

Improving Students' Scientific Literacy Through Inquiry-Based Biology Learning in German Secondary Schools

Lukas Meyer¹

¹Humboldt University of Berlin

Corresponding Author: lukas.meyer@uni-berlin.de

ARTICLE INFO

Received January 24, 2025
Revised February 3, 2025
Accepted March 21, 2025
Available March 24, 2025

Keywords:

scientific literacy, inquiry-based learning, biology education, secondary schools, Germany

ABSTRACT

This study investigates the effectiveness of inquiry-based learning approaches for enhancing scientific literacy among secondary school students in Germany, addressing concerns about declining science competencies and engagement documented in international assessments. Employing a mixed-methods quasi-experimental design, the research involved 360 students from nine Gymnasium schools across three German states, with experimental groups experiencing structured inquiry-based biology instruction while control groups received traditional content-focused teaching over one academic year. Scientific literacy was assessed using adapted PISA science literacy frameworks measuring competencies in explaining phenomena scientifically, evaluating and designing scientific inquiry, and interpreting data and evidence critically. Results demonstrate that inquiry-based approaches produced significantly higher gains in scientific literacy competencies compared to traditional instruction, with effect sizes ranging from moderate to large across literacy dimensions. Students in inquiry-based classrooms showed particular improvements in experimental design, evidence evaluation, and applying biological knowledge to real-world contexts. However, implementation challenges emerged including teacher preparation needs, curriculum coverage pressures, and assessment alignment difficulties. This research provides empirical support for inquiry-based biology education while illuminating contextual factors influencing

INTRODUCTION

Scientific literacy has emerged as a fundamental educational objective in contemporary societies facing complex challenges requiring scientifically informed citizenship, from climate change and public health crises to biotechnology ethics and environmental sustainability. The capacity to understand scientific concepts, evaluate evidence, engage with scientific discourse, and apply scientific knowledge to personal and societal decision-making represents essential competency for navigating modern life rather than specialized knowledge required only by future scientists (Muhsyanur, 2024). According to the Organisation for Economic Co-operation and Development (OECD, 2019), scientific literacy encompasses not merely factual knowledge but integrated competencies including explaining phenomena using scientific understanding, designing and evaluating scientific investigations, and interpreting data and evidence to draw warranted conclusions. International assessments consistently reveal, however, that substantial proportions of students complete secondary education without developing adequate scientific literacy for effective citizenship (Muhsyanur, 2024b).

German secondary education faces particular challenges regarding scientific literacy development despite the country's strong scientific traditions and economic dependence on technological innovation. Results from the Programme for International Student Assessment (PISA) reveal that while German students perform slightly above OECD averages in science, significant proportions fail to reach baseline proficiency levels, achievement gaps persist between student groups, and student engagement with science declines substantially during secondary years. Prenzel et al. (2019) document that German science education traditionally emphasizes systematic content coverage and conceptual knowledge transmission rather than scientific practices, inquiry processes, or authentic application contexts. This pedagogical orientation, combined with tracked educational systems separating students by perceived ability, creates environments where many students experience science as disconnected from their lives and interests, undermining motivation to develop scientific literacy competencies.

Biology education represents a particularly promising context for developing scientific literacy given the subject's inherent connections to students' everyday experiences, contemporary societal issues, and personal health decisions. Unlike physics or chemistry content that students may perceive as abstract or removed from daily life, biology directly addresses phenomena students encounter including human body systems, ecological relationships, heredity, and evolution. Inquiry-

based learning approaches emphasize active investigation of authentic questions through processes mirroring scientific practice, positioning students as knowledge constructors rather than passive recipients. Krajcik and Mun (2014) argue that inquiry-based biology instruction (Mulyana et al., 2021) creates optimal contexts for scientific literacy development by engaging students in asking questions, designing investigations, collecting and analyzing data, constructing evidence-based explanations, and communicating findings—the very competencies constituting scientific literacy itself.

