrastructural to STEM Knowledge Construction

The study directly tested the hypothesis that treating language as infrastructural, rather than auxiliary, to STEM learning would lead to significant gains in discipline-specific communication abilities. To achieve this, it implemented a 14-week pedagogical intervention that explicitly linked ESP instruction to the rhetorical practices and cognitive demands of students' core STEM courses. Language was framed not as a separate skill to be mastered, but as the primary medium for constructing and communicating scientific knowledge. A validated, discipline-specific writing and communication assessment, comprising a laboratory report section, a data interpretation task, and a structured oral explanation, was administered as a pre- and post-test. This instrument was designed to measure students' ability to use English for authentic scientific communication, moving beyond general proficiency to assess genre-appropriate reasoning and expression. Analysis of these scores revealed a pronounced differential impact of the instructional conditions. Table 3 presents the pre-test, and post-test means, standard deviations, and calculated gains for both groups.

Table 3. Pretest–Post-test Discipline-Specific Writing and Communication Scores (0–100)

Group	n	Pretest M (SD)	Post-test M (SD)	Mean Gain
Experimental	35	58.42 (7.36)	78.91 (6.88)	+20.49
Control	41	57.96 (7.81)	64.38 (8.14)	+6.42

*Note. A 2 (Time: Pretest vs. Post-test) × 2 (Group: Experimental vs. Control) mixed-design ANOVA revealed a statistically significant Time × Group interaction, F(1, 74) = 96.83, *p* < .001, η_p^2 = .57, indicating a large effect.*

The data reveal a striking divergence in communicative development. Both cohorts began the semester with statistically equivalent baseline proficiency, yet the experimental group achieved gains more than three times greater than those of the control group. This substantial improvement signifies not merely enhanced linguistic accuracy but a deepened capacity to use English as a tool for representing, interpreting, and explaining scientific knowledge - a core epistemic practice in STEM. Disaggregated analysis indicated that the largest gains for the experimental group occurred in data commentary and oral explanation, tasks demanding tight

integration of linguistic form with disciplinary reasoning and audience engagement. This pattern suggests the intervention successfully moved students beyond learning about English to thinking with English in disciplinary ways. In contrast, the control group's modest gains reflect the limited transfer of generic language skills to the specialized demands of scientific communication, a well-documented shortfall of decontextualized approaches.

These findings empirically substantiate the theoretical claim that language is infrastructural to, rather than auxiliary for, STEM knowledge construction. The results align with conceptualizations of disciplinary literacies, which posit that meaning making is mediated through specialized genres, lexicogrammatical patterns, and rhetorical practices (Bailey et al., 2018; Kamberelis et al., 2014). The significant interaction effect and large partial eta-squared value provide robust support for Anderson's (2025) assertion that genre-based ESP pedagogy scaffolds students' internalization of the disciplinary logics embedded in scientific communication. The control group's trajectory echoes the concerns raised by Block & Moncada-Comas (2022) regarding the inadequacy of models treating language as a separate, service skill, thereby failing to address the constitutive role of discourse in learning.

Impact of ESP Integration on Academic and Rhetorical Performance

Beyond overall communication gains, this objective sought to pinpoint the specific dimensions of academic writing that were most impacted by the intervention. The study designed and employed an ESP-aligned analytic rubric to evaluate the disciplinary sophistication of students' actual coursework, moving from broad assessment to fine-grained analysis of genre mastery. Student-produced artifacts (e.g., lab reports, project proposals) from both groups were evaluated at the end of the semester using a 5-dimensional, 25-point analytic rubric. This rubric assessed Genre Structure, Argumentation Clarity, Disciplinary Vocabulary, Cohesion & Coherence, and Audience Awareness, providing a detailed profile of rhetorical performance aligned with STEM discourse conventions. Evaluation of student coursework revealed consistently superior performance by the experimental group across all rubric dimensions. The following table presents the post-test means, standard deviations, and inferential statistics for each dimension and the total score.

