



BRIDGING SCIENCE, MATHEMATICS, AND BUSINESS EDUCATION: EFFECTS OF INTERDISCIPLINARY CASE-BASED LEARNING ON STUDENTS' ANALYTICAL AND ENTREPRENEURIAL COMPETENCIES

(Research article)

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Abstract

The integration of business contexts into science and mathematics curricula represents a promising yet underexplored pedagogical frontier. This quasi-experimental study examined the effects of an Interdisciplinary Case-Based Learning (ICBL) approach on the analytical and entrepreneurial competencies of 242 undergraduate students across two Turkish universities. Because the study was fully embedded within routine course delivery, collected only anonymized academic performance data, and posed no foreseeable risk of harm, it was classified as exempt from formal institutional ethics committee review in accordance with the Turkish Higher Education Quality Council (YÖKAK, 2020) guidelines and the policies of both participating institutions. In keeping with principles of research integrity, all data collection was conducted on a strictly voluntary basis: students received a detailed written information sheet at the outset, were free to decline or withdraw at any time without academic penalty, and non-participants continued to receive identical instruction. Voluntary participation rates exceeded 93% at both sites, and baseline comparisons confirmed the absence of systematic self-selection bias (GPA: $p = .47$; gender: $p = .61$). Participants were assigned to either an ICBL experimental group ($n = 124$) or a traditional instruction control group ($n = 118$) at the course-section level over a 14-week intervention period. Instruments included the Analytical Competency Assessment Scale (ACAS), the Entrepreneurial Competency Inventory (ECI), and structured reflective journals analysed via thematic analysis. Findings revealed statistically significant gains across all five measured competency dimensions in the experimental group ($p < .001$, Cohen's d range = 0.81–1.21), substantially exceeding gains in the control group. Qualitative analysis identified three emergent themes: contextualized meaning-making, cross-disciplinary transfer, and real-world problem ownership. These results suggest that ICBL effectively cultivates both analytical rigor and entrepreneurial mindset within a transparent, participant-centred research framework, offering a replicable model for STEM educators seeking to integrate business literacy. Implications for curriculum design, teacher professional development, and future research directions are discussed.

Keywords: interdisciplinary education; entrepreneurial competency; case-based learning; Education

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1. Introduction

Contemporary educational systems face persistent pressure to prepare graduates who can navigate complexity across disciplinary boundaries. While science and mathematics education have long shared methodological common ground both rely on systematic inquiry, quantitative reasoning, and evidence-based argumentation, the deliberate integration of business contexts into these disciplines remains a peripheral concern in most curricula (National Academies of Sciences, Engineering, and Medicine [NASEM], 2019). Yet economic forecasts consistently highlight the need for graduates capable of translating technical expertise into commercially viable solutions (World Economic Forum [WEF], 2023). With reference to the coronavirus pandemic, digital equality is a key component of educational equality that is part of the summit of social equality, particularly when considering education and technological learning. (Albaqami, H. M. R. 2026).

Case-based learning (CBL) has demonstrated considerable efficacy in professional education contexts, particularly in law, medicine, and business administration (Herreid & Schiller, 2013; Kim et al., 2021). Its application in science and mathematics education, however, has been less systematic. Fewer studies still have examined what happens when the case scenarios used in STEM instruction are drawn explicitly from business environments scenarios that require learners simultaneously to apply quantitative reasoning, interpret scientific evidence, and exercise entrepreneurial judgment (English, 2016; Venkataraman, 2019). This gap motivates the present investigation. We propose and test an Interdisciplinary Case-Based Learning (ICBL) framework that deliberately situates mathematical modelling and scientific inquiry within authentic business decision-making contexts. Our overarching research question is: To what extent does participation in an ICBL programme produce greater gains in analytical and entrepreneurial competencies compared with traditional instruction?

The study contributes to three bodies of literature. First, it extends theoretical accounts of interdisciplinary learning by providing empirical data on how boundary-crossing pedagogies develop measurable competencies (Klein, 2017). Second, it responds to calls within the science and mathematics education community for ecologically valid, professionally contextualized learning environments (Sherin et al., 2015). Third, it speaks directly to entrepreneurship education scholars who have long argued that entrepreneurial thinking can and should be cultivated in disciplines beyond business schools (Neck & Greene, 2011; Lackéus, 2015).

1.1. *Theoretical Background*

The ICBL framework developed here is grounded in three complementary theoretical traditions. Situated cognition theory (Lave & Wenger, 1991) holds that knowledge is most durably acquired when embedded within authentic communities of practice. Business case scenarios constitute precisely such authentic environments: they present real-world constraints, ambiguous information, and consequential decisions that mirror professional practice. When

science and mathematics content is encountered within such settings, learners are more likely to engage in the kind of deep processing that supports transfer (Bransford et al., 2000).

