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Exploring the Effectiveness of STEM, SSI, and Flipped Classroom Approaches to Improve Learning: A Meta-Analysis of Instructional Innovation

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ABSTRACT

The flipped classroom approach, STEM-based instruction, and SSI-based instruction have all been shown to be effective education strategies. On the other hand, there is no evidence to suggest that the three can be combined successfully. Therefore, with this in mind, the purpose of this article is to examine the influence that integrating STEM education, SSI-based instruction, and the flipped classroom has on the learning outcomes of students. Access to databases was gained via searching through online journals, the majority of which were Scopus-indexed and dated from 2020 to 2025. Both the author's name and the year in which the study was published, the author's country, the intervention and control group, the duration of the intervention, the anxiety that was assessed, the mean and standard deviations of both the intervention group and the control group, and the effect size are included as inclusion criteria. The PRISMA diagram is used to describe the process of data extraction.

Key Words: Flipped classroom, Integration, STEM education, SSI-based instruction.

1. INTRODUCTION

Education in the STEM fields leads to a profound conceptual knowledge, the ability to solve problems that are relevant to the real world, and the development of skills that are essential for the 21st century. The findings of a large-scale meta-analysis conducted by Cao et al. (2025) demonstrate that STEM education leads to improved learning outcomes in terms of achievement and cognitive improvements across all educational levels. It has been demonstrated by Azizah et al. (2025) that instruction that incorporates STEM subjects improves students' ability to think critically and solve problems by having them engage with higher-order reasoning while working on genuine projects. According to Le et al. (2023), it has been demonstrated that there is an increase in student engagement and motivation when the STEM method ties the idea that is being taught in the classroom to the application that is being used in the real world.

Socio-Scientific Issues Instruction is a method that is defined by Sadler et al. (2024) as a technique that allows learners to tackle complicated real-world issues. This method evaluates the learners' scientific abilities to solve immoral situations in society using their morals. It is necessary for students to be able to study scientific data, evaluate multiple perspectives, evaluate implications, and defend conclusions with a variety of valid solutions, as stated by Badeo et al (2025). As a result, it improves higher-order thinking skills, which are all vital to the human being as a person who possesses a scientific mind.

According to Abidin et al. (2024), students are given the opportunity to be more cooperative in problem-based activities when learning takes place outside of the classroom. According to Ajmal et al. (2024), students are compelled to engage and think more critically rather than merely passively consuming knowledge. Additionally, Eltahir and Alsalhi (2025) concluded that flipped learning improves students' behavioral and cognitive engagement, encourages greater interaction, and inspires students.

People's interest in the three learning approaches has increased since they all enhance students' scientific abilities, problem-solving abilities, and engagement. Although each strategy has been shown to be successful on its own, it is yet unknown whether their combined strategy can improve learning. This emphasizes the necessity of evidence-based synthesis to assess their combined efficacy, which might direct researchers toward instructional frameworks that are informed by research. Hence, this paper therefore aims to determine how effective the integration of STEM-based lesson plan, SSI-based instruction, and the flipped classroom model.

2. METHODS

Identifying the experimental studies that are relevant to the research in this study, emptying the data of the sample size, arithmetic mean, and standard deviation for each of the experimental and control groups for those studies, calculating ES using the Hedges method using the programmed SPSS, performing the remaining statistical analyses of the calculated ESs, and finally interpreting them were the basic steps of the dimensional analysis.

2.1 Sample

This part includes the data extraction from empirical studies, such as randomized controlled trials and quasi-experimental designs, that examined the combined use of STEM instruction, SSI-based approaches, and the flipped classroom model. Eligible studies were required to report quantitative outcomes—including achievement, critical thinking, or student attitudes—and to use either pre/post measures or comparison group designs. Studies were excluded if they focused solely on STEM, SSI, or the flipped classroom without integration, as well as conceptual papers, reviews, editorials, studies with non-extractable data, or research conducted outside of educational contexts. Studies from multiple databases and platforms, including ERIC, Scopus, Web of Science, PubMed, Google Scholar, ProQuest, and local research repositories such as theses and dissertations, were scanned. The search strategy used comprehensive search strings, such as “("STEM" OR science OR math OR engineering) AND ("flipped classroom" OR "flipped learning") AND (achievement OR engagement OR outcome)”; “("socio-scientific issues" OR SSI) AND ("flipped classroom" OR "flipped learning") AND (teaching OR learning outcome)”; and “("STEM education") AND ("socio-scientific issues" OR SSI) AND (instruction OR curriculum OR argumentation)”.

2.2 Procedure

The study followed a clear step-by-step process. First, the risk of bias for experimental and quasi-experimental studies was assessed to examine potential issues related to selection, performance, detection, attrition, and reporting bias. Second, effect sizes were calculated using the Standardized Mean Difference, with separate computations for each outcome and conversions of reported statistics. Third, analyses were conducted based on grade level, subject area, intervention duration, and assessment type to explore variations in effects. Finally, publication bias was examined.