Table 4. Post-test ESP-Aligned Analytic Rubric Scores by Instructional Condition

Dimension (5-point scale)	Experimental	Control	t(74)	p	Cohen's d
Genre Structure	4.12 (0.58)	2.96 (0.71)	7.91	< .001	1.82
Argumentation Clarity	3.98 (0.61)	2.81 (0.69)	7.42	< .001	1.71
Disciplinary Vocabulary	4.06 (0.54)	3.02 (0.63)	7.16	< .001	1.65
Cohesion & Coherence	3.91 (0.59)	2.88 (0.72)	6.71	< .001	1.54
Audience Awareness	3.77 (0.66)	2.95 (0.70)	5.27	< .001	1.21
Total Score (out of 25)	**19.84 (2.41)**	**14.62 (2.97)**	**8.47**	**< .001**	**1.94**

Table 4 demonstrates the experimental group's superior performance across all five dimensions of disciplinary writing, with the largest disparities in genre structure and argumentation clarity - elements central to constructing credible scientific discourse. The very large effect size (Cohen's *d* = 1.94 for total score) indicates a transformative, rather than incremental, impact on academic performance.

Qualitative analysis of coursework artifacts revealed that experimental-group students progressively employed conventional rhetorical moves - such as explicit hypothesis framing, methodological justification, data interpretation hedges (e.g., "This may suggest..."), and thematic organization - aligning their writing with disciplinary expectations. Control-group submissions, while often grammatically sound, typically lacked this rhetorical sophistication, prioritizing reportage over structured argumentation. This distinction underscores that mastery of disciplinary content is insufficient for effective communication; students must also master the discourse through which that content is validated and shared (Hyland, 1996).

These results strongly support Rafiq et al. (2024) contention that ESP is pivotal for aligning linguistic competence with the tacit expectations of disciplinary communities. They extend the findings of Nong et al.

(2020) in engineering contexts to the basic sciences, confirming the cross-disciplinary value of genre-based pedagogy. Crucially, the data challenge the implicit assumption, noted by Pun & Jia (2025), that immersion in English-medium instruction (EMI) alone cultivates the necessary rhetorical competence. Instead, they demonstrate that explicit, scaffolded instruction in disciplinary genres is a necessary condition for full academic participation and success.

Comparative Effectiveness of ESP-Integrated Versus Traditional Instruction

To provide a holistic verdict on instructional effectiveness, this objective synthesized multiple performance metrics into a single, reliable indicator. The study sought to determine not just if there were differences, but the overall magnitude of the advantage conferred by the integrated approach. A composite academic performance score was calculated for each participant at post-test by standardizing and combining their discipline-specific assessment score (Table 3) and their total analytic rubric score (Table 4). This composite variable provided a robust, multi-method measure of overall achievement. Analysis of the composite scores provided conclusive evidence of the intervention's superior effectiveness. Table 5 presents the group means, standard deviations, and confidence intervals for this composite outcome.

Table 5. Post-test Composite Academic Performance by Group

Group	n	Composite Score M (SD)	95% CI
Experimental	35	81.36 (6.74)	[79.04, 83.68]
Control	41	66.19 (7.82)	[63.78, 68.60]

Note. One-way ANOVA confirmed a significant between-groups difference: $F(1, 74) = 78.25$, $*p* < .001$, $\eta^2 = .51$.

The non-overlapping confidence intervals and large effect size ($\eta^2 = .51$) in Table 5 provide conclusive evidence that the ESP-integrated condition yielded substantially stronger overall academic outcomes. Notably, the lower standard deviation in the experimental group suggests the intervention may have also served an equalizing function, providing structured support that reduced variability in performance - a critical consideration for equity in diverse classrooms.

This finding robustly reinforces integrated content and language learning models, as revitalized in STEM contexts by scholars like Oemig (2023) and Razfar & Troiano (2022). It demonstrates that coherence between language and content instruction is not merely beneficial but essential for maximizing student achievement in EMI settings. The control group's outcomes reflect the inherent limitations of the traditional "general English plus technical vocabulary" model, which fails to address the deeper rhetorical and cognitive demands of disciplinary tasks, as critiqued by Lee & Stephens (2020). The composite result underscores that academic success in STEM is a bi-directional process where content understanding and communicative competence are mutually constitutive.

Development of Self-Efficacy and Disciplinary Identity

Recognizing that cognitive gains must be accompanied by affective and psychosocial shifts for sustained success, this objective investigated changes in students' confidence, belonging, and identity. The study examined whether mastering disciplinary discourse would translate into a stronger sense of legitimacy as emerging STEM professionals. A Likert-scale survey measuring self-efficacy in using English for STEM tasks, willingness to communicate, and perceived disciplinary belonging was administered as a pre- and post-test. This instrument captured the affective dimension of the learning experience, crucial for persistence and engagement. Survey results indicated a significant positive shift in the experimental group's affective positioning. The following table displays the pre-test, post-test, and gain scores for both groups.