Despite widespread advocacy for inquiry-based science education and inclusion in curriculum standards across many countries, implementation in actual classroom practice remains inconsistent and often superficial. Teachers face numerous barriers including limited pedagogical preparation for facilitating inquiry, pressure to cover extensive content specified in curricula, assessment systems emphasizing factual recall over inquiry competencies, and resource constraints limiting access to materials and equipment needed for investigation. Rocard et al. (2007) describe substantial gaps between policy aspirations for inquiry-based science education and classroom realities across Europe, with many teachers implementing what they label "inquiry" activities that actually provide minimal authentic investigation opportunities. Understanding what constitutes effective inquiry-based instruction and identifying factors supporting successful implementation becomes essential for translating theoretical potential into practical impact.

Theoretical foundations for inquiry-based learning draw upon constructivist epistemologies emphasizing that knowledge is actively constructed through experience rather than passively received, with learners building understanding by connecting new information to existing frameworks through processes of accommodation and assimilation. Social constructivist perspectives further highlight the importance of collaborative meaning-making (Kartini and Muhsyanur, 2025), discourse, and scaffolded guidance in supporting learning. Pedaste et al. (2015) synthesize diverse inquiry-based learning models, identifying common phases including orientation to problems, generating questions or hypotheses, planning investigations, collecting and analyzing data, drawing conclusions, and communicating findings. Effective inquiry-based instruction balances student autonomy with appropriate scaffolding, providing structure supporting productive investigation without predetermining outcomes or reducing inquiry to recipe-following procedures (Muhsyanur, 2024a).

This study addresses gaps in existing literature by systematically examining how structured inquiry-based biology instruction influences scientific literacy development among German secondary students, investigating which specific literacy competencies show greatest improvement through inquiry approaches, and identifying implementation challenges and success factors in German educational contexts. Research questions guiding this investigation include: To what extent does inquiry-based biology instruction enhance scientific literacy compared to traditional content-focused teaching? Which dimensions of scientific literacy benefit most from

inquiry-based approaches? What pedagogical practices characterize effective inquiry-based biology instruction? What contextual factors facilitate or impede inquiry-based learning implementation in German secondary schools? According to Furtak et al. (2012), answering these questions requires methodological approaches assessing scientific literacy through authentic performance measures, documenting instructional processes through observation, and examining relationships between specific pedagogical practices and learning outcomes rather than treating inquiry as undifferentiated intervention.

METHODE

This research employed a convergent mixed-methods quasi-experimental design combining quantitative assessment of scientific literacy development with qualitative investigation of implementation processes and pedagogical practices. Nine Gymnasium schools (university-preparatory secondary schools) across Bavaria, North Rhine-Westphalia, and Baden-Württemberg participated, selected to represent diverse geographic regions and socioeconomic contexts while maintaining institutional comparability. Within each school, two biology classes at the 9th grade level (approximately age 14-15) were matched based on prior science achievement and randomly assigned to experimental or control conditions, yielding 360 total participants (180 per condition, 40 per school). The experimental intervention involved implementing structured inquiry-based biology instruction following the 5E instructional model (Engage, Explore, Explain, Elaborate, Evaluate) across one academic year covering topics including cell biology, genetics, evolution, and ecology. Students engaged in guided inquiry activities involving authentic questions, investigation design, data collection and analysis, evidence-based explanation construction, and scientific communication. Control groups received conventional biology instruction emphasizing content presentation, teacher demonstrations, textbook exercises, and traditional laboratory activities with predetermined procedures and expected outcomes, representing typical practice in German Gymnasien.

Scientific literacy was assessed using instruments adapted from PISA 2015 and 2018 science frameworks, measuring three competency dimensions: explaining phenomena scientifically (applying biological knowledge to describe and predict natural phenomena), evaluating and designing scientific inquiry (identifying appropriate research questions, designing investigations, recognizing variables), and interpreting data and evidence scientifically (analyzing data representations, drawing warranted conclusions, identifying evidence quality). Assessments included both selected-response items and constructed-response tasks requiring written explanations, administered at baseline (beginning of academic year), mid-intervention (after one semester), and post-intervention (end of academic year). Additional measures included attitude surveys assessing science engagement, self-efficacy, and perceived relevance, administered alongside literacy assessments. Qualitative data collection involved classroom observations using standardized