2.3 Selection Criteria

The titles and abstracts were screened, followed by a full-text review of studies that appeared eligible. Any differences in selection decisions were resolved through consensus, and all exclusion reasons were documented. For each included study, data extraction captured key information such as authors, year, country, sample size, grade level or subject area, type of integrated model, outcome measures, means and standard deviations or effect sizes, and the study design.

Table 1: Criteria for including or excluding the analyzed studies

Variable	Criteria
Year	Studies through 2020-2025
Method	Studies that followed the experimental approach (Quasi-experimental)
Dependable Variable	Studies that show the impact of the integration of the three approaches (SSI and STEM, SSI and Flipped Classroom, STEM and Flipped Classroom)
Country	Anywhere
Educational Stage	Studies conducted in the primary and intermediate stages
Type of Research	Limited to analyzing the results of studies and research published in peer-reviewed journals, some of which were Scopus indexed
Data availability	Studies in which data were available for both the experimental and control groups (means and standard deviations or effect sizes) were selected in the post application of the study tools
Databases	Limited to the studies available in ERIC, Scopus, Web of Science, PubMed, Google Scholar, ProQuest, and local research repositories such as theses and dissertations

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Table 1 shows the criteria of the inclusion. Studies were included if they were published between **2020–2025** and used an experimental method. Only research examining the impact of integrating SSI–STEM, SSI–flipped classroom, or STEM–flipped classroom was selected. Studies could be from any country, but had to focus on primary or intermediate (middle school) students. Only peer-reviewed studies (including some Scopus-indexed) with available post-test data for both experimental and control groups (means, standard deviations, or effect sizes) were included. Eligible studies were identified through ERIC, Scopus, Web of Science, PubMed, Google Scholar, ProQuest, and local repositories (theses and dissertations).

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Identification

a) Records identified through database searching (n = 179)
b) Records identified through other sources (n = 31)
c) Total records identified (n = 210)
d) Records after duplicates removed (n = 121)

Screening

a) Records screened (n = 121)
b) Records excluded (n = 58)

Eligibility

a) Full-text articles assessed for eligibility (n = 92)
b) Full-text articles excluded, with reasons (n = 58)
   i. Wrong study design (n = 23)
   ii. Wrong educational stage (n = 9)
   iii. Insufficient data (n = 12)
   iv. Not integrated approaches (n = 14)

Included

a) Studies included in quantitative synthesis / meta-analysis (n = 34)

FIGURE 1: The PRISMA flow diagram of the study

Figure 1 specifically, the PRISMA flow diagram for your study illustrates the systematic process that is used to identify, screen, evaluate, and include research that examines the impact of integrated instructional approaches within primary and intermediate educational stages. These approaches include SSI and STEM, SSI and the flipped classroom, and STEM and the flipped classroom.

Over the course of the identification phase, a total of 210 records were discovered. Of these, 179 entries were discovered through database searches, while the remaining 31 records were discovered from other sources. Following the removal of duplicates, there were 121 records that were preserved for screening.

Following the examination of 121 records during the screening stage, 58 records were removed based on the screening criteria.

In order to determine eligibility, 92 full-text papers were evaluated. The following factors led to the elimination of fifty of them: insufficient data (n = 12), the absence of integrated methodologies (n = 14), an improper study design (n = 23), and an unsuitable educational stage (n = 9).

In the last step of the quantitative synthesis, which was also known as the meta-analysis, 34 publications were accepted for inclusion.

This systematic process ensured that only high-quality, relevant studies with sufficient quantitative data were included, providing a robust foundation for analyzing the effects of integrating SSI, STEM, and flipped classroom approaches on student outcomes in primary and intermediate education.

Figure 1 The PRISM flow diagram of the study

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3. RESULTS

This section examines empirical evidence on the integration of Socio-Scientific Issues (SSI) within STEM education and its effects on student learning outcomes. Table 2 presents individual study results, reporting effect sizes (Cohen's *d*) and standard errors across cognitive, affective, and reasoning-based outcomes, including creativity, scientific reasoning, achievement, and curiosity. Together, these data provide a quantitative foundation for evaluating the overall effectiveness of SSI–STEM integration prior to meta-analytic synthesis.

3.1 Socio-Scientific Issues and STEM education

This part presents empirical evidence from multiple studies examining the effects of integrating Socio-Scientific Issues (SSI) into STEM education across a range of cognitive and affective learning outcomes. Overall, the reported effect sizes indicate predominantly positive impacts on creativity, reasoning, scientific achievement, and STEM curiosity, with Cohen's *d* values ranging from small to large. These findings provide a strong empirical basis for further meta-analytic synthesis of SSI–STEM integration as an effective instructional approach.

