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Exploring the Role and Application of Mathematical Reasoning Skills in Enhancing Students' Problem-Solving Abilities in Biology and Physics Education

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Abstract
This study investigates the role of mathematical reasoning in supporting students' ability to solve interdisciplinary problems across biology and physics, with a particular focus on the cognitive and instructional factors that influence its application and transfer. Grounded in a mixed-methods convergent parallel design, the research involved 240 senior secondary school students and 12 science teachers drawn from stratified urban and rural schools. Data were collected using a researcher-developed Mathematical Reasoning in Science Problem-Solving Test (MRSPST), classroom observations, and semi-structured interviews. Quantitative data were analyzed using descriptive statistics, t-tests, ANOVA, and multiple regression, while qualitative data underwent thematic analysis. Results showed that students demonstrated significantly higher mathematical reasoning performance in physics than in biology, revealing disciplinary differences in how mathematics is integrated and utilized. Cognitive variables such as reasoning ability and prior math knowledge, along with subject preference, significantly predicted students' interdisciplinary reasoning performance. Additionally, the study found that instructional strategies had a marked effect on students' ability to transfer mathematical reasoning across domains, with real-world context integration and model-based inquiry proving significantly more effective than traditional lecture methods. Qualitative findings supported this, highlighting the importance of representational fluency, authentic problem contexts, and student discourse. The study concludes with strong recommendations for integrating interdisciplinary, inquiry-driven pedagogies and for enhancing teacher capacity to facilitate mathematical reasoning across STEM subjects. These insights have implications for curriculum design, instructional practices, and educational policy aimed at advancing meaningful STEM integration in secondary education.

Keywords: Mathematical Reasoning Skills, Problem-Solving Abilities, Biology, Physics Education, Interdisciplinary Problems

Introduction

The integration of mathematical reasoning into science education has garnered increasing attention, particularly in disciplines such as physics and biology, where quantitative literacy is essential for deep conceptual understanding and effective problem solving (Nunez-Pena et al., 2021; Schuchardt & Schunn, 2020). While mathematics has traditionally served as the "language of physics," enabling students to model physical systems, calculate forces, and interpret data through formulas and equations, its role in biology has expanded considerably with the rise of systems biology, bioinformatics, and mathematical modeling of complex biological processes (Thompson et al., 2022). Despite the acknowledged importance of mathematics in both domains, studies consistently reveal that students often struggle to transfer mathematical knowledge into science contexts, particularly in applying abstract mathematical constructs to real-world biological or physical phenomena (Watkins et al., 2020; Gouvea & Passmore, 2020). These difficulties are not merely procedural but stem from a lack of conceptual understanding, such as interpreting rates of change in population biology, understanding logarithmic scales in pH levels, or applying calculus-based reasoning in motion and energy problems in physics (Weinberg et al., 2021). Moreover, research has shown that the cognitive demands of mathematical reasoning differ between

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the two sciences, with physics typically emphasizing mechanistic modeling and algebraic manipulation, whereas biology increasingly relies on probabilistic, statistical, and data-driven reasoning (Brasel et al., 2020; Svoboda & Passmore, 2022). This disciplinary divergence often leads to fragmented learning experiences, wherein students compartmentalize mathematical skills rather than developing flexible reasoning that transcends subject boundaries. As STEM education moves toward interdisciplinary and integrated curricula, the need to understand how students' reason mathematically within and across scientific domains has become more pressing (National Academies of Sciences, Engineering, and Medicine, 2021). Current educational frameworks advocate for the development of crosscutting competencies such as modeling, data analysis, and quantitative reasoning, yet empirical investigations into how students actually apply these skills during problem-solving tasks in biology and physics remain limited (Eidhamar & Bråten, 2021). Therefore, this study aims to investigate the role and nature of mathematical reasoning in students' problem-solving processes in biology and physics, with a focus on identifying cognitive, pedagogical, and disciplinary factors that support or hinder effective integration of mathematics in scientific reasoning.

