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The Effectiveness of Generative Learning Model in Enhancing Students' Science Competence: A Meta-Analysis (2015-2024)

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Abstract: This meta-analysis synthesizes 20 empirical studies (2015-2024) to evaluate the generative learning model's effectiveness in enhancing students' science competence. Using Cohen's d formula, effect sizes were analyzed across education levels, subject materials, and student competencies. Results demonstrated high overall effectiveness across all educational levels, with junior high school showing the highest average effect size (ES = 1.18), followed by elementary school (ES = 1.11), and senior high school (ES = 1.02). The model proved particularly effective for conceptual physics topics, with the highest effect sizes in Work and Energy (ES = 4.07) and Newton's Laws (ES = 2.90). Regarding student competencies, the model excels in developing Generic Physics Skills (ES = 4.07), Concept Mastery (ES = 1.75), and Science Process Skills (ES = 1.67), while showing moderate effectiveness in Critical Thinking Skills (ES = 0.23). Technology integration appears to amplify effectiveness. Heterogeneity analysis revealed significant variation attributable to implementation contexts, instructional scaffolding, and teacher competence. These findings provide robust empirical support for adopting generative learning models in science education, particularly when combined with appropriate instructional support and technology integration. Future research should focus on optimizing implementation for specific subject materials and enhancing critical thinking outcomes.

Keywords: generative learning model, cognitive conflict, science competence, meta-analysis, effect size

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1. Introduction

Science education in the modern era faces increasingly complex challenges, particularly in preparing students to master scientific concepts and develop high-level thinking skills. In this context, science learning must focus on content mastery while simultaneously developing scientific thinking processes and problem-solving abilities (Sujarwanto, 2023; Julia, 2024). With rapid technological advancements, science education must adapt to the characteristics of digital native generations, requiring innovation in learning models to achieve comprehensive educational goals (Verawati, 2023; Mansir, 2024). To address these demands, educators must implement evidence-based instructional strategies that actively engage students in meaningful learning experiences while fostering critical thinking and scientific literacy.

Based on constructivist theory, the generative learning model emphasizes active student engagement in constructing knowledge through integrating new information with prior knowledge (Yuliati, 2017). This model consists of four phases: preliminary exploration, focus, challenge and confrontation, and concept application. Through these phases, students develop deep and meaningful conceptual understanding (Julia, 2024). The generative learning model with cognitive conflict strategy is operationalized through six systematic and well-structured syntaxes: (1) orientation, which serves to activate prior knowledge and generate meaningful learning through cognitive processes; (2) cognitive conflict, which aims to stimulate student curiosity by presenting challenging situations; (3) disclosure, where students are encouraged to consider problem-solving strategies related to cognitive conflicts; (4) construction, which enables students to independently develop conceptual knowledge; (5) application, which promotes students to practice and apply their learning, expand knowledge, and develop skills in real-world contexts; and (6) evaluation and reflection, which provides feedback on the construction process and outcomes achieved during learning. Each syntax is designed to complement one another and create comprehensive and meaningful learning experiences. This approach has been shown to be particularly effective when combined with appropriate instructional scaffolding and peer interaction opportunities (Akmam, 2022).

Research indicates that this model enhances students' scientific competence, significantly improving conceptual understanding and scientific process skills (Azizah & Fauziah, 2023; Roviati & Widodo, 2019). Integrating digital technology in learning enriches student experiences through simulations, visualizations, and virtual interactions (Irsan, 2021). Adapting the generative learning model to modern technology is crucial for maintaining its relevance in the 21st century (Verawati, 2023; Mansir, 2024). By combining these elements strategically, educators can create dynamic learning experiences that not only meet contemporary educational standards but also prepare students with the competencies necessary to navigate an increasingly complex and technology-driven world.

To ensure rigorous and appropriate assessment of the generative learning model's effectiveness, this study establishes specific measurement indicators aligned with the model's objectives. These indicators encompass cognitive outcomes (conceptual understanding and scientific process skills), behavioral dimensions (student engagement, active participation, and problem-solving performance), and affective aspects (learning motivation, scientific curiosity, and collaborative quality). Such comprehensive measurement ensures that research objectives are achieved appropriately and that the model's impact can be accurately evaluated across multiple dimensions of student learning.