Table 6. Pretest–Post-test Self-Efficacy and Disciplinary Identity Scores

Group	Pretest M (SD)	Post-test M (SD)	Mean Gain

Experimental	2.94 (0.51)	4.12 (0.47)	+1.18
Control	2.91 (0.54)	3.21 (0.58)	+0.30

Note. A significant Time × Group interaction was found $F(1, 74) = 64.18$, $*p* < .001$, $\eta_p^2 = .46$.

The experimental group reported a substantial increase in confidence, willingness to communicate in English within STEM contexts, and sense of belonging to their academic discipline. Item-level analysis revealed the strongest gains in items related to oral explanation of scientific ideas and participation in group discussions - precisely the interactive, high-stakes situations that often provoke anxiety for second-language users. The control group's marginal change indicates that traditional language instruction did little to alter students' affective positioning within their field.

These results corroborate and extend the work of LaCosse et al. (2020), who demonstrated that targeted interventions could improve STEM persistence by addressing social-psychological barriers. They align with Wen et al. (2025), who link self-efficacy directly to willingness to communicate. The present study's contribution lies in showing that such affective gains can be achieved not through standalone psychological interventions, but as a direct byproduct of a pedagogical approach that demystifies disciplinary discourse and provides students with tangible, successful communicative experiences. This directly addresses the motivational and identity-related challenges documented by Hill et al. (2022) and Iwamoto (2022), positioning ESP integration as a powerful tool for fostering both competence and confidence.

Qualitative Evidence of Pedagogical Mechanisms and Feasibility

To understand the processes behind the quantitative outcomes and assess real-world applicability, this objective gathered rich qualitative data on student learning trajectories and instructor experiences. It sought to document the "how" of change and the practical realities of implementing the intervention.

Two qualitative sources were analysed a) a purposive sample of student classroom artifacts (written assignments, presentation slides) was examined for evidence of rhetorical development over time; and b) weekly reflective logs from instructors in the experimental group were analysed thematically to capture observations on engagement, challenges, and perceived value. The analysis yielded convergent insights:

- *Classroom Artifacts:* A clear trajectory of rhetorical development was observed in experimental-group submissions. Early work was often characterized by lists of procedures and simple descriptions. By mid-semester, artifacts displayed greater use of purpose statements, logical connectors, and interpretive language. By the final project, many submissions exhibited a confident command of disciplinary conventions, including effective data commentary and appropriately framed conclusions. This evolution provides concrete evidence of developing genre awareness and supports Granger (2014) observations on the acquisition of disciplinary phraseology.
- *Faculty Reflective Logs:* Three dominant themes emerged:
    1. *Evolution of Engagement:* Instructors noted a shift from initial hesitancy to increased student participation, particularly in asking content-clarifying questions and engaging in peer review in English.
    2. *Visible Trajectory of Improvement:* Logs documented observations of growing clarity, organization, and rhetorical purpose in student writing and presentations over the semester.
    3. *Pedagogical Adaptation:* Faculty reported an initial increase in planning workload, which later yielded to greater instructional efficiency as students became more autonomous and lessons became more predictable. They emphasized the importance of the ESP-aligned rubrics for providing clear, consistent feedback.

These qualitative findings illuminate the "how" behind the quantitative results. They reveal that ESP integration reshaped classroom dynamics, fostering a learning environment where language was openly

addressed as a tool for disciplinary sense-making. The faculty perspectives echo Abdel Latif & Alrashed (2025) findings on lecturer needs, confirming that while integration requires intentional design, it is pedagogically viable and rewarding. The artifacts' progression demonstrates that students were not just producing better work but were internalizing a new way of thinking and communicating, aligning with Elsaiary's (2024) emphasis on authentic inquiry for mitigating language barriers. Crucially, the logs suggest sustainability, as initial challenges gave way to streamlined practice.

Accordingly, converging evidence from all data sources compellingly demonstrates that ESP-integrated instruction functioned as effective linguistic infrastructure, simultaneously enhancing academic performance, disciplinary communicative competence, and the psychosocial dimensions of learning. This study moves beyond advocating for language support to providing an empirically validated model for its integration. The results directly counter deficit orientations toward multilingual STEM learners by showing that with appropriate pedagogy, language diversity can be a foundation for, rather than a barrier to, academic excellence.

