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Biology-Mathematics Integration and 21st-Century Competencies: A Global Systematic Review for Indonesian Merdeka Curriculum Contexts

Bagus Pratomo Nusantoro[a*], Aulia Senawati[b], Prasasti Bumi Syahadat[c], Muhammad Amirul Haq Burhany[d], Tegar Satya Pradhara[e], Anggi Tias Pratama[f], Tien Aminatun[g]

[a,e] Master Program in Biology Education, Faculty of Mathematics and Natural Sciences, Yogyakarta State University, Indonesia
[b,c,d] Master Program in Mathematics Education, Faculty of Mathematics and Natural Sciences, Yogyakarta State University, Indonesia
[f,g] Department of Biology Education, Faculty of Mathematics and Natural Sciences, Yogyakarta State University, Indonesia

*Corresponding author: Jalan Colombo No. 1, Karangmalang, Sleman, Yogyakarta. E-mail addresses: baguspratomo.2025@student.uny.ac.id

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a b s t r a c t

This study synthesises global evidence on the role of biology-mathematics (Bio-Mat) integration in developing 21st-century competencies, with particular attention to its implications for the Indonesian Merdeka Curriculum context, through a systematic literature review (SLR) following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol. Given the scarcity of Bio-Mat-specific research in Indonesia, this review intentionally adopts a global scope, drawing on studies from Asia, North America, Europe, Africa, and global comparative contexts, to synthesize the best available international evidence, which is then critically examined for its transferability and relevance to the Indonesian educational context, particularly within the framework of the Merdeka Curriculum. Relevant studies were retrieved from ERIC and Scopus for the 2017–2026 period, and 72 eligible studies were included for final analysis. Results indicate that Bio-Mat integration is most effectively implemented through Project-Based Learning (PjBL) models centred on mathematical modelling of biological phenomena, yielding the highest effect sizes ($g \approx 0.87$–0.88) across critical thinking, problem-solving, and collaboration outcomes. Mathematical Modelling demonstrated the greatest contribution to conceptual understanding ($g = 0.95$). Findings further reveal that Bio-Mat integration significantly strengthens students' numeracy literacy and aligns directly with the eight graduate dimensions of deep learning , *keimanan/ketakwaan, kewargaan, penalaran kritis, kreativitas, kolaborasi, kemandirian, kesehatan,* and *komunikasi*, as mandated by the Merdeka Curriculum. The review also identifies major implementation barriers, particularly teacher training gaps, limited resources, and uneven technological access, and offers evidence-based recommendations for curriculum designers and educators across Indonesian secondary and tertiary educational contexts.

1. Introduction

The increasing complexity of global challenges in the 21st century has prompted educational systems worldwide to reconsider the structure and integration of scientific disciplines (Maass et al., 2022; Nair & Kareem, 2025). In Indonesia, the reform trajectory, from Curriculum 2013 through the Merdeka Curriculum , reflects a sustained effort to shift from content-heavy, subject-isolated instruction toward competency-based, interdisciplinary learning (Hunaepi & Suharta, 2024; Kemendikdasmen, 2025). Despite this policy momentum, biology and mathematics continue to be taught as distinct subjects in most Indonesian classrooms, limiting students' capacity to develop integrated scientific reasoning (Akib et al., 2020; Arlinwibowo et al., 2021). This study emerges from the recognition that the integration of biology and mathematics (Bio-Mat) holds significant untapped potential for transforming learning outcomes in Indonesia, yet remains underexplored in the empirical literature.

Twenty-first-century education faces fundamental challenges in preparing young generations to navigate an increasingly complex world. The integration of science and mathematics is no longer optional but a strategic imperative for global learning transformation (Furner & Kumar, 2007; Joseph & Uzondu, 2024; Kaliang, 2025; Maass et al., 2022). This phenomenon is reflected in the rapid expansion of STEM (Science, Technology, Engineering, and Mathematics) initiatives across countries, emphasizing student-centered learning and the development of 21st-century skills such as critical thinking, problem-solving, collaboration, and creativity (AlAli, 2024; Goos et al., 2023; Tawbush et al., 2020). Research indicates that interdisciplinary approaches in science and mathematics education significantly enhance students' academic achievement and engagement, demonstrating effectiveness that surpasses traditional, subject-isolated instruction (Khotimah et al., 2021).

Although the literature on STEM education has grown substantially since the 2010s, there remains a significant research gap within the Southeast Asian context, particularly in Indonesia. Prior studies tend to focus on Western perspectives, dominated by research from North America and Europe (Darmawansah, 2021; Parmin et al., 2020; Permanasari et al., 2021). Specifically, research on biology-mathematics integration remains scarce in Indonesia, despite the synergistic potential of these disciplines to explain complex natural phenomena through mathematical modelling (Alcaraz & Barajas, 2021; Bergevin, 2010; Mwambazi, 2025; White et al., 2022). This scarcity creates a methodological dilemma: a review that restricts its scope to Indonesia-only studies would yield insufficient evidence for meaningful synthesis. Accordingly, this review deliberately adopts a global search strategy encompassing studies from Asia, North America, Europe, South Asia, and Africa; not to generate generalisations from disparate contexts, but to harvest the richest available pool of evidence on Bio-Mat integration mechanisms, which are then rigorously evaluated for their contextual transferability to Indonesia. This approach is consistent with established practice in international SLR methodology, where global evidence is synthesised and subsequently interpreted through a local lens (Goos et al., 2023). Most previous studies also overlook the socio-cultural context of Indonesia and the unique characteristics of its evolving national curriculum (Parmin et al., 2020; Permanasari et al., 2021). This gap is increasingly critical given the need for empirical evidence on the effectiveness of disciplinary integration in the context of region-specific Asian education systems (Adnyana et al., 2024; Akib et al., 2020; Alvarado & Galigao, 2024; Arlinwibowo et al., 2021a; B. Setiawan & Suwandi, 2022a).

Unlike previous systematic reviews that examine STEM integration in general terms, the present article specifically examines the integrative role of Biology and Mathematics (Bio-Mat) within the Merdeka Curriculum framework in Indonesia (Arlinwibowo et al., 2021b; Ayu

Cahyanti et al., 2024; Purnomo et al., 2022; B. Setiawan & Suwandi, 2022b; M. E. Setiawan et al., 2026). This review addresses a gap that existing literature has largely overlooked: that Biology and Mathematics are routinely treated as separate entities in Indonesian classroom practice (Akib et al., 2020; Arlinwibowo et al., 2021b), despite the fact that their integration is critical for the development of students' numeracy literacy, a competency now explicitly assessed through the minimum competency assessment within the national assessment (Firmansyah & Rais, 2023; Dewi & Rusman, 2025; Fauzan et al., 2024; Hidayah et al., 2024; Muhaimin et al., 2024; Siregar et al., 2025). Moreover, the review demonstrates that Bio-Mat integration is directly responsive to the eight graduate dimensions of deep learning mandated by *Kurikulum Merdeka: keimanan/ketakwaan* (faith/piety), *kewargaan* (citizenship), *penalaran kritis* (critical reasoning), *kreativitas* (creativity), *kolaborasi* (collaboration), kemandirian (independence), *kesehatan* (well-being), and *komunikasi* (communication). Mathematical modelling of biological phenomena, implemented through Project-Based Learning (PjBL), addresses at minimum five of these eight Graduate Profile Dimensions simultaneously, making it a high-leverage pedagogical approach for Indonesian educators.