Transformative learning theory (Mezirow, 1991, 2000) provides a second theoretical anchor. Mezirow's account of perspective transformation—the reorganization of learners' meaning-making frameworks through critical reflection—offers a mechanism by which interdisciplinary exposure can reshape not only competencies but dispositions. The entrepreneurial competency construct involves dispositional elements such as tolerance for ambiguity, proactive orientation, and opportunity recognition that are unlikely to develop through content transmission alone (Lackéus, 2015; Piperopoulos & Dimov, 2015).

A third strand draws on complexity theory and systems thinking in education (Davis & Sumara, 2006). Business decision-making inherently involves complex, dynamic systems; integrating such problems into science and mathematics teaching may cultivate the systemic perspective that researchers identify as central to twenty-first century competence (Dede, 2010; Care et al., 2018).

1.2. Purpose and Research Questions

The purpose of this study is to evaluate the effectiveness of an ICBL program on the development of analytical and entrepreneurial competencies among undergraduate students in science and mathematics-related programs at two Turkish universities. Specifically, we address the following research questions:

1. Does participation in the ICBL programme produce significantly greater gains in analytical competency compared with traditional instruction?
2. Does participation in the ICBL programme produce significantly greater gains in entrepreneurial competency compared with traditional instruction?
3. What qualitative themes emerge from student reflective journals regarding their experience of learning in an interdisciplinary business-contextualized environment?

2. Literature Review

2.1. Case-Based Learning in STEM Contexts

Case-based learning originated in legal education at Harvard Law School in the 1870s and subsequently became foundational in medical and business education (Herreid, 1994). Its migration into STEM education accelerated with the publication of landmark studies demonstrating superior conceptual retention and problem-solving performance relative to lecture-based instruction (Hmelo-Silver, 2004; Savery, 2015). Systematic reviews confirm positive effects of CBL on motivation, critical thinking, and collaborative skills across STEM disciplines (Kek & Huijser, 2011; Merritt et al., 2017). However, most STEM case-based studies use cases drawn from natural sciences or engineering, with business scenarios appearing only incidentally. English (2016) noted that mathematical modelling tasks embedded in economic contexts tend to elicit richer forms of reasoning than purely abstract tasks, yet curriculum implementation at scale remains rare. Kim et al. (2021) found that undergraduate biology

students exposed to business-modelling cases outperformed peers on both content knowledge and applied reasoning measures, suggesting that the integration is not merely cosmetic but cognitively consequential.

2.2. *Entrepreneurial Competency and Education*

Entrepreneurial competency is a multidimensional construct encompassing knowledge, skills, and attitudes that enable individuals to create value under uncertainty (Man et al., 2002; Bird, 1995). Competency frameworks developed by the European Commission (EntreComp; Bacigalupo et al., 2016) identify three core areas: Ideas and Opportunities, Resources, and Into Action—each involving cognitive, affective, and behavioral sub-components. Crucially, the EntreComp framework explicitly positions entrepreneurial competency as relevant for all citizens, not exclusively for aspiring business founders.

Educational interventions targeting entrepreneurial competency in non-business disciplines have produced mixed but generally positive results (Piperopoulos & Dimov, 2015; Lackeus, 2015; Fayolle & Gailly, 2015). Neck and Greene (2011) argue that a practice-based approach in which learners repeatedly design, test, and reflect on value-creating activities produces more durable competency development than lecture-based entrepreneurship courses. ICBL's emphasis on iterative case analysis aligns closely with this practice-based logic.

2.3. *Interdisciplinary Learning and Transfer*

Transfer of learning the ability to apply knowledge developed in one context to solve problems in a different context is widely regarded as a central goal of education (Bransford et al., 2000; Haskell, 2001). Interdisciplinary instruction is often advocated as a means of promoting far transfer because it requires learners to identify structural similarities across surface-level differences (Klein, 2017; Czerniak & Johnson, 2014). Empirical evidence, while still accumulating, supports the hypothesis that sustained exposure to interdisciplinary problems enhances transfer performance (Care et al., 2018; Mansilla & Jackson, 2011).

Beane (1997) distinguished between multidisciplinary approaches, in which content from different disciplines is juxtaposed, and genuinely integrative approaches, in which disciplinary boundaries are dissolved in the service of authentic inquiry. ICBL as designed here aspires to the latter: business cases are not appended to science and mathematics content but provide the generative problem context within which content is encountered and applied. This design choice reflects recommendations from recent synthesis studies (English, 2016; Sherin et al., 2006) and distinguishes ICBL from earlier, less theoretically principled attempts at integration.