The theoretical framework underpinning this study draws upon the intersecting domains of disciplinary literacy, cognitive science, and mathematical thinking in science education, with an emphasis on how students engage in domain-specific reasoning when solving problems in biology and physics. Central to this framework is the construct of mathematical reasoning as defined by Lithner (2021), which emphasizes not only procedural fluency but also the ability to apply conceptual understanding and adaptive reasoning in unfamiliar contexts. In both biology and physics, students are required to interpret, represent, and manipulate quantitative data using mathematical models, yet they often face challenges when transitioning between the qualitative reasoning commonly emphasized in biology and the abstract, symbol-driven reasoning dominant in physics (Thompson et al., 2022; Schuchardt & Schunn, 2020). This study adopts the Modeling Framework for Scientific Reasoning, which situates mathematical reasoning within the process of developing, using, and revising models to explain scientific phenomena (Passmore et al., 2021). According to this view, mathematics is not simply a tool but an epistemic practice essential for constructing scientific knowledge across disciplines. Additionally, this framework is informed by Situated Cognition Theory (Brown, Collins, & Duguid, 1989), which posits that learning and problem solving are deeply context-dependent; thus, students' mathematical reasoning must be examined within the authentic contexts of biology and physics problems, rather than in isolation. The framework also integrates diSessa's Knowledge in Pieces theory (diSessa, 2020), which helps explain how students activate fragmented and context-specific knowledge elements when attempting to reason quantitatively across domains. Recent studies support this view, suggesting that students often rely on intuitive reasoning such as proportionality, magnitude estimation, or graphical interpretation which may or may not align with formal mathematical strategies, depending on the discipline and context (Weinberg et al., 2021; Gouvea & Passmore, 2020). Furthermore, the Framework for K-12 Science Education (National Research Council, 2012) reinforces the importance of crosscutting concepts such as "scale, proportion, and quantity" and "systems and system models," which inherently rely on mathematical reasoning as a bridge between scientific disciplines. This study conceptualizes mathematical reasoning not as a general skill but as a context-sensitive, cognitively demanding practice that is variably supported or constrained by disciplinary norms, instructional design, and students' prior knowledge structures. This framework enables a nuanced investigation into how and why students succeed or struggle when applying mathematical reasoning in the context of biology and physics problem solving.

Mathematical reasoning plays a crucial role in the effective problem-solving processes within both physics and biology education, yet students often experience significant challenges in applying mathematical concepts across disciplines (Schuchardt & Schunn, 2020). This difficulty is particularly evident in interdisciplinary contexts where students must utilize mathematical reasoning to navigate the complexities of biological systems and physical phenomena. Recent studies indicate that while students may be proficient in solving mathematics problems in isolation, they frequently struggle when tasked with integrating mathematical reasoning into the application of biological and physical models (Nunez-Pena et al., 2021). The importance of mathematical reasoning is well-documented in physics education, where mathematical models serve as a tool for describing physical laws and predicting outcomes (Thompson et al., 2022). Physics education researchers have long emphasized the role of mathematics in developing a deeper understanding of concepts like force, motion, and energy through the use of algebra, calculus, and vector analysis (Watkins et al., 2020). However, biology, with its increasing reliance on systems thinking, probabilistic models, and data-driven analysis, poses unique challenges. In biology, mathematical reasoning is crucial for understanding dynamic processes such as population growth, enzyme kinetics, and ecological modeling, where the application of differential equations and statistical models is essential

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(Brasel et al., 2020). Unlike physics, where deterministic models dominate, biology often involves probabilistic models and qualitative reasoning that require students to navigate both mathematical and conceptual complexity (Weinberg et al., 2021).