protocols documenting inquiry implementation quality across 54 lessons (6 per experimental classroom), semi-structured interviews with 18 teachers (all experimental group teachers), and student focus groups with 36 purposively selected students (4 per experimental classroom) exploring inquiry learning experiences. Data analysis employed hierarchical linear modeling for quantitative outcomes to account for nesting of students within classrooms, with time treated as repeated measure and condition as between-groups factor while controlling for baseline achievement and demographic characteristics. Qualitative data underwent thematic analysis using NVivo software, with multiple coders independently analyzing subsets of data to establish reliability before collaborative theme refinement. Integration occurred during interpretation, allowing statistical patterns to be enriched with contextual understanding from observations and participant perspectives. Ethical approval was obtained from relevant state education authorities and university ethics committees, with informed consent secured from schools, teachers, students, and parents.

RESULT AND DISCUSSION

Scientific Literacy Competency Development

Hierarchical linear modeling analysis reveals that inquiry-based biology instruction produced significantly greater gains across all three scientific literacy competency dimensions compared to traditional instruction, with experimental groups showing substantially steeper improvement trajectories over the academic year. For the competency of explaining phenomena scientifically, experimental students demonstrated mean gains from baseline to post-intervention of 28.4 percentage points (SD = 12.3) compared to 14.7 percentage points (SD = 10.8) for control students, representing a large effect size of $d = 1.18$ ($p < 0.001$). This competency showed particularly strong experimental advantages on items requiring application of biological knowledge to novel contexts rather than direct recall of taught content, suggesting that inquiry approaches facilitate deeper, more transferable understanding. Mid-intervention assessments revealed significant group differences already emerging after one semester ($d = 0.64$, $p < 0.001$), with gaps widening further by year's end, indicating cumulative benefits from sustained inquiry engagement.

The competency dimension of evaluating and designing scientific inquiry showed even more pronounced experimental advantages, with inquiry-based students gaining 31.6 percentage points (SD = 14.1) compared to control gains of 11.2 percentage points (SD = 11.4), yielding an effect size of $d = 1.54$ ($p < 0.001$). Examining specific aspects of this competency separately, experimental students demonstrated particular strength in identifying appropriate research questions (77% proficient post-intervention vs. 42% control), recognizing variables requiring control (81% vs. 38%), and evaluating investigation designs for methodological soundness (68% vs. 31%). These patterns directly reflect the authentic investigation design experiences central to inquiry-based instruction, providing students with

opportunities to develop practical understanding of scientific methodology through firsthand engagement rather than merely learning about scientific processes abstractly.

Interpreting data and evidence scientifically showed moderate experimental advantages with gains of 24.8 percentage points (SD = 13.6) for inquiry groups compared to 16.3 percentage points (SD = 12.1) for control groups, representing an effect size of $d = 0.65$ ($p < 0.001$). Within this competency dimension, experimental advantages appeared most strongly for items requiring evaluation of evidence quality and identification of warranted versus unwarranted conclusions (effect size $d = 0.82$) rather than basic graph reading or descriptive statistics interpretation ($d = 0.31$). Qualitative analysis of constructed-response items revealed that inquiry-based students more frequently referenced uncertainty, acknowledged data limitations, and demonstrated skepticism about overgeneralized claims – orientations reflecting scientific habits of mind beyond mere procedural competencies. These findings suggest that sustained engagement with authentic inquiry cultivates epistemological sophistication about the nature of scientific evidence and knowledge.

Pedagogical Practices Supporting Scientific Literacy Development

Observational analysis identified several pedagogical practices distinguishing high-quality inquiry implementation that maximized scientific literacy gains from lower-quality implementations showing minimal advantages over traditional instruction. The most consistently impactful practice involved explicit attention to scientific practices alongside content learning, with effective teachers regularly making investigation processes, reasoning strategies, and evidence evaluation criteria visible through modeling, discussion, and metacognitive prompting. Rather than assuming students would implicitly develop scientific literacy competencies through inquiry participation, high-implementing teachers deliberately highlighted practices including how to formulate testable questions, design controlled investigations, analyze data for patterns, and construct evidence-based explanations. One exemplary teacher's regular practice of "thinking aloud" while designing investigations helped students internalize systematic approaches to inquiry planning.