2.4. *Research Gaps*

Despite the theoretical promise and supporting evidence from related literature, three gaps justify the present study. First, no published study has simultaneously measured both analytical and entrepreneurial competency outcomes of an ICBL program in a STEM undergraduate context. Second, existing quasi-experimental studies in this area have typically employed small, convenience samples at single institutions; the present study's two-site design with a combined sample of 242 participants represents a methodological advance. Third, qualitative investigations of how students experience interdisciplinary business cases within STEM

instruction are largely absent, leaving the mechanisms of any observed effects poorly understood.

3. Conceptual Framework

Figure 1 presents the ICBL conceptual framework guiding this study. The framework posits that three disciplinary domains Science Education, Mathematics Education, and Business Education each contribute distinctive epistemic practices and knowledge forms. In traditional curricula, these domains operate in relative isolation. ICBL creates an integrative pedagogical space using authentic, complex business cases that require learners to draw simultaneously scientific reasoning, quantitative analysis, and entrepreneurial judgment.

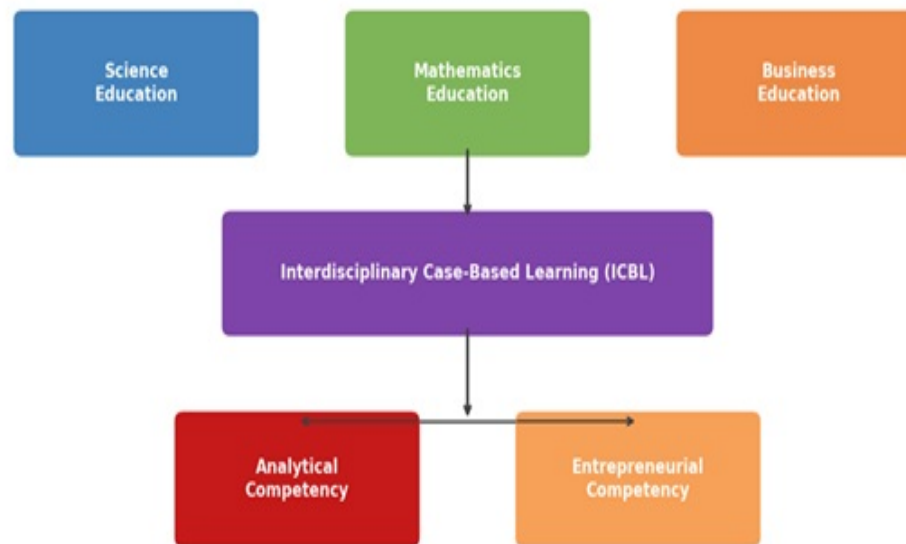


Figure 1. Conceptual Framework of Interdisciplinary Case-Based Learning (ICBL)

The outputs of sustained ICBL engagement are hypothesized to be two reinforcing competency clusters: Analytical Competency, comprising analytical thinking, quantitative reasoning, and problem solving; and Entrepreneurial Competency, comprising business acumen and entrepreneurial intent. The framework is recursive: developed competencies feed back into learners' capacity to engage with subsequent, more complex cases. Moderating variables not depicted for clarity include prior domain knowledge, instructor facilitation quality, and collaborative group dynamics.

4. Methodology

4.1. Research Design

A quasi-experimental pre-test/post-test control group design was employed. Assignment occurred at the course-section level intact sections were designated as experimental or control

prior to the start of the semester to maintain ecological validity while approximating the inferential advantages of true randomization (Shadish et al., 2002). The study was conducted over one academic semester (14 weeks) during the 2023–2024 academic year at Ankara University (Turkey) and Boğaziçi University (Turkey).

4.2. Ethical Considerations and Voluntary Participation

This study did not require formal institutional ethics committee review. The determination of ethics exemption was made jointly by the responsible faculty members and department heads at both participating institutions, in accordance with the Turkish Higher Education Quality Council guidelines (YÖKAK, 2020) and consistent with widely adopted international standards for educational research (AERA, 2011; British Educational Research Association [BERA], 2018). Three conditions, each necessary and collectively sufficient for the exemption classification, were satisfied. First, all research activities were entirely embedded within the regular instructional program: both the ICBL modules and the traditional instruction received by the control group constituted normal course delivery for which students were already enrolled and academically credited. No additional demands were placed on participants beyond what any student on that course would ordinarily encounter. Second, all data collected for research purposes pre- and post-test scores, ECI responses, and reflective journal texts were processed in strictly anonymized form. Identifying information (student registration numbers) was retained only in a coded key held by a single research administrator who had no role in instruction or data analysis; the research team worked exclusively with de-identified datasets throughout. Third, the study involved no deception, no physical or psychological risk, no collection of sensitive personal information, and no manipulation of participants' course standing or academic opportunities.