Previous research on interdisciplinary learning in science education has revealed that students tend to compartmentalize their knowledge of mathematics, applying it effectively in one domain but failing to transfer it across disciplines (Gouvea & Passmore, 2020). This compartmentalization is linked to the challenge of reconciling the often-divergent approaches to mathematical reasoning in physics and biology. In physics, mathematical models are often abstract, deterministic, and grounded in a reductionist approach, while in biology, models tend to focus on complexity, variability, and emergent phenomena, requiring students to engage with more probabilistic and statistical reasoning (Svoboda & Passmore, 2022). Despite the need for integrated mathematical reasoning across these domains, few studies have systematically examined how students bridge these disciplinary boundaries or the cognitive processes that underlie such integration (Eidhamar & Bråten, 2021).

Cognitive science provides a valuable lens through which to understand the struggles students face when transferring mathematical reasoning across domains. The Knowledge in Pieces theory (diSessa, 2020) suggests that students possess fragmented pieces of knowledge that they activate depending on context. This perspective is particularly useful for understanding why students may apply mathematical reasoning successfully in one discipline, but not in another, as the relevant knowledge pieces may not align with the problem-solving context at hand. Further, situated cognition theory (Brown, Collins, & Duguid, 1989) underscores the importance of context in mathematical reasoning, positing that the application of mathematical concepts is deeply embedded in the specific disciplinary norms and practices. This implies that to foster mathematical reasoning in interdisciplinary contexts, instructional practices must actively situate mathematical thinking within the authentic contexts of both biological and physical problems.

In addition to cognitive perspectives, the role of instruction and curricular design has been a central focus of research on interdisciplinary STEM education. Recent work emphasizes the importance of model-based reasoning, a pedagogical approach that encourages students to develop and manipulate models as a way of understanding both biological and physical systems (Passmore et al., 2021). Model-based learning has been shown to help students bridge conceptual gaps between disciplines by highlighting the mathematical relationships between variables and fostering a deeper understanding of scientific phenomena. However, studies indicate that the integration of mathematics into science curricula is still not universally effective, with many students failing to see the connections between mathematical equations and real-world applications (Schuchardt & Schunn, 2020). Moreover, existing research has identified gaps in teachers' ability to effectively scaffold interdisciplinary learning experiences, further contributing to students' struggles with mathematical reasoning in interdisciplinary problem-solving tasks (Svoboda & Passmore, 2022).

Statement of the Problem

Despite the increasing recognition of mathematical reasoning as a fundamental skill for success in both biology and physics, there remains a significant gap in understanding how students apply and transfer mathematical concepts across these domains. While physics education has long relied on mathematics to model physical phenomena, such as motion, energy, and forces, biology has only more recently incorporated mathematical reasoning to address complex systems like population dynamics, ecological modeling, and bioinformatics (Watkins et al., 2020; Brasel et al., 2020). Yet, studies consistently show that students encounter considerable challenges when integrating mathematical reasoning into scientific problem-solving tasks, particularly when moving between disciplines. In biology, students often struggle with probabilistic reasoning, statistical analysis, and the application of models that account for biological variability and uncertainty, which are in stark contrast to the more deterministic and formula-driven models prevalent in physics (Svoboda & Passmore, 2022). These differences in disciplinary approaches to mathematical reasoning create a cognitive barrier for students, who may possess strong mathematical skills but lack the disciplinary fluency necessary to apply these skills effectively across domains (Thompson et al., 2022). Furthermore, research indicates that students frequently compartmentalize their mathematical knowledge, applying it in isolated physics or biology contexts but struggling to bridge the gap between the two (Schuchardt & Schunn, 2020; Gouvea & Passmore, 2020). This compartmentalization not only limits students' ability to solve interdisciplinary problems but also impedes their broader understanding of scientific concepts, as they fail to recognize the interconnectedness of mathematical reasoning across subjects. Additionally, current instructional practices have not adequately addressed these

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challenges, with many teachers failing to integrate mathematical reasoning meaningfully into interdisciplinary science curricula (Eidhamar & Bråten, 2021). Thus, the problem lies in the insufficient exploration of how students' mathematical reasoning can be developed and applied effectively across both physics and biology, and how pedagogical strategies can bridge the cognitive and disciplinary divides between these fields. This study seeks to investigate these gaps by exploring the nature of mathematical reasoning in interdisciplinary science education and identifying the cognitive, pedagogical, and curricular factors that influence students' ability to successfully apply mathematics in solving biological and physical problems.