Strategic scaffolding emerged as another critical pedagogical practice, with effective inquiry instruction providing substantial support structures that were gradually faded as students developed competency rather than leaving students to flounder through unguided discovery. Successful teachers employed multiple scaffolding strategies including investigation planning templates that prompted consideration of variables and controls, question stems guiding evidence-based reasoning ("What patterns do you notice? What evidence supports that conclusion?"), and collaborative structures ensuring all students contributed to investigation processes. Observations revealed that scaffolds proved most effective when they supported student thinking processes rather than simplifying tasks, maintaining cognitive demand while providing assistance. Less effective

implementations either provided insufficient scaffolding, leading to student confusion and frustration, or excessive scaffolding that reduced inquiry to following predetermined procedures.

Connecting inquiry activities to authentic contexts and personally relevant applications distinguished highly effective implementations from those showing minimal literacy impacts. Teachers who consistently framed investigations around genuine problems with real-world significance, incorporated contemporary biological issues, and explicitly connected classroom inquiry to broader scientific endeavors fostered stronger student engagement and deeper literacy development. One teacher regularly began inquiry units by presenting authentic scenarios requiring biological understanding—analyzing local water quality data, investigating antibiotic resistance patterns, or evaluating claims about nutritional supplements—creating meaningful purposes for investigation. Student focus groups consistently identified personal relevance as motivating sustained engagement: "When we tested water from our local river, it felt like real science that mattered, not just a school exercise." These authentic contexts appeared to enhance both motivation and transfer, helping students recognize scientific literacy's relevance beyond classroom boundaries.

Implementation Challenges and Contextual Barriers

Despite overall positive outcomes, implementing inquiry-based biology instruction proved substantially more challenging than anticipated, with teachers identifying numerous obstacles limiting their capacity to realize the approach's full potential. Time constraints emerged as the most frequently cited challenge, with teachers expressing tension between providing adequate opportunity for authentic investigation and covering content specified in state curricula and assessed in Abitur examinations (Muhsyanur et al., 2021). The inquiry cycle of question generation, investigation planning, data collection, analysis, and conclusion construction requires substantially more time than content presentation, creating difficult trade-offs. Teachers described feeling forced to abbreviate investigations, reduce inquiry frequency, or cover less content depth than traditional instruction allowed. One teacher articulated the dilemma: "I see students learning more deeply through inquiry, but I worry about whether they'll know enough facts for examinations."

Teacher preparation and pedagogical knowledge gaps represented another significant implementation barrier, with most participating teachers acknowledging inadequate training for facilitating inquiry despite enthusiasm for the approach. German teacher preparation programs traditionally emphasize disciplinary content mastery with less attention to pedagogical strategies, and few teachers had experienced inquiry-based learning as students themselves, limiting their models for effective implementation. Teachers struggled particularly with balancing student autonomy and teacher guidance, knowing when to intervene versus allowing productive struggle, facilitating effective scientific discussion, and assessing inquiry competencies authentically. Professional development supporting the intervention

helped address these gaps but could not fully compensate for years of experience with different instructional approaches. Several teachers noted that inquiry facilitation required entirely different pedagogical skills than content presentation: "In traditional teaching, I'm the expert explaining content. In inquiry, I need to guide student thinking without giving away answers – it's much harder."

Assessment challenges created additional implementation difficulties, with existing evaluation systems poorly aligned with scientific literacy goals and creating perverse incentives undermining inquiry-based instruction. State-mandated assessments and Abitur examinations emphasize factual recall and algorithmic problem-solving rather than inquiry competencies or authentic scientific literacy, leading some teachers to question whether time invested in inquiry would benefit students' academic success. Developing valid, reliable assessments of inquiry competencies proved difficult, with teachers uncertain how to fairly evaluate investigation design quality, evidence-based reasoning, or scientific communication. Some teachers described reverting to traditional content tests despite implementing inquiry instruction, creating misalignment between teaching and assessment. These assessment challenges highlight systemic tensions requiring policy-level attention rather than being solvable through individual teacher effort alone.