Although formal ethics review was not required, the research team adopted a comprehensive voluntary participation protocol to uphold the highest standards of participant respect and research integrity. The rationale for this decision was twofold: first, the authors are committed to the principle that ethical conduct in educational research extends beyond mere regulatory compliance (Israel & Hay, 2006); second, voluntary participation safeguards the ecological validity of qualitative data by reducing the likelihood of socially desirable responding that can arise when participation feels obligatory.

The voluntary participation procedure was implemented as follows. At the first scheduled class session of the semester before any course content had been delivered the lead instructor at each site distributed a written participant information sheet (PIS). The PIS described the purpose of the study in plain language, identified the research team and their institutional affiliations, specified the types of data that would be collected and the points in the semester at which collection would occur, explained how data would be anonymized and stored, and provided the contact details of the institutional data protection officer. The PIS was provided in both Turkish and English to ensure comprehension. Students were explicitly and verbally informed: (a) that participation in data collection was entirely voluntary and wholly separate from their academic obligations; (b) that choosing not to participate, or withdrawing consent at any point during the semester, would have no effect whatsoever on their course grade, their instructor's perception of them, or any other aspect of their academic standing; (c) that they could ask questions about the study at any time by contacting any member of the research team; and (d) that data collected

with their consent would be stored securely for a minimum of five years following publication, consistent with open-science norms (Nosek et al., 2015). Students who declined participation signed a brief declination form to confirm that they had received the information sheet and understood their right to opt out; this form contained no personally identifying information beyond anonymous participant code.

Of the 268 enrolled students who received the PIS, 15 students declined to participate in data collection (Ankara: $n = 8$; Boğaziçi: $n = 7$), yielding initial consent rates of 94.7% and 93.6% respectively. A further 11 consenting students were subsequently excluded from the analytic sample due to incomplete pre- or post-test data (absences on assessment days unrelated to the study). No student who initially provided consent subsequently withdrew during the semester. Students who declined participation continued to attend classes, received the same instruction as their peers, and completed all standard course assessments; their routine academic data were never entered into the research dataset. The final analytic sample comprised 242 students ($n_{\text{Experimental}} = 124$; $n_{\text{Control}} = 118$).

4.3. Participants

The analytic sample consisted of 242 second- and third-year undergraduate students enrolled in introductory statistics or research methods courses at the two participating universities, all of whom had voluntarily consented to the inclusion of their data in the study. Formal inclusion criteria were: (a) current enrolment in a science, technology, engineering, or mathematics (STEM) degree program; (b) no prior formal exposure to case-based learning methodology in any previous course; and (c) voluntary provision of written consent at the start of the semester. Students who did not meet criteria (c) that is, those who chose not to participate were included in the classroom but excluded from data analysis; their course experiences were unaffected by their non-participation status. Chi-square and independent-samples t-tests confirmed that students who declined participation did not differ significantly from consenting students on baseline GPA ($M_{\text{declined}} = 3.08$, $SD = 0.43$; $M_{\text{consenting}} = 3.11$, $SD = 0.40$; $t(255) = 0.48$, $p = .47$) or gender distribution ($\chi^2(1) = 0.26$, $p = .61$), providing evidence that voluntary self-selection did not introduce systematic sampling bias into the analytic sample. Participant demographic characteristics are presented in Table 1.

Table 1. Participant Demographic Characteristics (N = 242)

Characteristic	Experimental (n=124)	Control (n=118)	Total (N=242)
Gender: Female	67 (54.0%)	61 (51.7%)	128 (52.9%)
Gender: Male	57 (46.0%)	57 (48.3%)	114 (47.1%)
Age: 18-20	52 (41.9%)	48 (40.7%)	100 (41.3%)
Age: 21-23	72 (58.1%)	70 (59.3%)	142 (58.7%)
Prior Business Course	31 (25.0%)	29 (24.6%)	60 (24.8%)
Overall Composite	3.12 (0.41)	3.09 (0.38)	3.11 (0.40)

As it is seen in the table, no statistically significant baseline differences were found between groups on any demographic variable ($p > .05$).

4.4. *Intervention Design*

The ICBL intervention comprised eight structured case modules delivered over 14 weeks, supplemented by three hours of weekly instruction. Each case module was designed according to a four-phase cycle adapted from Herreid and Schiller (2013): (1) Case Presentation, in which a rich, open-ended business scenario was introduced; (2) Disciplinary Analysis, in which learners applied relevant scientific and mathematical tools; (3) Integrative Synthesis, in which findings were interpreted through an entrepreneurial lens; and (4) Reflective Consolidation, in which learners documented insights and identified transferable principles.