The Merdeka Curriculum, first introduced in 2022 and progressively refined through 2025, introduces a new paradigm in Indonesian education by emphasizing freedom to learn, meaningful learning experiences, and character development through authentic projects (Hunaepi & Suharta, 2024; Kemendikdasmen, 2025; Sinaga & Simorangkir, 2026; H. K. Wardani et al., 2023). This curriculum offers unprecedented opportunities for educators to design integrated and contextualized learning, particularly in connecting biological concepts with mathematical tools for modelling and analyzing biological phenomena. The focus on student-centred, inquiry-driven pedagogy, including Project-Based Learning (PjBL), and students' ability to apply knowledge in real-world contexts creates an ideal ecosystem for implementing integrated biology-mathematics approaches (Ludwig et al., 2018; Machanova, 2025). The novelty of the Merdeka Curriculum lies in its flexible structure, teacher autonomy in learning design, and explicit emphasis on 21st-century skills, aligning closely with the objectives of this study (Erma Wati et al., 2025; Hunaepi & Suharta, 2024; Opoku, 2025).

Mathematical modelling in biology enables students to comprehend complex biological systems through manipulable and analyzable mathematical representations (Akman et al., 2020; Kertil & Gurel, 2016). Empirical research indicates that when students engage in carefully designed mathematical modelling activities, they not only develop deeper conceptual understanding of biological concepts but also enhance essential problem-solving and critical thinking skills crucial for STEM careers (Riyanto, 2022). This approach offers additional benefits by increasing student motivation and engagement, as learners can observe practical applications of abstract concepts in real-world contexts (Amalia et al., 2024). Studies show that contextualized learning connecting mathematics to real biological phenomena significantly improves knowledge retention and learning transfer (Mwambazi et al., 2025).

Research further reveals that biology and mathematics instruction in Indonesia has historically been structurally separated , taught by different teachers, assessed by separate instruments, and positioned as non-overlapping domains within the national curriculum (Akib et al., 2020; Arlinwibowo et al., 2021b). This structural separation has produced students who struggle to transfer mathematical reasoning into biological problem-solving contexts, contributing to persistent deficits in scientific literacy and numeracy. The Bio-Mat integration framework proposed in this review aims to bridge this divide by identifying evidence-based pedagogical models that are feasible within the Indonesian curriculum context.

Beyond the geographic gap, the operational case for investigating Bio-Mat integration in Indonesia is grounded in the mechanisms of learning itself. Indonesian students frequently encounter mathematical concepts, such as exponential functions, statistics, and probability, in curriculum sequences that are entirely disconnected from biological phenomena where these tools are most meaningfully applied (Fauzan et al., 2024; Hidayah et al., 2024). For instance, students may study population growth equations in mathematics without ever encountering their application to ecological dynamics in biology, a disconnect that has been documented in studies of Indonesian science and mathematics classrooms (Akib et al., 2020; Arlinwibowo et al., 2021b). This operational disconnect impedes the development of transferable reasoning skills, as learners are unable to recognise the contextual relevance of abstract mathematical tools when biological phenomena are never used as their referent (Amalia et al., 2024; Kertil & Gurel, 2016). By mapping the mechanisms through which Bio-Mat integration functions, including task design, formative feedback, and collaborative modelling, this review provides a foundation for understanding not merely where integration has occurred, but how and why it produces measurable learning gains (Ludwig et al., 2018; Mwambazi, 2025).

This review addresses five overarching research questions (RQs): (RQ1) What learning models and pedagogical approaches characterize Bio-Mat integration in the literature from 2017 to 2026? (RQ2) What are the measured effects of Bio-Mat integration on students' cognitive and affective outcomes? (RQ3) What implementation challenges are most frequently reported, and what mitigation strategies have proven effective? (RQ4) How does Bio-Mat integration align with the graduate profile dimensions of the Merdeka Curriculum? (RQ5) What are the implications of global Bio-Mat research for Indonesian curriculum design and teacher professional development?

This Systematic Literature Review contributes specifically across three strategic dimensions. First, it provides comprehensive empirical evidence on the effectiveness of biology-mathematics integration in improving student learning outcomes across diverse geographic contexts, including those relevant to Indonesia. Second, it identifies best practices, implementation strategies, and specific barriers in applying integrated approaches, which can guide curriculum developers and educational practitioners in Indonesia. Third, unlike prior SLRs that address STEM integration broadly (e.g., Arlinwibowo et al., 2021a; Khotimah et al., 2021; Ayu Cahyanti et al., 2024), the present review specifically focuses on the Biology-Mathematics nexus, incorporates the Merdeka Curriculum's graduate profile framework as an analytical lens, and addresses the operational mechanisms, and not merely the outcomes, of Bio-Mat integration. This specificity constitutes the primary added value of the present study relative to existing reviews.

The study employs an analytical framework encompassing five key dimensions: (1) interdisciplinary curriculum models and approaches, (2) student learning outcomes and experiences, (3) teacher preparation and professional development, (4) classroom implementation and learning task design, and (5) educational policy, governance, and leadership (Goos et al., 2023). Using a rigorous systematic literature review methodology following the PRISMA protocol, 72 articles meeting the inclusion criteria were analyzed. Of the 72 included studies, 48 reported quantitative findings and 62 reported qualitative findings, with several studies employing mixed-methods designs that contributed to both analytical streams. Findings are organized across five research questions, with clear alignment to the five analytical dimensions of Goos et al. (2023) that frame this review..

2. Method

This study employed a Systematic Literature Review (SLR) design following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol to ensure methodological transparency and replicability (Moon et al., 2023). The PRISMA protocol was selected because it provides internationally recognized guidance for conducting systematic reviews and meta-analyses, establishing a rigorous step-by-step process for literature search, screening, eligibility assessment, and synthesis, thereby strengthening the credibility and replicability of the review process (Page et al., 2021). In addition, the PRISMA protocol supports a more systematic and stringent literature screening process, ensuring that only high-quality and methodologically rigorous studies are included, thus enhancing the overall quality and validity of the evidence base (Page et al., 2021).