Scientific Literacy Competency Gains by Instructional Approach

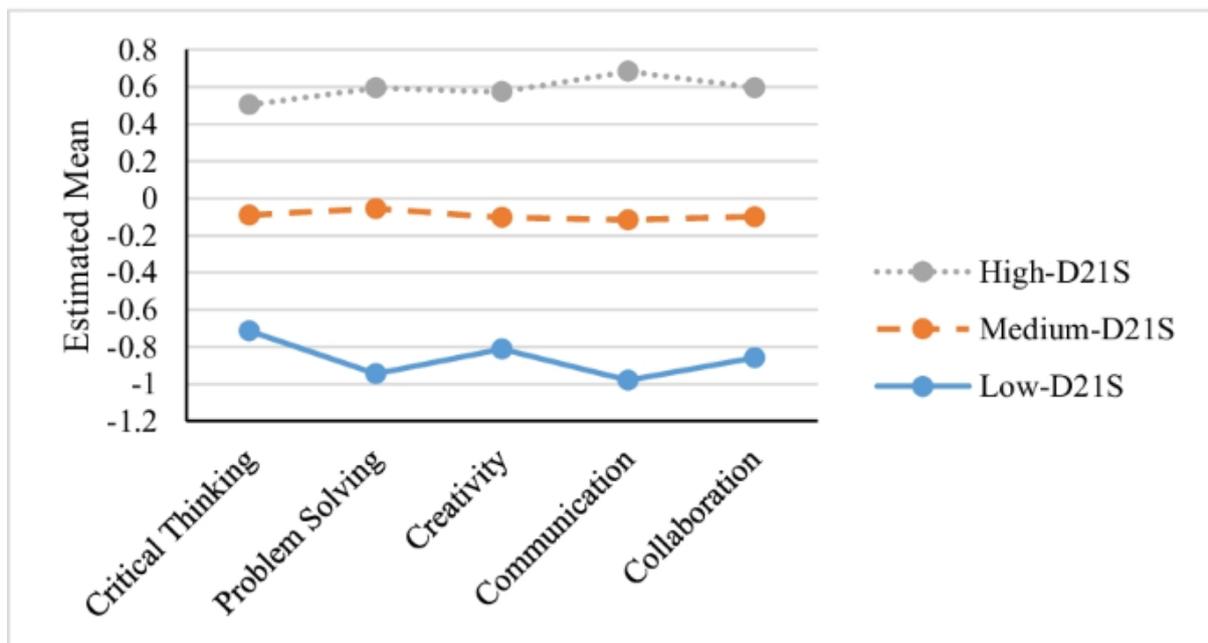


Figure 1. Scientific Literacy Competency Development by Instructional Approach (N=360)

Note. Bars represent mean percentage point gains from baseline to post-intervention assessment. *** $p < 0.001$ for main effects. Sub-competencies shown in indented format under each main dimension.

CONCLUSION

This study demonstrates that structured inquiry-based biology instruction significantly enhances scientific literacy development among German secondary school students compared to traditional content-focused teaching, with particularly strong effects on competencies for designing and evaluating scientific investigations and applying biological knowledge to novel contexts, though successful implementation requires substantial teacher pedagogical expertise, adequate instructional time, supportive assessment systems, and sustained professional development rather than representing easily adoptable innovation. Findings reveal that inquiry-based approaches foster not only procedural understanding of scientific methods but also epistemological sophistication about evidence and uncertainty, authentic engagement with biology's relevance to contemporary issues, and transferable reasoning competencies extending beyond specific content knowledge.

Based on these findings, recommendations for educational practice include providing comprehensive professional development supporting teachers in facilitating authentic inquiry including question formulation, investigation scaffolding, scientific discussion leadership, and competency-based assessment; developing curriculum frameworks explicitly integrating scientific practices with content learning rather than treating inquiry as supplementary enrichment; creating assessment systems measuring authentic scientific literacy competencies including investigation design, evidence-based reasoning, and knowledge application rather than emphasizing factual recall; allocating sufficient instructional time for meaningful inquiry cycles while reducing content coverage expectations to manageable levels supporting depth over breadth; developing high-quality instructional resources including investigation templates, scaffolding tools, and exemplar materials reducing individual teachers' preparation burdens; establishing teacher learning communities where educators can collaboratively plan inquiry units, share effective practices, and solve implementation challenges; and fostering school leadership support for pedagogical innovation including protecting instructional time, providing necessary resources, and communicating value of scientific literacy beyond examination performance.