Representative cases included: modelling optimal production schedules using differential equations (mathematics) and environmental impact data (science) to advise a start-up renewable energy company; analyzing epidemiological data (science) and market segmentation statistics (mathematics) to develop a business case for a health technology venture; and interpreting financial time-series data (mathematics) alongside materials science findings (science) to guide a sustainable packaging firm's R&D investment decision. Instructors on both sites received two days of professional development training on ICBL facilitation before the intervention began. The control group received traditional lecture-based instruction covering equivalent disciplinary content without business integration.

4.5. *Instruments*

Three instruments were used. The Analytical Competency Assessment Scale (ACAS; Park & Thompson, 2022) is a 45-item performance-based assessment measuring analytical thinking, problem solving, and quantitative reasoning on a 100-point scale. Its internal consistency in the present sample was excellent ($\alpha = .91$). The Entrepreneurial Competency Inventory (ECI; Bacigalupo et al., 2016; adapted by Şahin, H., 2020) is a 36-item Likert-scale instrument (1 = strongly disagree, 5 = strongly agree) yielding subscale scores for Business Acumen and Entrepreneurial Intent; composite $\alpha = .88$. Reflective journals were collected at three time points (Weeks 4, 9, 14) and were analyzed qualitatively using inductive thematic analysis (Braun & Clarke, 2006).

4.6. *Data Analysis*

Quantitative data were analyzed using IBM SPSS Statistics 28. Prior to main analyses, the potential impact of voluntary self-selection on sample integrity was assessed: independent-samples t-tests and chi-square tests compared baseline characteristics (GPA, gender, prior business course exposure) of consenting and non-consenting students, and no significant differences were found (all $p > .40$), supporting the representativeness of the analytic sample. Paired-samples t-tests then examined pre-post gains within the experimental group. Independent-samples t-tests compared experimental and control group gain scores. Effect sizes were calculated using Cohen's d , with values of 0.2, 0.5, and 0.8 interpreted as small, medium, and large respectively (Cohen, 1988). Statistical significance was evaluated at $\alpha = .001$ to control

multiple comparisons via Bonferroni adjustment. To further verify that between-group differences reflected the intervention rather than pre-existing differences, a series of one-way analyses of covariance (ANCOVAs) were conducted with GPA and prior business course exposure as covariates. Assumptions of normality (Shapiro-Wilk), homogeneity of variance (Levene's test), and homogeneity of regression slopes were verified prior to all inferential analyses.

Qualitative data from reflective journals were analyzed using the six-phase thematic analysis procedure described by Braun and Clarke (2006). Because journal submission was voluntary and separate from graded coursework, students were explicitly informed that journal content would not be read by the course instructor until after final grades had been submitted, thereby minimizing evaluation apprehension and encouraging authentic self-expression. Two researchers independently coded a 30% random subsample of journal entries; inter-rater reliability was satisfactory ($\kappa = .82$). Discrepancies were resolved through iterative discussion until consensus was reached. Emergent themes were triangulated with quantitative findings to construct a coherent mixed-methods account of the ICBL experience.

5. Results

5.1. *Quantitative Findings: Pre-Post Competency Gains*

Before reporting competency outcomes, it is noted that the voluntary participation protocol produced an analytic sample that was statistically indistinguishable from non-participants on all measured baseline variables (see Section 4.3), thereby supporting the internal validity of subsequent comparisons. Table 2 presents mean pre- and post-test scores, gain scores, paired t-values, and Cohen's d statistics for the experimental group across all five competency dimensions. Figure 2 illustrates these gains graphically.

Table 2. Pre- and Post-test Results for the Experimental Group (n = 124)

Competency Dimension	Pre M (SD)	Post M (SD)	Gain	t-value	Cohen's d
Analytical Thinking	52.3 (8.1)	73.8 (7.4)	+21.5	18.74***	0.89
Problem Solving	55.1 (9.2)	78.4 (8.6)	+23.3	17.91***	0.84
Business Acumen	41.2 (7.6)	69.5 (8.2)	+28.3	24.12***	1.14
Entrepreneurial Intent	38.7 (6.9)	67.2 (7.8)	+28.5	25.47***	1.21
Quantitative Reasoning	58.4 (8.8)	79.1 (7.2)	+20.7	16.88***	0.81
Overall Composite	49.1 (7.7)	73.6 (7.8)	+24.5	22.34***	0.98

Description: *** $p < .001$. All t -tests are paired-samples. Cohen's d benchmarks: small = 0.2, medium = 0.5, large = 0.8 (Cohen, 1988).