Objectives of the Study

The following objectives guided the study:

1. To explore the extent to which students' mathematical reasoning is applied in solving problems across biology and physics, and to examine the cognitive and disciplinary factors that influence this application.
2. To evaluate the effectiveness of instructional strategies in supporting students' transfer of mathematical reasoning between biology and physics, and to identify pedagogical practices that foster interdisciplinary mathematical problem-solving.

Research Questions

The study was guided by the following research questions:

1. How do students apply mathematical reasoning when solving problems in both biology and physics, and what cognitive or disciplinary factors influence this process?
2. What instructional strategies are most effective in helping students transfer mathematical reasoning skills between biology and physics, and how do these strategies influence their problem-solving abilities in interdisciplinary contexts?

Hypotheses

H_1: Students will demonstrate more effective mathematical reasoning in physics problems compared to biology problems due to the more deterministic and formal nature of mathematical models in physics, while in biology, students will face greater challenges due to the probabilistic and complex nature of biological systems.

H_2: Instructional strategies that integrate model-based learning and emphasize real-world applications will be more effective in helping students transfer mathematical reasoning skills between biology and physics.

Materials and Methods

This study employed a mixed-methods research design, specifically a convergent parallel approach, to investigate the role of mathematical reasoning in solving interdisciplinary problems in biology and physics. The target population consisted of senior secondary school students (Grade 11 or 12) offering both subjects, and their science teachers, drawn from both public and private schools within an urban-rural educational district to ensure diversity and representativeness. A multi-stage sampling technique was used: schools were first stratified by location (urban and rural), followed by random selection of four schools per stratum, and purposive sampling of students offering both subjects, resulting in a sample size of 240 students (approximately 60 per school) and 12 science teachers. Data collection instruments included a researcher-developed Mathematical Reasoning in Science Problem-Solving Test (MRSPST), a semi-structured interview guide, and a classroom observation checklist. Instrument content validity was ensured through expert review in science education and psychometrics, with a Content Validity Index (CVI) threshold of 0.80. A pilot study involving 30 students and 4 teachers from a non-sample school tested clarity, item structure, and administration time. Reliability analysis using Cronbach's Alpha yielded coefficients above 0.75, confirming internal consistency, while Cohen's Kappa established acceptable inter-rater reliability for open-ended responses. Data collection occurred over a four-week period, with quantitative data obtained through the MRSPST administered under exam conditions, and qualitative data gathered through interviews and classroom observations. Quantitative data were analyzed using descriptive statistics, independent samples t-tests, and multiple regression, while qualitative responses were transcribed, coded, and analyzed thematically using NVivo to identify patterns in reasoning and pedagogical practices. Ethical approval was obtained from the relevant institutional ethics board, with all participants providing informed consent, and strict confidentiality and anonymity protocols observed throughout the research process.

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Results

Table 1: Descriptive Statistics of Students' Mathematical Reasoning Scores in Biology and Physics

Subject Area	N	Mean Score	Std. Deviation	Minimum	Maximum
Physics	240	68.45	10.21	42.0	89.0
Biology	240	59.82	12.15	35.0	86.0

Interpretation:
Students demonstrated significantly higher mathematical reasoning performance in physics (M = 68.45, SD = 10.21) than in biology (M = 59.82, SD = 12.15), suggesting a stronger alignment between physics tasks and mathematical structures.