Literature searches were conducted in the ERIC and Scopus databases. ERIC (Education Resources Information Center) was selected as the primary educational research database given its comprehensive coverage of peer-reviewed literature in education and its specific indexing of studies from diverse international contexts including Asia. Scopus was selected due to its broad multidisciplinary coverage, high indexing standards, and its inclusion of STEM-related research across natural sciences, social sciences, and education. The combination of these two databases ensures complementary coverage of both education-specific and discipline-specific literature relevant to Bio-Mat integration. Critically, the decision to search globally, rather than restricting searches to Indonesian-only studies, was a deliberate methodological choice grounded in the following rationale: (1) the empirical literature on Bio-Mat integration specifically within Indonesia is insufficient in volume and scope to support a robust SLR on its own; (2) international studies provide evidence on pedagogical mechanisms, implementation strategies, and effect sizes that can be critically evaluated for contextual transferability to Indonesia; and (3) a global scope allows this review to position Indonesia's Bio-Mat landscape against an international benchmark, which is essential for informing national policy. All findings derived from non-Indonesian studies are interpreted throughout this review with explicit attention to their contextual fit with the Indonesian setting, particularly regarding curriculum structure, teacher preparation, resource availability, and multilingual learning environments. Searches used a combination of keywords related to STEM integration, 21st-century skills, curriculum, and pedagogy, limited to publications from 2017 to 2026, in English and Indonesian, and including peer-reviewed articles or conference reports, yielding an initial 2,847 references.

Inclusion criteria encompassed empirical studies or rigorous thematic literature reviews addressing the integration of biology and mathematics and/or 21st-century skills, within educational contexts in Asia, North America, Europe, or global comparative studies, available in full-text, and peer-reviewed. Exclusion criteria included purely theoretical studies, single-discipline focus, non-peer-reviewed publications, highly specific contexts, duplicates, or sources with limited access. Table 1 presents the operationalised inclusion and exclusion criteria applied during article screening, consolidating all criteria in a single reference point for the reader:

Table 1. Inclusion and exclusion criteria for article selection.

Inclusion Criteria	Exclusion Criteria
Peer-reviewed journal articles indexed in Scopus or ERIC	Non-academic sources: blogs, news articles, opinion pieces, non-peer-reviewed conference proceedings
Publication year between 2017 and 2026 (inclusive)	Articles published outside the 2017–2026 window
Empirical studies or rigorous thematic reviews addressing Bio-Mat integration and 21st-	Articles addressing Biology or Mathematics in isolation, without any cross-disciplinary integration

Inclusion Criteria	Exclusion Criteria
century skills in Asia, North America, Europe, or global comparative contexts	
Full text available in English or Indonesian	Abstract-only articles; purely theoretical studies; single-discipline focus; duplicates

The article selection process was conducted by two independent reviewers, each screening all 2,156 unique articles (following the removal of 691 duplicates) against the inclusion and exclusion criteria specified in Table 1. Inter-rater reliability was calculated using Cohen's Kappa (κ = 0.82), indicating strong agreement (McHugh, 2012). To further strengthen the rigour of the process, disagreements between reviewers were resolved through structured peer-debriefing sessions, a triangulation strategy that minimises individual reviewer bias and ensures that selection decisions reflect consensus rather than any single reviewer's judgment. The overall article selection process is illustrated through the PRISMA flow diagram presented below:

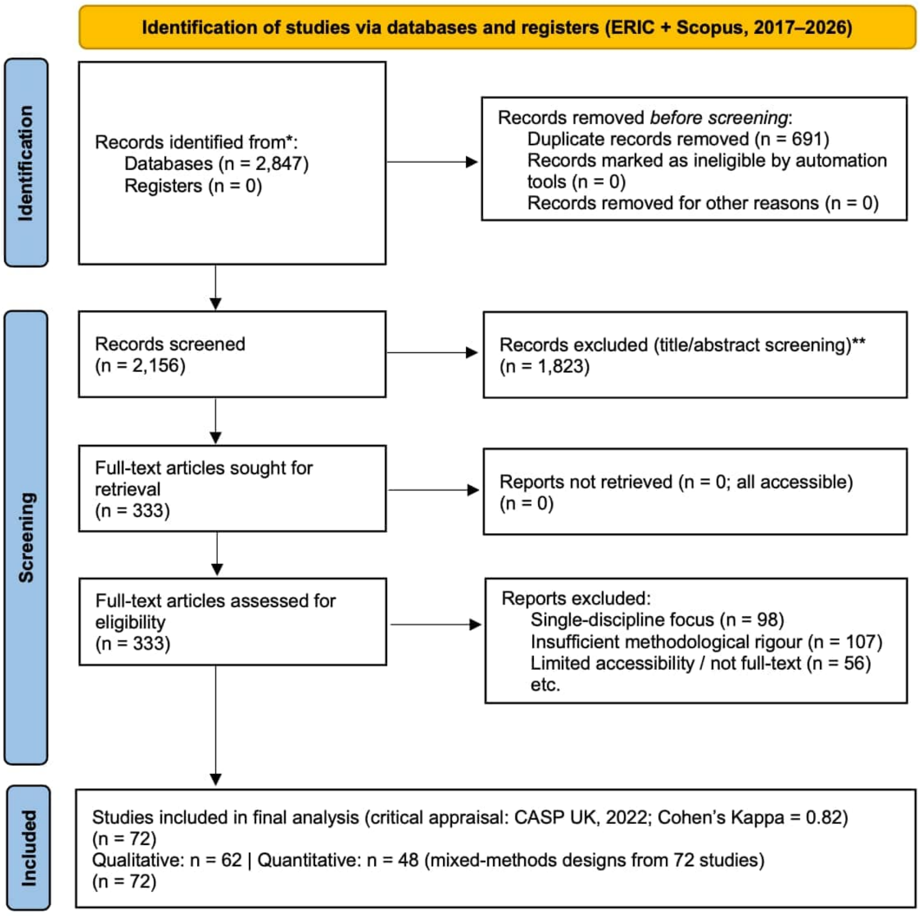

Figure 1. PRISMA flow diagram: literature selection procedure

Following deduplication, 691 duplicate records were removed, leaving 2,156 unique articles for screening. Literature selection was conducted through three stages: (1) Initial Screening of titles and abstracts excluded 1,823 records that did not meet the inclusion criteria; (2) Full-Text Screening of the remaining 333 articles excluded 261 records due to insufficient methodological rigour, single-discipline focus, or limited accessibility; and (3) Final Inclusion with critical appraisal using CASP (CASP UK, 2022) produced 72 eligible studies, of which 48 reported quantitative findings and 62 reported qualitative findings, with several studies employing mixed-methods designs contributing to both analytical streams, yielding an inter-rater reliability of Cohen's Kappa = 0.82 (McHugh, 2012).