Meta-analysis provides a systematic and rigorous approach to integrating and synthesizing findings from empirical studies on the effectiveness of the generative learning model. Rather than relying on individual studies with potentially limited scope, meta-analysis enables comprehensive quantitative analysis of effect sizes to provide accurate estimation of the model's overall impact and identify optimal implementation conditions in diverse science education contexts. The period 2015-2024 offers strategic timing for this research, reflecting recent developments in science education practices and significant educational technology advancements. Analyzing this timeframe provides relevant insights into contemporary educational contexts and evidence-based practices (Verawati, 2023; Yuliati, 2017).

Research on the generative learning model spans various educational contexts and levels, allowing comprehensive analysis of its effectiveness (Verawati, 2023; Azizah & Fauziah, 2023). This diversity is essential for optimizing model implementation, particularly in addressing complex science education challenges in the digital era (Verawati, 2023; Suparya et al., 2022). Understanding how the generative learning model performs across these varied settings enables educators to tailor their implementation strategies to specific student populations and institutional constraints, thereby enhancing the model's potential to foster meaningful science learning experiences.

However, despite the growing body of research supporting the generative learning model's effectiveness, significant gaps remain in understanding its cumulative impact, optimal implementation conditions, and effectiveness across different educational contexts and student populations. Given the urgency of evaluating science education models and the necessity of providing robust empirical evidence, this meta-analysis investigates the generative learning model's effectiveness in enhancing students' scientific competence. The model's relevance to modern educational needs, particularly in developing high-level thinking skills and scientific literacy, necessitates comprehensive validation through synthesizing existing empirical evidence (Verawati, 2023; Yuliati, 2017).

This meta-analysis study pursues six interconnected objectives. First, it synthesizes and quantifies the overall effectiveness of the generative learning model in enhancing students' science competence by analyzing effect sizes across multiple empirical studies conducted between 2015-2024. Second, it evaluates the differential effectiveness across different educational levels (elementary, junior high, and senior high school), identifying which stages benefit most from this approach. Third, it assesses effectiveness across various science subject materials (physics, biology, and general science), determining which content domains are most conducive to the model. Fourth, it examines the model's impact on diverse student competencies, encompassing cognitive outcomes (conceptual understanding, scientific process

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skills, science literacy, critical thinking), behavioral indicators (learning outcomes, problem-solving ability, engagement), and affective dimensions (attitudes, motivation, collaborative quality). Fifth, it identifies optimal implementation conditions and contextual factors that enhance effectiveness, including instructional scaffolding, technology integration, and teacher competence. Finally, it provides empirical evidence and practical guidance for educators optimizing the model's implementation across diverse contexts, thereby advancing science education practices in the digital era. Collectively, these objectives establish a comprehensive, evidence-based foundation for understanding the generative learning model's effectiveness and potential to enhance science education outcomes.

2. Method

This research employs a meta-analysis method to integrate findings from various individual studies on the effectiveness of the generative learning model. The meta-analysis was conducted through a rigorous selection process and evaluation of studies relevant to the research question.

Study Selection and Inclusion Criteria

The studies included in this meta-analysis were limited to research published between 2015-2024. Literature searches were performed using the keywords "model pembelajaran generatif," "generative learning model," "Impact," "Pengaruh," "Effect," and "pembelajaran generatif" combined with keywords related to science and physics education. Article searches were conducted through the Google Scholar database. Selected studies had to meet the following inclusion criteria: (1) Articles published between 2015-2024; (2) Research measuring the impact of generative learning models on students' science competencies; (3) Research presenting adequate statistical data for calculating effect size. Studies were excluded if they did not provide sufficient quantitative data or were not published in peer-reviewed sources. In searching for the studies, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were employed to obtain systematic results. The systematic review flow diagram follows PRISMA rules, as shown in Figure 1.