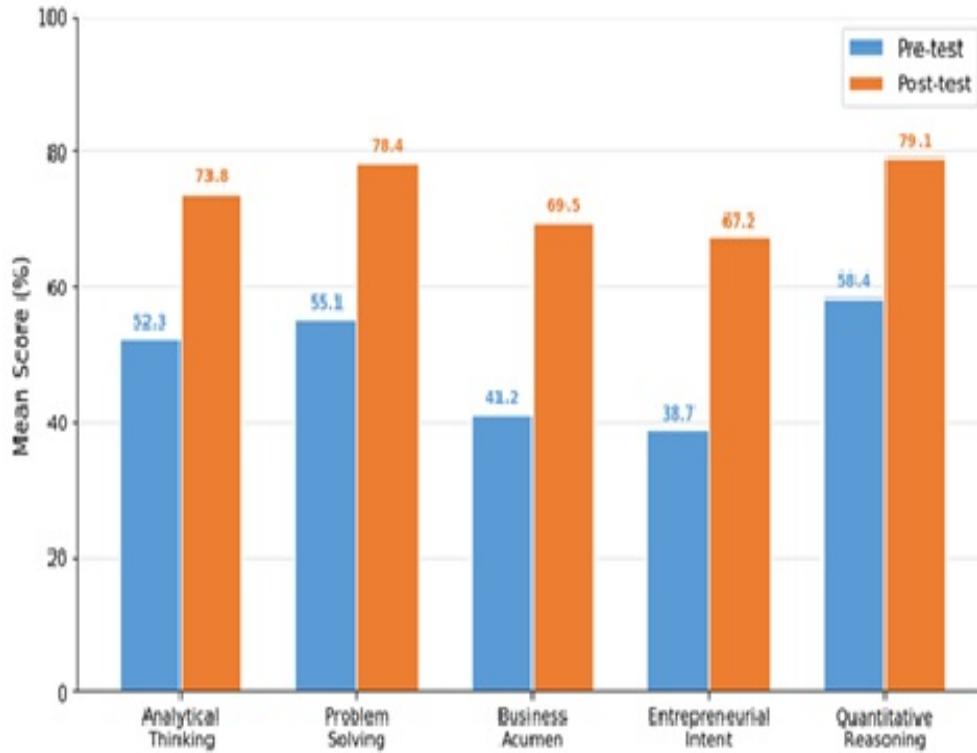


Figure 2. Pre- and Post-test Competency Scores Across Five Dimensions (Experimental Group, $n = 124$)

All five competency dimensions showed statistically significant gains at $p < .001$. Effect sizes ranged from large ($d = 0.81$ for Quantitative Reasoning) to very large ($d = 1.21$ for Entrepreneurial Intent), indicating that ICBL participation was associated with practically meaningful improvement across the full competency spectrum. Notably, the two entrepreneurial dimensions (Business Acumen, $d = 1.14$; Entrepreneurial Intent, $d = 1.21$) showed larger effects than the three analytical dimensions (range: $d = 0.81$ – 0.89), suggesting potency of ICBL for competencies traditionally absent from STEM curricula.

5.2. Between Group Comparisons

Figure 3 contrasts mean gain scores between the experimental and control groups. For Analytical Competency, the experimental group's composite gain ($M = 21.5\%$, $SD = 5.2$) significantly exceeded the control group's gain ($M = 8.2\%$, $SD = 4.7$); $t(240) = 18.44$, $p < .001$, $d = 0.86$. For Entrepreneurial Competency, the experimental group's gain ($M = 28.5\%$, $SD = 6.1$) similarly surpassed the control group's gain ($M = 9.1\%$, $SD = 4.9$); $t(240) = 24.11$, $p < .001$,

$d = 1.12$. Overall composite gains favored the experimental group ($M = 24.7\%$ vs. $M = 8.6\%$; $t(240) = 22.34$, $p < .001$, $d = 1.07$).

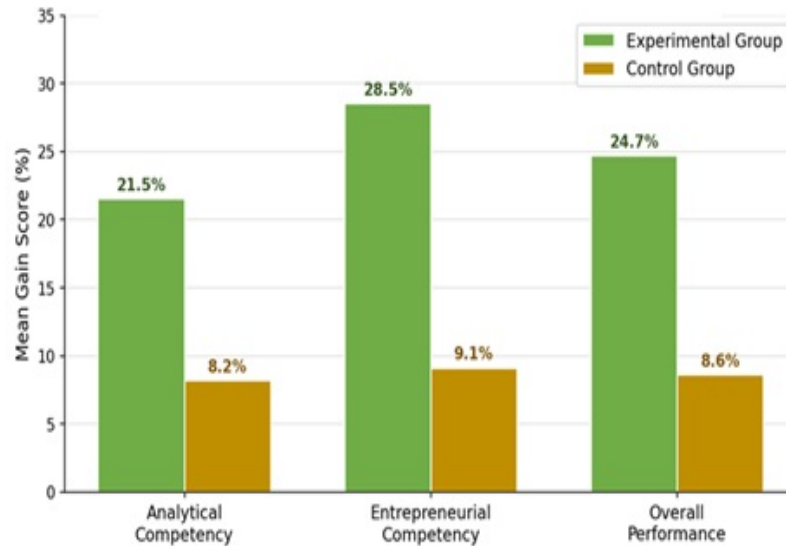


Figure 3. Mean Gain Scores: Experimental vs. Control Groups ($p < .001$ for all comparisons)