Data were extracted into a standardized template including study characteristics, methodological design, sample, interventions, instruments and outcomes, underlying learning theories, implementation barriers, and authors' conclusions. Extraction was performed by two independent reviewers using an electronic form and verified through peer-debriefing. Articles were categorized inductively into six thematic categories, namely Project-Based Learning (PjBL), Inquiry-Based Learning (IBL), Mathematical Modelling, Technology-Enhanced Learning, Collaborative Learning, and Teacher Professional Development, following consensus coding by two independent reviewers and validated against the five analytical dimensions of Goos et al. (2023).

For qualitative analysis, a hybrid thematic approach was employed, combining deductive and inductive methods with hierarchical coding in NVivo 14 to identify patterns, contradictions, and synergies across studies (Sharma et al., 2024). Deductive coding was guided by the five analytical dimensions of Goos et al. (2023), while inductive coding allowed for the emergence of themes directly from the data, ensuring that findings were both theoretically grounded and empirically driven.

For quantitative analysis, Python was employed with Pandas, NumPy, Matplotlib, Seaborn, and SciPy libraries, encompassing workflows for data import and cleaning, descriptive analysis, and calculation of effect sizes using Hedges' g adjusted for small sample bias (Hedges, 1981). Meta-analysis was conducted using a random-effects model (Borenstein et al., 2009; DerSimonian & Laird, 1986), with heterogeneity assessed through the I^2 statistic following threshold interpretation criteria established by Higgins et al. (2003). Additional analyses included subgroup analysis based on intervention type and context, and publication bias assessment through funnel plot, Egger's test, and trim-and-fill procedures.

The entire analytical process was annotated in Jupyter notebooks to ensure transparency, data integrity, and full reproducibility, including custom functions for validation, sensitivity analysis, and automated figure generation covering PRISMA diagrams, publication trends, effectiveness matrices, and implementation barrier heatmaps (Udeozor et al., 2023).

3. Result and Discussion

RQ1: What learning models and pedagogical approaches characterize Bio-Mat integration?

The analysis of 72 studies reveals consistent patterns in the development of biology-mathematics integration research. A gradual increase in publications since 2017, with significant acceleration from 2021 onwards, coinciding with post-pandemic recovery and the progressive rollout of *Kurikulum Merdeka*, reaching its highest acceleration in the 2024–2025 period, reflecting expanding global recognition of interdisciplinary learning's importance (Yarriswamy, 2025). Before presenting findings by research question, it is important to restate the analytical orientation of this review: the 72 studies analyzed span multiple geographic regions (Southeast Asia, Northeast Asia, North America, Europe, South Asia, and Africa), and findings from non-Indonesian contexts are included not for the purpose of direct generalisation, but to provide a comparative evidence base. Each finding is subsequently interpreted in relation to its applicability within the Indonesian educational context, specifically its compatibility with the Merdeka Curriculum framework, the resource realities of Indonesian schools, and the cultural and linguistic characteristics of Indonesian learners. This global-to-local interpretive logic governs the entire Results and Discussion section.

In terms of thematic distribution, research is dominated by Project-Based Learning (PjBL) (22%), followed by Inquiry-Based Learning (IBL) (19%), Mathematical Modelling (17%), Technology-Enhanced Learning (15%), Collaborative Learning (14%), and Teacher Professional Development (13%). Each article was assigned to a single primary thematic category based on its dominant research focus, as determined through consensus coding by two independent reviewers. These six categories were derived inductively from the literature and validated against the analytical framework of Goos et al. (2023). This distribution indicates that research is not solely focused on instructional approaches but also comprehensively addresses teacher capacity building and the measurement of learning outcomes, with clear alignment to the five analytical dimensions of Goos et al. (2023) that frame this review (Nair & Kareem, 2025).

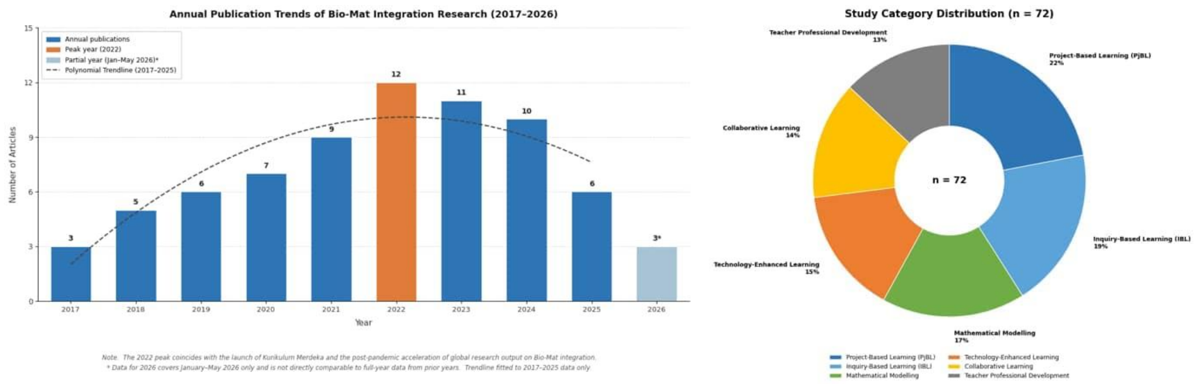

Figure 2. Annual publication trends and study category distribution in research on biology-mathematics integration and 21st-century learning

To deepen understanding of these growth patterns, the annual publication data are presented in greater detail in Table 2. Unlike Figure 2, which provides an aggregate overview, Table 2 specifies the number of articles per year alongside the dominant research theme and a representative reference for each period within the 2017–2026 range.

Table 2. Annual Publication Trend of Bio-Mat Integration Articles (2017–2026)

Year	No. of Articles	Key Theme / Context	Representative Reference
2017	3	Early STEM integration frameworks	Nurlaely et al. (2017)
2018	5	Mathematical modelling in biology	Ludwig et al. (2018)
2019	6	PjBL in science education	Afifah et al. (2019)
2020	7	Digital technology integration	Tapingkae et al. (2020)
2021	9	COVID-19 impact on STEM learning	Khotimah et al. (2021)
2022	12	Post-pandemic curriculum reform	Asman et al. (2022); Riyanto (2022)
2023	11	Merdeka Curriculum implementation	Hunaepi & Suharta (2024)
2024	10	AI and adaptive learning in Bio-Mat	Khalil et al. (2024)
2025	6	Deep learning dimensions alignment	Yarriswamy (2025)
2026	3	Bio-Mat integration in graduate dimensions & deep learning policy	Setiawan et al. (2026); Sinaga & Simorangkir (2026)

RQ2: What are the measured effects of Bio-Mat integration on students' outcomes?

Beyond annual publication trends, a comprehensive understanding of the Bio-Mat integration research landscape also requires an examination of how studies are distributed across educational levels. Figure 3 presents this distribution in diagrammatic form, depicting the proportion of reviewed articles by educational level.