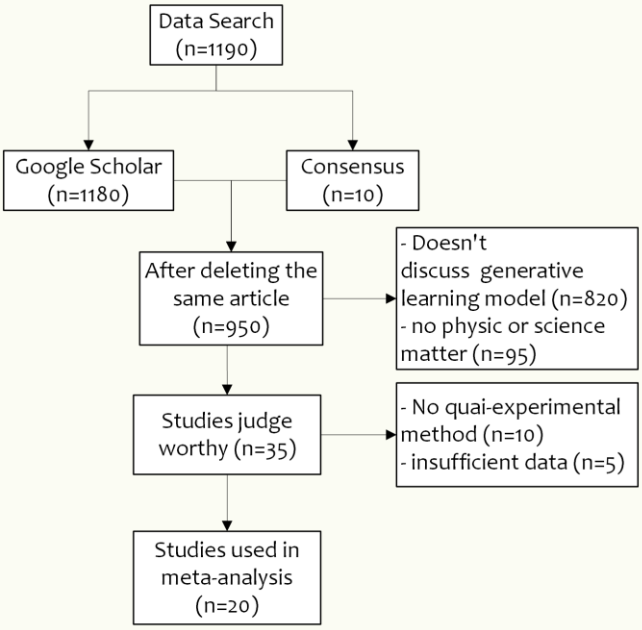

Fig 1. Meta-analysis Flow Diagram (PRISMA)

Data Analysis and Effect Size Calculation

This meta-analysis combines quantitative data from several studies to estimate the effect of the generative learning model on students' science competencies. Excel and JASP applications were used as tools to estimate the effect size. The Excel application processed raw data until effect sizes were calculated. In contrast, the JASP application was used to analyze heterogeneity, forest plots, funnel plots, and publication bias. To process and determine the effect size, this research used Cohen's d formula. The effect size interpretation used the following criteria: 0 ≤ ES ≤ 0.2 (low), 0.2 ≤ ES ≤ 0.8 (moderate), and ES ≥ 0.8 (high). Heterogeneity analysis used forest plots and funnel plots to evaluate publication bias and ensure the validity of the meta-analysis results.

3. Result and Discussion

This research identified 20 articles (2015-2024) meeting the inclusion criteria, focusing on elementary (ELS), junior high (JHS), and senior high school (SHS) education. Table 1 presents the characteristics and effect sizes of each study.

Table 1. Characteristics of Meta-analysis Studies

ID	Authors	ES	Level	Material	Student Competence
Study 1	(Hasanah Parni & Dwi Sundari, 2023)	0,28	SHS	Dynamic fluid	Learning outcome
Study 2	(Rosdianto, 2019)	1,67	JHS	Light	Science Process Skill
Study 3	(Agustin et al., 2024)	0,56	SHS	Wave	Learning outcome

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Study 4	(Hendini & Dwi Sundari, 2023)	0,26	SHS	Static Fluid	Learning outcome
Study 5	(Kartika, 2017)	1,22	SHS	Tempearture and Heat	Science literacy
Study 6	(Sari et al., 2018)	1,00	ELS	Science	knowledge competency
Study 7	(Sadewi et al., 2020)	1,22	ELS	Science	knowledge competency
Study 8	(Halmuniati et al., 2022)	0,19	SHS	Mechanical wave	Learning outcome
Study 9	(Andriani et al., 2023)	1,12	JHS	Heat	Learning outcome
Study 10	(Sudirman et al., 2015)	4,07	SHS	Work and Energy	Generic Physics Skill
Study 11	(Setiawan Uki et al., 2017)	0,23	SHS	Dynamic fluid	Critical thinking skills
Study 12	(Fatimah, 2019)	0,56	SHS	Optical instruments	Problem Solving Ability
Study 13	(Tampubolon, 2019)	2,45	SHS	Vibrations, waves and sounds	Mastery of concepts
Study 14	(Yani et al., 2016) study 1	0,53	JHS	Science	Knowledge competency
Study 15	(Yani et al., 2016) study 2	0,59	JHS	Science	Attitude
Study 16	(Yani et al., 2016) study 3	0,59	JHS	Science	Skills
Study 17	(Effendi & Pantriani, 2020)	0,85	JHS	Work and Simple Machine	Learning outcome
Study 18	(Rosdianto, 2017)	2,9	JHS	Newton's Laws	Learning outcome
Study 19	(Riyanti et al., 2016)	1,05	SHS	Circulation System	Concept Understanding
Study 20	(Ayu Lestra et al., 2024)	0,31	SHS	Motion Dynamics	Learning outcome

Table 1 provides a comprehensive overview of the studies included in the meta-analysis, with each entry detailing the authors, publication year, effect size, education level, study material, and student competence measured. The effect sizes ranged from the lowest at 0.19 to the highest at 4.07, indicating significant variation in the impact of the generative learning model across different contexts.

Effect of Generative Learning Model Based on Education Level

To evaluate the effect of the generative learning model across different education levels, a detailed analysis was conducted. Table 2 presents the breakdown of effect sizes by educational stages.