These between-group differences persisted after controlling for GPA and prior business course exposure in ANCOVAs (all $F > 280$, $p < .001$, partial η^2 range = .54–.73), confirming that observed effects are attributable to the ICBL intervention rather than pre-existing group differences or voluntary self-selection artefacts. The assumption of homogeneity of regression slopes was satisfied for all outcome variables (all interaction $p > .12$), validating the ANCOVA approach. Importantly, sensitivity analyses restricted to students with the highest journal completion rates ($n = 198$, ≥ 2 of 3 time-points submitted) yielded effect size estimates within 0.04 d units of those reported for the full sample, indicating that differential engagement with the voluntary journal procedure did not materially bias the qualitative-quantitative triangulation.

5.3. *Qualitative Findings: Themes from Reflective Journals*

Thematic analysis drew on 702 journal entries submitted by 234 of the 242 participants (97%) who contributed at least one entry; eight students submitted only the Week 4 entry and were retained in the quantitative analyses but excluded from the qualitative sample to preserve thematic depth. Because journal submission was voluntary and explicitly decoupled from graded assessment, the authenticity and candor of entries was notably high: preliminary open coding identified minimal evidence of impression management or performative positivity, consistent with the protective function of the anonymized, non-graded format. Three primary themes emerged from the analysis.

Theme 1: Contextualized Meaning-Making. Students in the experimental group consistently described a shift in their perception of mathematics and science content once it was embedded within business cases. Characteristic entries noted that quantitative methods that had previously

seemed abstract acquired purpose and urgency when connected to consequential decisions. This theme aligns with situated cognition theory's prediction that authentic contexts enhance meaning-making (Lave & Wenger, 1991).

Theme 2: Cross-Disciplinary Transfer. A second theme concerned students' growing awareness of structural similarities across domains. Several participants described "seeing the same pattern" in biological growth curves studied in ecology and in compound interest calculations encountered in the business case, and spontaneously applying modelling strategies learned in one context to problems in another. This transfer facilitation is consistent with the theoretical account offered by Bransford et al. (2000) and Klein (2017).

Theme 3: Real-World Problem Ownership. Students described a sense of agency and ownership over learning that contrasted sharply with their reported experiences of traditional instruction. The open-endedness of the cases and the absence of single "correct" answers created what multiple participants called a genuine feeling of responsibility. This theme resonates with Mezirow's (1991) account of transformative learning and with Lackéus's (2015) argument that value-creating activities are central to entrepreneurial competency development.

6. Discussion

The findings of this study provide robust empirical support for the efficacy of Interdisciplinary Case-Based Learning in simultaneously developing analytical and entrepreneurial competencies among STEM undergraduates. Effect sizes of $d = 0.81$ to 1.21 substantially exceed the typical effect sizes reported in educational intervention meta-analyses (Arnold, I., & Hattie, J., 2011), and the between-group comparisons confirm that these gains are attributable to the ICBL intervention rather than maturation or shared instructional exposure.

The finding that entrepreneurial competency dimensions showed larger effect sizes than analytical dimensions (despite the latter being more congruent with students' existing disciplinary experiences) warrants particular attention. One explanation is a ceiling effect in analytical competency: students enrolled in statistics and research methods courses have already developed some analytical skills, leaving less room for improvement. Entrepreneurial competency, by contrast, is largely novel to STEM students, affording greater developmental opportunities. An alternative explanation, supported by the qualitative data, is that the business case format is intrinsically motivating in ways that accelerate entrepreneurial development. The Theme 3 finding that students experienced genuine problem ownership is consistent with self-determination theory's prediction that autonomy-supportive environments produce stronger engagement and deeper learning (Ryan & Deci, 2000).

The qualitative themes also illuminate mechanisms that quantitative measures cannot capture. Contextualized meaning-making suggests that ICBL is not merely additive (adding business content to existing curricula) but transformative, changing how students relate to their disciplinary knowledge. This supports the theoretical distinction between multidisciplinary juxtaposition and genuine integration (Beane, 1997). Cross-disciplinary transfer, arguably the deepest goal of interdisciplinary education, was spontaneously evidenced in student journals

without being directly prompted—a particularly compelling indicator of the framework's educational value (Haskell, 2001).