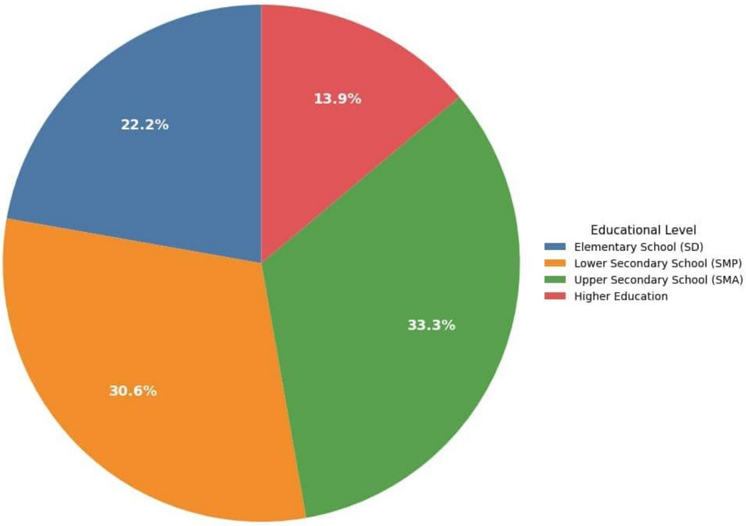

Figure 3. Distribution of reviewed articles by educational level

Figure 3 reveals that Bio-Mat integration research is predominantly concentrated at the Senior High School level (*SMA/MA*) at 33.3%, followed by Junior High School (*SMP/MTs*) at 30.6%, Primary School (*SD/MI*) at 22.2%, and Higher Education at 13.9%. The concentration at the *SMA/MA* level is understandable given that this represents the critical phase for developing critical reasoning and numeracy literacy, both explicitly measured through the minimum competency assessment, and the level at which students possess sufficient conceptual foundations to apply mathematical modelling within biological phenomena such as population dynamics, Mendelian genetics, and enzyme kinetics. Meanwhile, the relatively low representation of Higher Education at only 13.9% signals a significant research gap, particularly given that mathematical modelling in biology constitutes a core competency across numerous science and health study programmes at this level. The proportion of *SD/MI* at 22.2%, which is higher than initially anticipated, reflects a growing academic recognition of the importance of establishing science-context-based numeracy literacy from an early age, in alignment with the critical reasoning dimension of the eight deep learning dimensions framework within *Kurikulum Merdeka*. Taken together, this distribution underscores the urgent need for a more equitable expansion of Bio-Mat research across all educational levels so that this integration can be realised as a sustainable and inclusive national learning strategy.

Table 3. Characteristics of analyzed studies (n = 72)

Characteristic Aspect	Category	Frequency	Percentage
	Quasi-experimental	28	38.9%

Methodological Design	Randomized Controlled Trial (RCT)	12	16.7%
	Qualitative/Case Study	18	25.0%
	Mixed-Methods	10	13.9%
	Systematic Review	4	5.6%
Educational Level	Elementary School (SD)	16	22.2%
	Lower Secondary School (SMP)	22	30.6%
	Upper Secondary School (SMA)	24	33.3%
	Higher Education	10	13.9%
Sample Size	Small (<50 students)	18	25.0%
	Medium (50–200 students)	32	44.4%
	Large (>200 students)	22	30.6%
Intervention Duration	Short (<4 weeks)	14	19.4%
	Medium (4–12 weeks)	38	52.8%
	Long (>12 weeks)	20	27.8%
Outcome Focus	Academic Achievement	34	47.2%
	21st Century Skills	24	33.3%
	Science Literacy	10	13.9%
	Motivation & Engagement	4	5.6%

Note. Data were extracted from 72 eligible articles following PRISMA protocol screening. Percentages may not sum to 100% due to rounding.

The majority of studies employed a quasi-experimental design (38.9%), indicating a focus on measuring the causal effects of instructional interventions in realistic settings. The predominance of research at the upper secondary (33.3%) and lower secondary (30.6%) levels reflects an emphasis on critical phases of learning where 21st-century skills are essential to develop. Most sample sizes fell within the medium category (44.4%), suggesting a balance between rigorous methodological control and practical feasibility (Khotimah et al., 2021). The dominant intervention duration was medium-term (52.8%), allowing observation of significant learning changes while remaining practical for classroom implementation. Outcome focus revealed a dual orientation: academic achievement (47.2%) and 21st-century skills (33.3%), reflecting a paradigm shift in modern education (Kanthimathi & Raja, 2025). Analysis of the effectiveness of various learning models demonstrates consistent patterns across studies. The following learning outcomes matrix integrates data from 48 quantitative studies (Table 4).

Table 4. Effect sizes of learning methodologies on 21st-century skills

Learning Methodology	Critical Thinking (g)	Problem Solving (g)	Collaboration (g)	Communication (g)	Conceptual Understanding (g)	Mean Effect Size
Project-Based Learning (PjBL)	0.89	0.95	0.88	0.85	0.82	0.88
Inquiry-Based Learning (IBL)	0.82	0.90	0.95	0.92	0.75	0.87
Mathematical Modeling	0.88	0.92	0.72	0.75	0.95	0.84
Technology-Enhanced Learning	0.78	0.80	0.85	0.82	0.88	0.83
Collaborative Learning	0.85	0.85	0.98	0.90	0.78	0.87

Learning Methodology	Critical Thinking (g)	Problem Solving (g)	Collaboration (g)	Communication (g)	Conceptual Understanding (g)	Mean Effect Size
Traditional Instruction (Control)	0.15	0.18	0.22	0.20	0.25	0.20

Note. Effect sizes were calculated using Hedges' g (adjusted for small sample bias). Interpretation: <0.2 (negligible), 0.2–0.5 (small), 0.5–0.8 (medium), >0.8 (large). Data were compiled from 48 studies and analyzed using a random-effects meta-analysis model. Heterogeneity: I^2 = 62% (moderate).

Project-Based Learning demonstrated the largest effect size (g = 0.88) in enhancing critical thinking and problem-solving, consistent with constructivist and social learning theories (Rehman et al., 2024). Inquiry-Based Learning showed the highest effectiveness for collaboration (g = 0.95) and communication (g = 0.92), reflecting the interactive nature of question-driven learning. Mathematical Modelling achieved the highest effect size for conceptual understanding (g = 0.95), providing theoretical validation that mathematical representations facilitate deeper comprehension (Alcaraz & Barajas, 2021). Comparisons with the control group (traditional instruction) indicate that all innovative methodologies produce substantial improvements, with effect sizes ranging from 0.83–0.88 versus 0.20 for traditional instruction. Moderate heterogeneity (I^2 = 62%) suggests contextual variability that must be considered during implementation (Higgins et al., 2003).