Table 2. Effect Size by Level Education

Level	ID	ES	Average ES	Category
ELS	Study 6	1,00	1,11	High
	Study 7	1,22		
JHS	Study 2	1,67	1,18	High
	Study 9	1,12		
	Study 14	0,53		
	Study 15	0,59		
	Study 16	0,59		
	Study 17	0,85		
	Study 18	2,9		
SHS	Study 1	0,28	1,02	High
	Study 3	0,56		
	Study 4	0,26		
	Study 5	1,22		
	Study 8	0,19		
	Study 10	4,07		
	Study 11	0,23		
	Study 12	0,56		
	Study 13	2,45		
	Study 19	1,05		
	Study 20	0,31		

The analysis reveals that the generative learning model demonstrates high effectiveness across all education levels. Junior High School (JHS) showed the highest average effect size (ES = 1.18), followed by Elementary School (ELS) (ES = 1.11), and Senior High School (SHS) (ES = 1.02). These consistently high effect sizes suggest that the model is adaptable and effective across different educational stages. The slightly higher effect in JHS may be attributed to students' developmental readiness for abstract thinking combined with their natural curiosity at this age, making them particularly receptive to the cognitive conflict and guided discovery inherent in the generative learning approach.

Effect of Generative Learning Model Based on Subject Materials

The analysis of subject materials provides insights into the model's effectiveness across different scientific topics. Table 3 illustrates the effect sizes for various materials studied.

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Table 3. Effect Size by Subject Materials

Material	ID	ES	Average ES	Category
Science	Study 6	1,00	0,79	Medium
	Study 7	1,22		
	Study 14	0,53		
	Study 15	0,59		
	Study 16	0,59		
Dynamic fluid	Study 1	0,28	0,26	Medium
	Study 11	0,23		
Light	Study 2	1,67	1,67	High
Wave	Study 3	0,56	1,07	High
	Study 8	0,19		
	Study 13	2,45		
Static Fluid	Study 4	0,26	0,26	Medium
Heat	Study 5	1,22	1,17	High
	Study 9	1,12		
Work and Energy	Study 10	4,07	4,07	High
Optical instruments	Study 12	0,56	0,56	Medium
Work and Simple Machine	Study 17	0,85	0,85	High
Newton's Laws	Study 18	2,9	2,90	High
Circulation System	Study 19	1,05	1,05	High
Motion Dynamics	Study 20	0,31	0,31	Medium

The analysis of subject materials reveals varying degrees of effectiveness across different scientific topics. The highest effect size was observed in Work and Energy topics (ES = 4.07), followed by Newton's Laws (ES = 2.90), and Light (ES = 1.67). Medium effect sizes were found in topics such as Dynamic Fluid (ES = 0.26), Static Fluid (ES = 0.26), and Motion Dynamics (ES = 0.31). This variation suggests that the generative learning model may be particularly effective for teaching conceptual physics topics that require students to construct and connect multiple ideas, such as abstract concepts involving energy, forces, and motion. The lower effect sizes in fluid dynamics topics might indicate areas where additional instructional support, enhanced visualizations, or modifications to the model could be beneficial.

Effect of Generative Learning Model Based on Student Competences

Table 4 provides a comprehensive analysis of the model's impact on various student competences.

Table 4. Effect Size by Student Competences

Student Competence	ID	ES	Average ES	Category
Learning outcome	Study 1	0,28	0,81	High
	Study 3	0,56		
	Study 4	0,26		
	Study 8	0,19		
	Study 9	1,12		
	Study 17	0,85		
	Study 18	2,9		
	Study 20	0,31		
Knowledge Competency	Study 6	1,00	0,92	High
	Study 7	1,22		
	Study 14	0,53		
Mastery of concepts	Study 13	2,45	1,75	High
	Study 19	1,05		
Science Process Skill	Study 2	1,67	1,67	High
Science literacy	Study 5	1,22	1,22	
Generic Physics Skill	Study 10	4,07	4,07	High
Critical thinking skills	Study 11	0,23	0,23	Medium
Problem Solving Ability	Study 12	0,56	0,56	Medium
Attitude	Study 15	0,59	0,59	Medium
Skills	Study 16	0,59	0,59	Medium

The analysis of student competencies reveals diverse impacts across different learning outcomes. The highest effect size was observed in Generic Physics Skills (ES = 4.07), followed by Mastery of Concepts (ES = 1.75), and Science Process Skills (ES = 1.67). Medium effect sizes were found in Critical Thinking Skills (ES = 0.23), Problem Solving Ability (ES = 0.56), and Attitude (ES = 0.59). These results suggest that the generative learning model is particularly effective in developing practical physics skills and conceptual understanding, while its impact on higher-order thinking skills such as critical thinking and problem-solving may require additional scaffolding, explicit metacognitive instruction, or complementary teaching strategies to fully develop these competencies.