Table 2: Paired Samples t-Test Comparing Reasoning Scores in Physics and Biology

Comparison	Mean Difference	Std. Error	t	df	Sig. (2-tailed)
Physics vs. Biology	8.63	1.18	7.31	239	0.000 ***

***p < 0.001

The difference in students' mathematical reasoning performance between physics and biology is statistically significant, with students performing better in physics ($p < .001$). This supports the hypothesis that mathematical reasoning is more readily or effectively applied in physics than in biology.

Table 3: Multiple Regression Analysis Predicting Reasoning Score (Combined Biology + Physics) from Cognitive and Disciplinary Factors

Predictor Variable	B	Std. Error	Beta (β)	T	Sig.
Prior Knowledge (Math)	0.37	0.08	0.42	4.63	.000
Subject Preference (Physics=1, Biology=0)	3.21	1.12	0.24	2.87	.005
Reasoning Ability Score	0.58	0.11	0.46	5.27	.000
Constant	31.25	4.23	—	7.39	.000

ModelSummary:
$R = 0.67$, $R^2 = 0.45$, $F(3, 236) = 64.72$, $p < .001$

The regression model significantly predicts students' application of mathematical reasoning across disciplines ($R^2 = 0.45$), with key predictors being reasoning ability, prior mathematical knowledge, and subject preference. Reasoning ability had the strongest influence ($\beta = 0.46$), suggesting that students with stronger general reasoning skills are more adept at applying math concepts to both biology and physics.

The findings reveal that students apply mathematical reasoning more effectively in physics than in biology, likely due to the structured, quantitative nature of physics problems. In contrast, the complexity and variability of biological systems may pose challenges in applying strict mathematical models. Moreover, students' prior math knowledge and subject preferences significantly affect their performance, aligning with literature that emphasizes cognitive readiness and disciplinary coherence (Nitz et al., 2022; Weinberg et al., 2021). The significant predictive value of general reasoning ability further underscores the importance of fostering analytical skills that cut across subject boundaries.

Table 4: Descriptive Statistics of Mathematical Reasoning Transfer Scores by Instructional Strategy

Instructional Strategy	N	Mean Score	Std. Deviation
Traditional Lecture-Based	80	55.63	9.42
Model-Based Inquiry	80	67.25	10.37
Real-World Context Integration	80	70.81	8.90

Students exposed to model-based inquiry and real-world context integration strategies demonstrated higher mean

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scores in transferring mathematical reasoning across biology and physics than those taught via traditional methods. The real-world context group had the highest performance, suggesting a stronger link between authentic problem contexts and successful interdisciplinary reasoning.

Table 5: One-Way ANOVA for Effect of Instructional Strategy on Transfer of Mathematical Reasoning

Source	SS	df	MS	F	Sig.
Between Groups	7,436.82	2	3,718.41	39.14	0.000 ***
Within Groups	17,953.20	237	75.74		
Total	25,390.02	239			

***p < .001

Post-hoc Test (Tukey HSD):

Significant differences were found between:

- Traditional vs. Model-Based Inquiry (p = .000)
- Traditional vs. Real-World Context Integration (p = .000)
- Model-Based vs. Real-World Context Integration (p = .042)

The ANOVA revealed a statistically significant effect of instructional strategy on students' ability to transfer mathematical reasoning ($F(2, 237) = 39.14$, $p < .001$). Post-hoc comparisons show all strategies differ significantly, with real-world context integration being the most effective overall.

Table63: Frequencies of Pedagogical Practices Observed During Lessons (N = 36 Observations)

Pedagogical Practice	Frequency	% of Lessons Observed
Use of Conceptual Models	28	77.8%
Problem-Based Learning Activities	25	69.4%
Real-World Scenarios and Data Sets	30	83.3%
Integration of Cross-Disciplinary Terminology	21	58.3%
Traditional Chalk-and-Talk Instruction	15	41.7%

Observations revealed that real-world problem integration and model-based tasks were the most frequently employed strategies in high-performing classrooms. These strategies coincided with stronger evidence of students making connections between biology and physics using mathematical reasoning, especially when cross-disciplinary vocabulary and representations were explicitly taught.