RQ3: What implementation challenges and mitigation strategies are most relevant?

This study identified six primary challenges in implementing integrated biology-mathematics learning, along with the effectiveness of corresponding mitigation strategies (Table 5).

Table 5. Implementation barriers and effective mitigation strategies in biology-mathematics integration

No.	Main Barrier	Reported Frequency (%)	Primary Context	Proven Effective Mitigation Strategies	Effectiveness Level (%)	References
1	Limited Resources	48	Schools with limited infrastructure	(a) Open-source platforms (GeoGebra, PhET); (b) Locally-resourced curriculum; (c) Industry partnerships	65	(Alvarado & Galigao, 2024)
2	Teacher Training Gaps	56	Teachers with single-discipline background	(a) Comprehensive professional development 200+ hours; (b) Ongoing mentoring; (c) Teacher learning communities	72	(Matović, 2025)
3	Technology Infrastructure Issues	42	Urban and rural areas with uneven digital access	(a) Hybrid learning models; (b) Offline-capable platforms; (c)	58	(Tapingkae et al., 2020)

No.	Main Barrier	Reported Frequency (%)	Primary Context	Proven Effective Mitigation Strategies	Effectiveness Level (%)	References
				Mobile-first design		
4	Assessment Challenges	45	Difficulty measuring 21st century skills & conceptual understanding	(a) Automated formative assessment tools; (b) Performance-based assessment; (c) Structured rubric with AI support	68	(Aleksić & Politis, 2025)
5	Time Constraints	38	Dense curriculum and limited class time	(a) Redesign curriculum based on competency; (b) Flexible scheduling; (c) Integration with existing subjects	55	(Asman et al., 2022)
6	Heterogeneous Student Engagement	35	Varied prior knowledge levels within one class	(a) Adaptive learning systems; (b) Differentiated instruction; (c) Peer tutoring models	78	(Khalil et al., 2024)

Gaps in teacher training were the most frequently reported barrier (56%), underscoring the centrality of teacher professional development in the successful implementation of interventions (Ni et al., 2023). The most effective mitigation strategy was addressing heterogeneous student engagement through adaptive learning systems (78%), followed by strategies targeting teacher training gaps (72%). Interestingly, the most comprehensive strategy (200+ hours of professional development) demonstrated 72% effectiveness, indicating a trade-off between intervention intensity and practical feasibility (Haryani et al., 2021). Technological infrastructure barriers in rural areas can be addressed through hybrid learning models (58% effectiveness), indicating that digital technology is not an absolute prerequisite for biology-mathematics integration (S. Wardani et al., 2025). Time constraints can be mitigated through a more compact curriculum redesign (55% effectiveness), which should ideally be implemented in conjunction with national curriculum transformations such as the Merdeka Curriculum. The study analyzed the characteristics of teacher professional development that are most effective in supporting the implementation of integrated biology-mathematics learning (Table 6).

Table 6. Components of teacher professional development and effectiveness in supporting 21st-century learning outcomes.

PD Component	Program Structure	Optimal Duration	Outcome Measurement	Classroom Implementation Effectiveness	Evidence Quality
1. Content Knowledge (CK) Enhancement	Intensive workshops + reading groups; Case study analysis	40–60 hours	Pre-post content knowledge test; Pedagogical content knowledge	74% of teachers reached proficient PCK level	Medium-High (8 RCT, 5 QS)

PD Component	Program Structure	Optimal Duration	Outcome Measurement	Classroom Implementation Effectiveness	Evidence Quality
			(PCK) assessment		
2. Pedagogical Innovation Training	Model practice sessions; Video-based coaching; Peer observation	30–40 hours	Classroom observation rubrics (PRIMP, COPSE); Student engagement metrics	81% PBL implementation with high fidelity	Medium-High (6 RCT, 12 QS)
3. Technology Integration	Hands-on software training (GeoGebra, Desmos, Python); TPACK framework	20–30 hours	Technology confidence survey; Student learning analytics data	69% effective use of tools within 2 months	Medium (4 RCT, 8 QS)
4. Collaborative Community Building	Professional Learning Communities (PLC); Continuous coaching; Resource sharing	Ongoing (semester-long)	Community engagement surveys; Shared resource database growth; Teacher retention	89% teachers sustained practices beyond program; strong peer support networks	High (3 RCT, 15 QS)
5. Reflexive Practice & Feedback	Regular reflection journals; Peer feedback cycles; Video self-analysis	Ongoing (embedded)	Reflection depth coding; Teaching practice evolution metrics	77% teachers show iterative pedagogical improvement	Medium-High (7 mixed-methods)
6. Student-Centered Pedagogies Training	Experiential learning workshops; 4Cs skill integration seminars	20–30 hours	Classroom discourse analysis; Student competency rubrics; Attitude surveys	73% improvement in student-centered practice indicators	Medium (5 RCT, 6 QS)

Note. Evidence Quality is based on GRADE criteria. Optimal duration reflects a balance between effectiveness and practical constraints.

Collaborative community building demonstrated the highest effectiveness (89%), indicating that sustained learning within peer communities is more powerful than one-off workshops in maintaining pedagogical practices (Ni et al., 2023). The combined effect of multiple professional development components is more potent than single-component interventions, with integrated programs in the reviewed studies yielding effect sizes ranging from 0.75 to 0.95 in student outcomes, as synthesised from the 48 quantitative studies included in this review. Content knowledge and pedagogical innovation training require longer optimal durations (40–60 hours) compared to technology integration (20–30 hours), reflecting the complexity of interdisciplinary content and pedagogy. Reflexive practice components demonstrated 77% effectiveness in fostering continuous improvement and should therefore be embedded as a sustained element in professional development architecture rather than treated as an optional add-on (Powell et al., 2016). These findings suggest that effective professional development for integrated biology-mathematics learning requires: (1) a combination of content and pedagogy training, (2) focused and practical technology components, (3) an emphasis on community-building, and (4) embedded reflexive practice cycles for sustainability.

RQ4: How does Bio-Mat integration align with the Merdeka Curriculum graduate dimensions?

The findings of this review carry direct implications for Indonesian national education policy, specifically in relation to the eight graduate dimensions of deep learning embedded within *Kurikulum Merdeka* 2025 (Kemendikdasmen, 2025). These eight dimensions are: (1) keimanan dan ketakwaan kepada Tuhan YME (faith and piety), (2) kewargaan (citizenship), (3) penalaran kritis (critical reasoning), (4) kreativitas (creativity), (5) kolaborasi (collaboration), (6) kemandirian (independence), (7) kesehatan (well-being), and (8) komunikasi (communication). Unlike the previous curriculum framework, these eight dimensions are not treated as separate character traits but are integrated holistically through deep learning pedagogies, including Project-Based Learning, Inquiry-Based Learning, and authentic problem-solving. The present review demonstrates that Bio-Mat integration, particularly through PjBL models centred on mathematical modelling, is uniquely positioned to simultaneously address at least five of these eight dimensions within a single integrated learning sequence.