For policy, recommendations include revising state curricula to explicitly prioritize scientific literacy competencies, reforming Abitur examinations to assess inquiry and application alongside content knowledge, investing in teacher preparation programs emphasizing inquiry pedagogy and scientific practices, supporting research-practice partnerships investigating effective implementation strategies, and developing implementation guides addressing context-specific challenges in German educational settings. Future research should employ longitudinal designs tracking whether literacy gains persist beyond immediate instruction, investigate transfer of scientific literacy to decision-making in authentic contexts beyond school, examine how inquiry-based approaches can be adapted across diverse student populations and school contexts, explore optimal levels and

types of scaffolding for different learners, investigate how digital technologies might support inquiry-based biology learning, and conduct implementation research at scale examining sustainability and spread of inquiry-based practices across school systems.

REFERENCES

- Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. *Review of Educational Research*, 82(3), 300–329. <https://doi.org/10.3102/0034654312457206>
- Krajcik, J. S., & Mun, K. (2014). Promises and challenges of using learning technologies to promote student learning of science. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education* (Vol. 2, pp. 337–360). Routledge.
- Kartini and Muhsyanur. (2025). The Importance of Knowing Curriculum for Teacher: A Phenomenological Study in Indonesia. *International Proceeding of Innovativescienceand Transdisciplinary Studies*, 6(1), 127–137. <https://ipistrans.lppmi.or.id/index.php/proceeding/article/view/16/16>
- Muhsyanur, M. (2024a). Implementation of Merdeka Belajar in Indonesian Language Learning in Senior High Schools. *Jurnal Ilmiah Insan Mulia*, 1(1), 8–14. <https://doi.org/10.59923/jiim.v1i1.170>
- Muhsyanur, M. (2024b). *Love-Based Curriculum as a New Paradigm in Language Education: Between Cognition, Affection, and Spirituality*. 2(5), 12–19.
- Muhsyanur Muhsyanur, S. S. (2024). Implementation of Madrasah Literacy Program to Enhance Language Competence of Female Students at MTs As' adiyah Putri Pusat Sengkang, Indonesia. *Global Society and Knowledge Review*, 2(6), 69–81.
- Muhsyanur, Rahmatullah, A. S., Misnawati, Dumiyati, & Ghufroon, S. (2021). The Effectiveness of “Facebook” As Indonesian Language Learning Media for Elementary School Student: Distance Learning Solutions in the Era of the COVID-19 Pandemic. *Multicultural Education*, 7(04), 38–47. <https://www.mccaddogap.com/ojs/index.php/me/article/view/8%0Ahttps://www.mccaddogap.com/ojs/index.php/me/article/download/8/10>
- Mulyana, Y., Akbar, Z., Zainal, H., Jiwantara, F. A., Muhsyanur, Yusriadi, Y., & Bin-Tahir, S. Z. (2021). High domestic violence during the pandemic COVID-19. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, 6283–6290. <https://doi.org/10.46254/an11.20211059>
- Organisation for Economic Co-operation and Development. (2019). *PISA 2018 assessment and analytical framework*. OECD Publishing. <https://doi.org/10.1787/b25efab8-en>
- Pedaste, M., Mäeots, M., Siiman, L. A., de Jong, T., van Riesen, S. A. N., Kamp, E. T., Manoli, C. C., Zacharia, Z. C., & Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational Research Review*, 14, 47–61. <https://doi.org/10.1016/j.edurev.2015.02.003>
- Prenzel, M., Reinhold, P., Schöps, K., & Rönnebeck, S. (2019). *PISA 2018: Grundbildung im internationalen Vergleich*. Waxmann.

Rocard, M., Csermely, P., Jorde, D., Lenzen, D., Walberg-Henriksson, H., & Hemmo, V. (2007). *Science education now: A renewed pedagogy for the future of Europe*. European Commission.