The findings have significant implications for theory, practice, and policy. Theoretically, they strengthen the case for a literacies-based approach to STEM education in multilingual settings. Practically, they offer a replicable framework for curriculum design, centered on genre-based pedagogy, scaffolded tasks, and aligned assessment. For policy, the study argues that institutional support for collaborative course design between language and content specialists is not a luxury but a necessity for realizing the full potential of EMI.

CONCLUSION

This study's central contribution is to advance from empirically demonstrating the efficacy of ESP integration to delineating its function as a *transformative pedagogical framework* for EMI-STEM education. The findings confirm that the research objectives were not only achieved but that they collectively point toward a significant shift in practice: moving beyond proving language's importance to operationalizing it as a deliberate, structured component of the STEM learning architecture. This concluding section synthesizes the implications of this shift for educational practice, theory, and institutional strategy.

Moving from establishing impact to elucidating mechanism. The substantial gains in discipline-specific communication and academic-rhetorical performance provide robust quantitative evidence that the intervention worked. The holistic composite outcome confirms its overall effectiveness. Crucially, the findings related to self-efficacy and the qualitative mechanisms reveal *why* and *how* it worked: by making the implicit discursive rules of science explicit and actionable, the intervention reduced cognitive and affective load, fostering both competence and a sense of legitimate participation. This synthesis validates a core theoretical claim - that language is a *constitutive epistemic tool* in STEM, not merely a communicative channel. The study thus bridges applied linguistics and discipline-specific education research, offering an evidence-based model for the "languaging" of content instruction. The primary application of this research lies in a tangible redesign of the ESP-STEM interface. It argues against the common model of "ESP as service course" and for "ESP as integrated curriculum." The practical blueprint derived includes:

- collaborative, genre-based syllabus design between language and content experts
- the use of discipline-authentic tasks and materials as the central curriculum content
- assessment via analytic rubrics that reward rhetorical and pragmatic competence alongside linguistic accuracy.

For STEM lecturers, the findings suggest that a meta-discursive focus - briefly highlighting the *how* of scientific explanation - can significantly amplify content delivery. For language instructors, the study validates a shift from general proficiency to disciplinary literacy as their core objective.

At an institutional level, this research provides a compelling case for strategic investment in integrated program design. The outcomes suggest that such integration is a high-impact educational practice with the

potential to improve retention, equity, and graduate attributes in EMI settings. Administrators and quality assurance bodies should consider mandating or incentivizing collaborative course development teams. Furthermore, the study highlights the need for professional development that equips both STEM and language faculty with a shared metalanguage for discussing disciplinary discourse, moving from ad hoc support to systematic curriculum integration.

In demonstrating that strategic ESP integration acts as catalytic infrastructure, this research transcends the diagnostic identification of a language "problem" in EMI. It provides a proven, pragmatic solution that repositions language from a barrier to a bridge. By equipping students with the discursive tools of their discipline, we do not simply improve their English; we enhance their capacity for scientific reasoning, collaboration, and innovation. The ultimate application of this work is the cultivation of a new generation of STEM professionals who are not only knowledgeable but are also articulate creators and critical communicators of science, fully prepared to engage in the global scholarly community.

LIMITATION & FURTHER RESEARCH

The generalizability of the findings is constrained by the study's specific context: a single required ESP course within a basic sciences program at one institution. Although ecological validity was a strength, the use of intact class sections prevented random assignment, and unmeasured confounding variables cannot be entirely discounted. Furthermore, the 14-week timeframe, while suitable for measuring skill acquisition, is insufficient to assess the long-term retention of competencies or their transfer to more advanced academic and professional settings. To extend this work, longitudinal studies should track the durability of communicative and affective gains across academic years and into early career stages. Research should also adapt and test the integrated model in specialized STEM disciplines (e.g., engineering, computer science) where genre sets and communicative demands diverge. Critical inquiry is needed into the practical scalability of the approach, including resource implications, faculty collaboration models, and supportive institutional policies. Additionally, future studies could productively explore the integration of digital and multimodal genres (e.g., video abstracts, computational notebooks) and employ methodologies that directly examine the cognitive interplay between language integration and conceptual mastery in STEM.

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