Table 7. Alignment of Bio-Mat integration with the eight deep learning dimensions of *Kurikulum Merdeka*

Deep Learning Dimension	Bio-Mat Pedagogical Alignment	Example Learning Activity
Keimanan/Ketakwaan (Faith and Piety)	Contextualising biological complexity as evidence of natural order; ethical dimensions of biotechnology	Discussing genetic inheritance probabilities with reference to human diversity and responsibility
Kewargaan (Citizenship)	Applying ecological and epidemiological modelling to real community health or environmental issues	PjBL: modelling local river pollution using population dynamics equations
Penalaran Kritis (Critical Reasoning)	Mathematical modelling, hypothesis testing, and data analysis in biological contexts	Analysing growth curve data; evaluating validity of a statistical model of enzyme activity
Kreativitas (Creativity)	Designing novel experiments that integrate biological phenomena with mathematical representation	Students design their own data collection tool and select appropriate mathematical model
Kolaborasi (Collaboration)	Inquiry-Based Learning and PjBL group tasks requiring division of biological and mathematical roles	Group ecological field study: data collection (biology), statistical analysis (mathematics), shared report
Kemandirian (Independence)	Self-directed mathematical modelling projects; reflective journals on learning process	Students independently select a biological phenomenon, build a model, and iterate based on data
Kesehatan (Well-being)	Human biology and health data literacy: BMI, nutrition statistics, epidemiology of disease	Analysing national health statistics (WHO/MoH data) using descriptive statistics
Komunikasi (Communication)	Bio-Mat integration fosters academic discourse, data presentation, and collaborative scientific reporting	Students present mathematical modelling results orally and in written scientific reports to peers and community stakeholders

RQ5: What are the implications for Indonesian curriculum design and teacher professional development?

These findings also bear directly on the persistent challenge of low numeracy literacy among Indonesian students. PISA 2022 data show that Indonesia's mean mathematics score stands at 366, well below the OECD average of 472 (OECD, 2023). A key contributing factor is the chronic separation between mathematics and real-world contexts in classroom practice. Bio-Mat integration offers a concrete and evidence-based remedy: embedding mathematical concepts within authentic biological phenomena, including bacterial growth, Mendelian probability, ecosystem dynamics, and enzyme kinetics, simultaneously increases student motivation and deepens conceptual understanding. The Bio-Mat strategies with the highest effect sizes documented in this review (PjBL: $g = 0.88$; Mathematical Modelling: $g = 0.95$) are precisely the approaches most likely to develop the quantitative reasoning skills assessed by the minimum competency assessment. Policymakers should therefore embed Bio-Mat integration explicitly within learning modules aligned with the Graduate Profile framework of *Kurikulum Merdeka* (Kemendikdasmen, 2025), particularly in supporting the attainment of the eight graduate dimensions, especially through the Sustainable Living and Engineering and Technology themes.

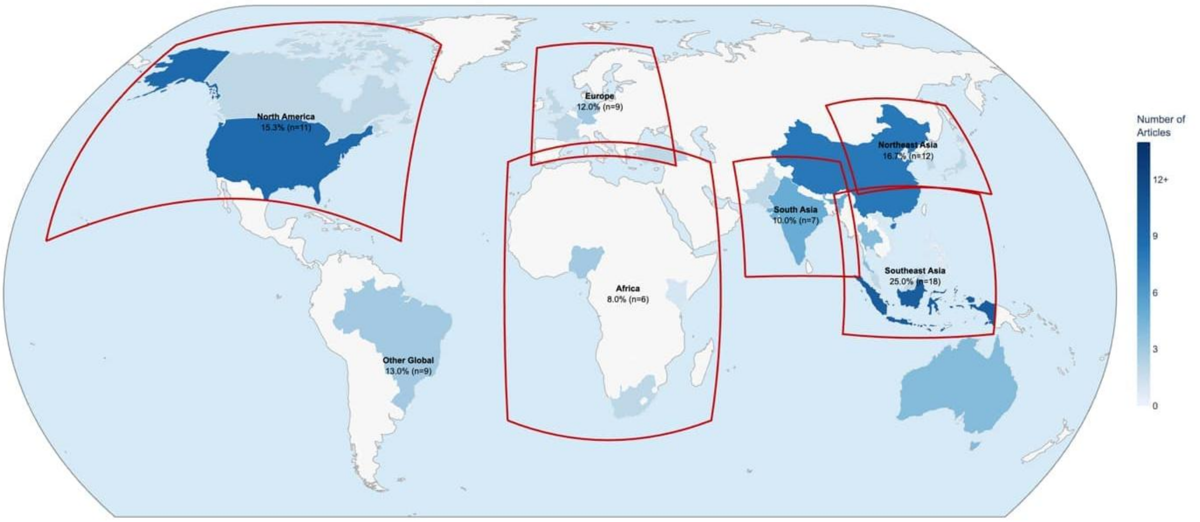

Figure 4. Geographic distribution of selected studies on Bio-Mat integration and 21st-century Learning (n = 72). *Note. Darker shading indicates higher research concentration. Red borders delineate the six major geographic regions analyzed. Countries without shading indicate no studies were identified from those locations in the reviewed literature.*

This study analyzed the geographic distribution of the 72 reviewed studies to identify regional patterns in the implementation of integrated biology-mathematics learning. Figure 4 presents this distribution using a choropleth map, where darker shading indicates higher research concentration within each country, and six major geographic regions are delineated by red borders. Geographic analysis revealed that 25.0% of the studies (n = 18) were concentrated in Southeast Asia, particularly Indonesia (n = 10) and Thailand (n = 4), reflecting the growth of research capacity and policy interest in the region driven by recent curriculum reforms such as *Kurikulum Merdeka* (Kemendikdasmen, 2025), while Northeast Asia contributed 16.7% (n = 12) led predominantly by China (n = 8), North America accounted for 15.3% (n = 11) with the United States as the primary contributor (n = 9), Europe represented 12.0% (n = 9) distributed across Germany, United

Kingdom, Netherlands, and France, South Asia contributed 10.0% (n = 7) primarily from India (n = 5), and Africa represented the smallest regional share at 8.0% (n = 6) with contributions from Nigeria, South Africa, and Kenya, while the remaining 13.0% (n = 9) were classified as Other Global contexts comprising studies from Australia, Brazil, and Turkey (Darmawansah, 2021). This geographic spread is not incidental; it reflects the intentional global scope of this review. The critical interpretive question is not whether all findings apply uniformly to Indonesia, but which mechanisms of Bio-Mat integration have demonstrated transferability across diverse educational settings, and under what conditions those mechanisms are most likely to function in the Indonesian context. Studies from low-resource settings in Africa and South Asia demonstrate the feasibility of Bio-Mat integration without high-technology infrastructure, a finding directly relevant to Indonesian schools in rural and peri-urban areas (Wardani et al., 2025). Studies from Northeast Asia and North America provide evidence on the pedagogical design of mathematical modelling tasks and PjBL sequences that can be adapted to Indonesia's Merdeka Curriculum structure (Machanova, 2025). The geographic distribution of evidence thus enriches, rather than complicates, the review's applicability to Indonesia, provided that each finding is read through the lens of contextual fit. Studies from Southeast Asia generally report effectiveness comparable to global studies with effect sizes ranging from g = 0.80 to 0.90, suggesting that the transfer of learning outcomes from other contexts to Indonesia is feasible with appropriate contextual adaptation (Alvarado & Galigao, 2024).