Visualization Analysis

The meta-analysis included visual representations to further understand the data distribution. Figure 2 (Forest Plot) and Figure 3 (Funnel Plot) provide additional insights into the study's findings.

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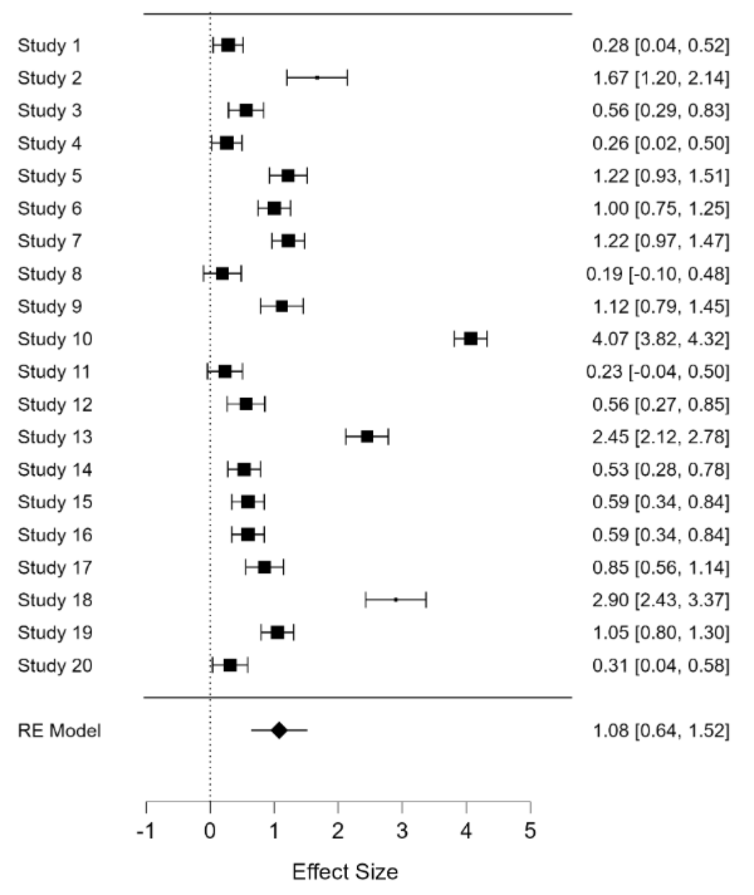