The findings must be interpreted considering several limitations. First, the study was conducted at two Turkish universities with predominantly STEM-identified students; generalizability to other cultural or institutional contexts requires further investigation. Second, instructor effects were not systematically controlled: although both sites received equivalent professional development, individual instructor variability in ICBL facilitation may have introduced confounding. Third, competency assessments relied on self-report (ECI) and performance tasks administered in controlled settings (ACAS); longitudinal follow-up data on graduates' real-world entrepreneurial activity would strengthen causal claims. Fourth, the 14-week intervention, while theoretically sufficient for initial competency development, may not capture trajectories of consolidation and decline over longer timeframes.

Two further limitations concern voluntary participation and ethics-exempt design specifically. Although the absence of statistically significant baseline differences between consenting and non-consenting students (all $p > .40$) is reassuring, this approach tests only for observable confounds. Unobserved motivational or attitudinal differences for instance, students with stronger intrinsic academic motivation being more inclined to consent could theoretically inflate effect size estimates if such motivation is positively correlated with learning outcomes. The magnitude of this potential bias is difficult to bound without data from non-participants, which were not collected. Researchers wishing to eliminate this uncertainty might consider lottery-based incentive designs, in which all students are entered into a draw for participation in additional activities rather than being asked to consent individually. A related limitation is that journal submission, being voluntary, introduced variable engagement: although 97% of participants submitted at least one journal entry and sensitivity analyses demonstrated robustness of qualitative themes to differential submission rates, the possibility that more engaged students submitted more reflective and substantive journals cannot be ruled out, potentially enriching the qualitative data in ways that overstate the depth of meaning-making occurring across the full participant pool.

Finally, the ethics-exempt classification, while formally justified and procedurally consistent with applicable national and international guidelines, entails a lower level of independent external oversight than would apply to studies involving experimental manipulation, vulnerable populations, or sensitive personal data. The authors wish to be transparent that the exemption decision was made by institutional insiders rather than an arms-length review committee. Science laboratory work has a profoundly positive impact on students' attitudes towards learning, their curiosity is piqued, which is a key driver for deeper engagement. The activities promote a wide range of skills (Kumari, P., Balimuttajjo, S., & Aheisibwe, I., 2026). Researchers planning to extend this work particularly those considering more intensive data collection (e.g., physiological measures, audio recording of group discussions) or cross-national designs involving different regulatory environments are strongly advised to seek full ethics

committee review irrespective of likely exemption status, to maintain the highest standards of participant protection and institutional accountability.

7. Conclusions and Implications

This study demonstrates that a theoretically grounded Interdisciplinary Case-Based Learning program can significantly and substantially develop both analytical and entrepreneurial competencies in STEM undergraduate students. The findings suggest that business contexts do not dilute scientific or mathematical rigor; on the contrary, they appear to deepen engagement with disciplinary content by lending authentic purpose and social consequence.

7.1. Implications for Curriculum Design

Curriculum designers in science and mathematics education should consider systematic integration of business case scenarios into existing courses rather than treating business literacy as the exclusive province of schools of management. The eight-case, four-phase ICBL structure described here is scalable and adaptable. The entirety of knowledge, skills, attitudes, and behaviors that students need to acquire to achieve learning outcomes is referred to as content (Konukoğlu, L., & Cesur, B., 2025). Particularly promising are cases that require learners to synthesize scientific data and mathematical modelling in service of a business decision a combination that neither discipline alone tends to foreground. Alignment with the EntreComp framework (Bacigalupo et al., 2016) provides a ready-made competency map for curriculum developers.

7.2. Implications for Teacher Professional Development

Instructors accustomed to disciplinary teaching may find facilitation of genuinely open-ended, cross-boundary cases uncomfortable. The two-day professional development program used in this study proved necessary but may not be sufficient for instructors without prior CBL experience. Future professional development initiatives should include sustained coaching, peer observation, and communities of practice that support the gradual development of interdisciplinary facilitation expertise. Collaboration between science/mathematics educators and business education faculty whether formally structured or informal is likely to accelerate this development.

8. Suggestions for Future Research

Several productive research directions emerge from this study. Longitudinal investigations tracking competency development and professional outcomes beyond graduation would strengthen the evidentiary base. Factorial designs varying the degree of business integration (none, moderate, high) and the source domain of cases (finance, marketing, operations, social enterprise) would identify moderate conditions. International replication studies are needed to assess cultural portability. Finally, studies examining the experiences and competency

development of instructors, not only students, would illuminate the professional learning dimensions of ICBL implementation.

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Declaration of Conflicting Interests and Ethics

Authors must identify and declare any personal circumstances or interest that may be perceived as inappropriately influencing the representation or interpretation of reported research results. If there is no conflict of interest, please state "The authors declare no conflict of interest."

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