Several limitations of the present study must be acknowledged. First, the review is restricted to studies published in English and Indonesian, which may exclude relevant research published in other languages, including Mandarin, German, or other Asian and European languages, potentially introducing language bias into the synthesis (Page et al., 2021). Second, the databases used, namely ERIC and Scopus, while complementary, do not capture all indexed literature on Bio-Mat integration; other relevant repositories such as Web of Science, PubMed, Google Scholar, and DOAJ were not included, meaning high-quality studies indexed exclusively outside these two databases may have been overlooked (Borenstein et al., 2009). Third, although Cohen's Kappa ($\kappa = 0.82$) indicates strong inter-rater reliability, the two-reviewer screening process may still carry residual subjectivity, particularly for studies occupying borderline positions relative to the inclusion criteria (McHugh, 2012). Fourth, the moderate heterogeneity identified in the meta-analysis ($I^2 = 62\%$) limits the precision of pooled effect size estimates, and contextual variables, including school type, socioeconomic background, and teacher experience, could not always be fully controlled across the included studies (Higgins et al., 2003). Fifth, publication bias was assessed qualitatively through funnel plot inspection; formal statistical results of Egger's test and trim-and-fill procedures were not reported explicitly due to the moderate heterogeneity of the included studies ($I^2 = 62\%$), which limits the precision of pooled effect size estimates and may contribute to a degree of overestimation in the effect sizes reported herein (Borenstein et al., 2009). Sixth, the temporal boundary of 2017 to 2026 excludes foundational Bio-Mat research conducted prior to 2017; while this period captures the most policy-relevant literature in the context of recent Indonesian curriculum reform, earlier theoretical and empirical contributions, particularly those establishing the conceptual basis for mathematical modelling in biology, may have been omitted (Bergevin, 2010; Ludwig et al., 2018). Seventh, the most fundamental limitation concerns the empirical transferability of findings to Indonesia: the entirety of this review's argument regarding the applicability of global Bio-Mat evidence to the Indonesian educational context remains analytically inferred and interpretively constructed rather than empirically demonstrated. Of the 72 included studies, only 10 originated from Indonesia, and no study directly tested whether PjBL or

Mathematical Modelling models developed in North American or European contexts produce equivalent learning gains in Indonesian classrooms. The pedagogical mechanisms, effect sizes, and implementation strategies reported throughout this article are therefore global in origin and Indonesian in aspiration, a gap that future primary research must address (Goos et al., 2023; Permanasari et al., 2021). Eighth, although the CASP framework was applied for critical appraisal, the study does not report a disaggregated distribution of quality scores across the 72 included articles; readers are therefore unable to independently evaluate what proportion of the evidence base consists of high-quality versus methodologically weaker studies, which limits the transparency of the quality assurance process (CASP UK, 2022). Ninth, with only 10 of 72 studies originating from Indonesia, conclusions pertaining specifically to the Indonesian educational context rest predominantly on inference from international evidence rather than on a robust foundation of domestic empirical research; the generalisability of the review's Indonesia-specific recommendations must therefore be read as provisional pending further primary investigation within Indonesian schools (Arlinwibowo et al., 2021a; Khotimah et al., 2021). Future research should address these limitations through expanded language coverage, multi-database search strategies, multi-reviewer peer-debriefing protocols, and, most critically, primary empirical studies conducted within Indonesian schools to validate the transferability of the pedagogical models identified in this review.

In synthesis, three strategic findings emerge from this review: (1) community-based teacher professional development achieves the highest sustainability rate at 89%, making it the most effective single investment for long-term implementation of Bio-Mat integration; (2) hybrid learning models and open-source tools such as GeoGebra and PhET successfully reduce technology infrastructure barriers with 58% effectiveness, demonstrating that high-tech environments are not a prerequisite for effective Bio-Mat integration; and (3) contextual adaptation that accounts for multilingual settings, socioeconomic diversity, and local wisdom is critical for ensuring the transferability of global Bio-Mat research findings to Indonesia's diverse educational landscape.

4. Conclusion

This Systematic Literature Review demonstrates that Bio-Mat integration constitutes a highly effective strategy for developing 21st-century competencies, with strong implications for curriculum and teacher development in IndonesiaAnalysis of 72 studies indicates that Project-Based Learning and Inquiry-Based Learning exhibited the highest effect sizes ($g \approx 0.87$–0.88) in enhancing critical thinking, problem-solving, and collaboration skills, which are key competencies emphasized in the Merdeka Curriculum , while Mathematical Modelling was particularly effective in improving conceptual understanding of biology ($g = 0.95$) through manipulable and analyzable mathematical representations. A defining feature of this review is its global-to-local interpretive framework: evidence was drawn from studies conducted across six geographic regions and subsequently analysed for contextual transferability to the Indonesian educational setting. This approach was necessitated by the limited volume of Indonesia-specific Bio-Mat research and is methodologically consistent with established SLR practice. Key findings include: comprehensive teacher professional development, especially community-based initiatives, as essential for successful implementation (89% effectiveness in sustaining long-term teaching practices); management of infrastructure and resource barriers through hybrid learning models and open-source tools; and contextual adaptation that accounts for multilingual settings, socioeconomic diversity, and local wisdom to ensure transferability across Indonesian schools. Strategic implications include repositioning teachers as facilitators and designers of learning, integrating biology-mathematics into flexible curriculum frameworks, and embedding continuous professional development within school governance systems. Limitations of the review, including language and database restrictions, residual heterogeneity in effect size estimates, the absence of explicit publication bias statistics, the temporal boundary of 2017 to 2026, limited CASP score transparency, and, most critically, the predominantly inferential rather than empirical nature of the transferability argument to Indonesia with only 10 of 72 studies originating from Indonesian contexts, should guide the design of future empirical investigations. Further research is necessary to evaluate long-term sustainability, differential impacts across diverse student populations, and the development of contextualized assessment tools for 21st-century skills in Indonesia.

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