Fig 2. Forest Plot

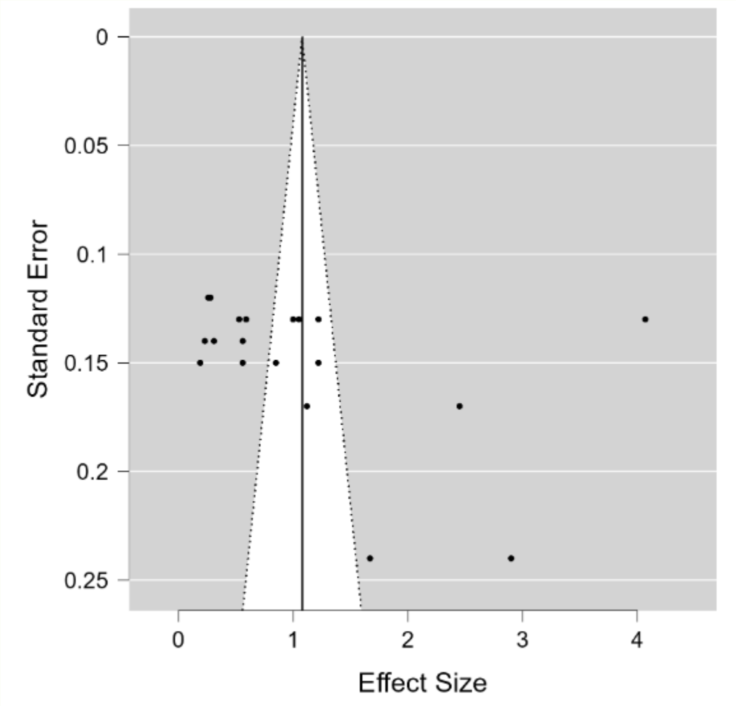

Fig 3. Funnel Plot

The forest plot (Figure 2) demonstrates the distribution of effect sizes across studies, with most studies showing positive effects of varying magnitudes. The funnel plot (Figure 3) suggests some asymmetry, indicating potential publication bias, though this is common in educational research. The heterogeneity analysis indicates significant variation in effect sizes across studies (Q-statistic significant), which can be attributed to differences in implementation contexts, student characteristics, specific educational outcomes measured, and variations in instructional design and technology integration.

Interpretation and Synthesis with Previous Research

These findings collectively suggest that the generative learning model is an effective pedagogical approach across educational levels, though its effectiveness varies by subject matter and targeted competencies. The model appears particularly strong in developing practical skills and conceptual understanding, while its impact on higher-order thinking skills may require additional instructional support.

The results of this meta-analysis reinforce previous research on the effectiveness of generative learning models in improving students' science competencies. Akmam et al. (2024) demonstrated that integrating cognitive conflict in generative learning models successfully enhanced students' creative thinking skills in physics learning. This finding is consistent with the high effect sizes in the meta-analysis for developing Generic Physics Skills (ES = 4.07) and Concept Mastery (ES = 1.75). Mufit et al. (2023) strengthened these results by showing that smartphone-based interactive multimedia integrated with cognitive conflict models effectively improved 21st-century skills, suggesting that technology integration enhances the model's impact.

Technology integration in the implementation of generative learning models demonstrates significant positive impacts on learning outcomes. Dhanil & Mufit (2024) revealed that virtual reality integration in science learning positively impacts student learning outcomes. This aligns with the meta-analysis findings showing high effectiveness in abstract topics such as Work and Energy (ES = 4.07) and Newton's Laws (ES = 2.90), suggesting that immersive technologies may amplify the model's effectiveness. Mufit & Dhanil (2024) also found that using augmented reality with cognitive conflict models effectively enhanced scientific literacy in static fluid material, demonstrating the potential of modern educational technologies.

Teachers' role in implementing generative learning models emerges as a key success factor. Novitra et al. (2024) emphasized that improving junior high school teachers' competence in designing instructional media to facilitate flexible learning is essential for successful implementation. Furthermore, Novitra (2021) revealed that developing online-based inquiry learning models can enhance the 21st-century skills of physics students in senior high school. These findings support the meta-analysis results showing the effectiveness of generative learning models at the secondary education level and underscore the importance of adequate teacher training and professional development.

Collectively, these studies support the results of this meta-analysis, which demonstrate the effectiveness of generative learning models in enhancing students'

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science competencies. Integrating modern technology such as virtual and augmented reality, combined with teachers' active role in designing instruction and providing appropriate scaffolding, becomes crucial in optimizing generative learning models' impact. This is reflected in the high effect sizes across various aspects of science competencies, from process skills to conceptual understanding.

4. Conclusion

The generative learning model demonstrates consistent and substantial effectiveness across all educational levels, with particularly powerful results in junior high school settings (ES = 1.18). Analysis of effect sizes reveals the highest effectiveness in conceptual physics topics such as Work and Energy (ES = 4.07) and Newton's Laws (ES = 2.90), while showing moderate effects in fluid dynamics subjects. The model excels at developing practical skills, scientific process skills, and conceptual understanding, but may require additional instructional support, explicit metacognitive strategies, or complementary approaches to enhance higher-order thinking skills such as critical thinking and problem-solving.

The comprehensive nature of this meta-analysis provides compelling evidence for the adoption of generative learning models in science education, particularly when combined with appropriate instructional scaffolding, technology integration, and well-trained teachers. Future research should focus on: (1) optimizing implementation strategies for specific subject materials, particularly in fluid dynamics where effect sizes are moderate; (2) developing and testing targeted instructional interventions to strengthen the model's impact on critical thinking and problem-solving abilities; (3) investigating the mechanisms through which technology integration enhances the model's effectiveness; and (4) exploring the role of teacher competence and professional development in implementation success.

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