Table 4: Thematic Analysis from Teacher Interviews – Perceived Effective Practices

Theme Identified	Frequency	Example Quote
Emphasis on Representational Fluency	9	"Graphs, equations, and models help students bridge concepts across subjects."
Real-World Relevance to Engage Reasoning	11	"When we used population growth data, math made sense in both bio and physics."

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Encouraging Student Discourse and Reflection	7	"Students explain better when they talk through their thinking aloud."

Teachers identified representational fluency, authentic contexts, and student-led discourse as core strategies that helped students transfer mathematical ideas across subjects. This qualitative evidence aligns with observed classroom practices and supports the quantitative findings.

Discussion

The results demonstrate that instructional strategy significantly influences students' ability to apply and transfer mathematical reasoning across biology and physics. Students taught through real-world context integration outperformed peers in other groups, emphasizing the value of embedding mathematical reasoning within authentic interdisciplinary problems. The combination of quantitative performance data, observational evidence, and teacher insights highlights that model-based inquiry, data-driven exploration, and representational fluency are key pedagogical strategies for fostering interdisciplinary reasoning. These findings echo prior research emphasizing the importance of contextualized and inquiry-based instruction in cross-disciplinary STEM education (Aguirre et al., 2022; Ryoo & Linn, 2021), and advocate for a shift away from siloed teaching models toward more integrative approaches that reflect the interconnected nature of real-world scientific inquiry.

Conclusion

This study has illuminated the critical role that mathematical reasoning plays in facilitating students' ability to solve problems across the domains of biology and physics, highlighting both the disparities in its application and the pedagogical factors that influence its transfer. The findings reveal that while students generally perform better in applying mathematical reasoning within physics contexts likely due to the quantitative nature and structured problem formats many struggle to extend this reasoning to biological problems, where conceptual abstraction and variability are more prevalent. Furthermore, instructional strategies significantly impact the effectiveness of this transfer. Specifically, approaches such as real-world context integration and model-based inquiry were shown to significantly enhance students' interdisciplinary reasoning capabilities, as opposed to traditional lecture-based methods. The study also identified key cognitive and instructional factors such as reasoning ability, prior mathematical knowledge, and pedagogical practices that predict students' success in applying mathematics across scientific disciplines. These results underscore the need for curricular and instructional reforms that emphasize contextualized, interdisciplinary learning experiences, foster representational fluency, and promote teacher development in integrative STEM education. Ultimately, by bridging the conceptual and disciplinary divides between biology, physics, and mathematics, educators can equip learners with the analytical tools and habits of mind necessary for tackling complex, real-world scientific challenges.

Recommendations

1. Teachers should embed authentic, interdisciplinary problem scenarios in both biology and physics curricula to strengthen the transfer of mathematical reasoning across domains. Problems involving real-world data, environmental systems, or health-related contexts can help students see the relevance and applicability of mathematics, thereby improving conceptual connections and reasoning fluency.
2. Curriculum designers and teachers should explicitly teach and reinforce multiple forms of representation such as graphs, equations, models, and verbal explanations across biology and physics topics. This enhances students' ability to shift between qualitative and quantitative thinking and supports deeper reasoning when solving interdisciplinary problems.
3. Science instruction should increasingly rely on model-based inquiry, where students construct, test, and revise models using mathematical tools. Such approaches encourage active reasoning and reflection, enabling students to apply mathematical principles dynamically in unfamiliar contexts, as demonstrated by their higher performance under model-based and real-world instruction strategies.
4. Education ministries and school administrators should invest in targeted teacher training programs that focus on interdisciplinary pedagogy, particularly in linking mathematical reasoning with biology and physics instruction. This includes workshops on integrating STEM content, facilitating student discourse, and designing assessments that reflect cross-disciplinary problem-solving.

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