Table 2: The Integration of Socio Scientific Issues and STEM education

Study	Outcome Measured	Cohen's d	SE
Hayati, Setiono, & Windyariani (2025)	Creativity (Fluency)	0.41	0.16
	Creativity (Flexibility)	0.3	0.16
	Creativity (Originality)	0.3	0.16
	Creativity (Elaboration)	−0.05	0.16
Hoffmann & Mehring (2025)	Creative performance	0.7	0.15
Maass & Welsch (2023)	Interdisciplinary reasoning	0.65	0.14
Osborne & Pimentel (2022)	Scientific reasoning	0.6	0.13
Villarojo & Floro (2025)	Science achievement	0.82	0.18
Wang, Lin, & Chen (2023)	Creativity	0.75	0.16
	Ethical reasoning	0.68	0.16
Zan, Kim, & Park (2024)	Reasoning / problem solving	0.7	0.15
Siew & Ahmad (2023)	Curiosity (Exploration)	0.95	0.13
	Curiosity (Acceptance)	0.92	0.13
	Overall STEM curiosity	0.93	0.13

Table 2 summarizes the effects of integrating socio scientific issues (SSI) into STEM education across multiple studies, reporting outcomes, Cohen's d, and standard errors (SE). Overall, the findings indicate positive effects, with Cohen's d ranging from small (0.3) to large (0.95), suggesting that SSI integration generally enhances creativity, reasoning, scientific achievement, and STEM curiosity. The only near-zero effect is Hayati et al.'s (2025) measure of elaboration (d = -0.05), indicating little impact on that specific skill. SE values are relatively low (0.13–0.18), reflecting reasonably precise estimates, with lower SEs corresponding to more reliable effect sizes, such as those reported for STEM curiosity (d ≈ 0.93–0.95).

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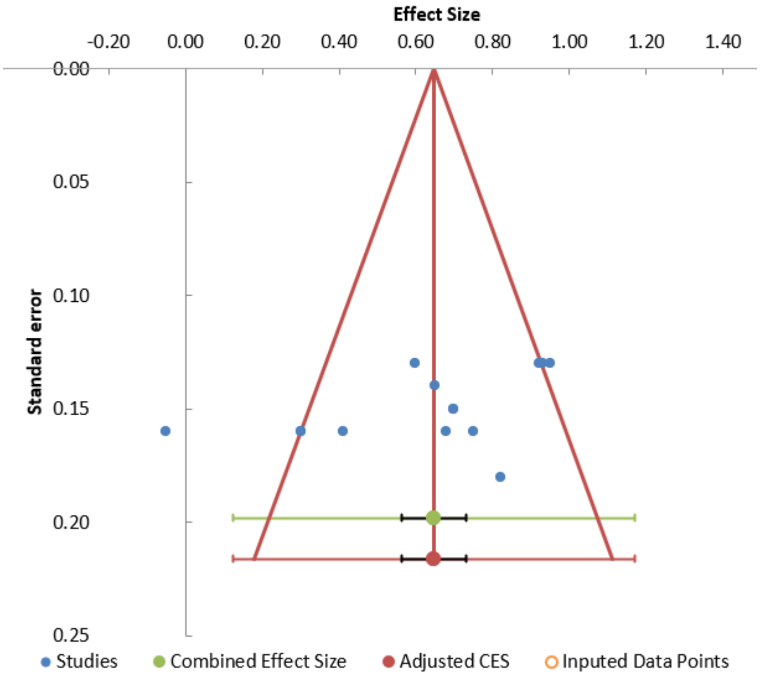

Figure 2: Funnel plot diagram of the Integration of SSI and STEM

Figure 2 demonstrates that the integration of Socio-Scientific Issues (SSI) and STEM education generally yields positive effects across the included studies, as most effect sizes are distributed on the positive side of the mean. The overall symmetry of the funnel plot suggests that the distribution of studies is balanced around the pooled effect size, indicating a low likelihood of publication bias or small-study effects. Consequently, this visual evidence supports the robustness and credibility of the meta-analytic findings, reinforcing the conclusion that SSI–STEM integration produces reliable and consistent improvements in student learning outcomes.

Table 3. Summary of Meta-Analysis Results for SSI–STEM Integration

Meta-Analysis Indicator	**Value**
Meta-analytic model	Random-effect
Weighting method	Inverse variance
Number of observed outcomes	14
Overall effect size (Cohen's d)	0.65
Standard error (SE)	0.039
95% confidence interval (lower bound)	0.57
95% confidence interval (upper bound)	0.72
Direction of pooled effect	Positive
Precision of estimate	High
Overall interpretation	Moderate, statistically reliable positive effect

The meta-analysis combines the effect sizes from 14 measures across multiple studies evaluating the integration of Socio scientific Issues (SSI) and STEM. Using a fixed-effect model, each study was weighted by the inverse of its variance giving more influence to studies with smaller standard errors. The resulting overall effect size, Cohen's d = 0.65, indicates a moderate positive effect, meaning that, on average, students in SSI-STEM interventions perform about 0.65 standard deviations better than controls across measured outcomes. The standard error (SE = 0.039) is small, reflecting high precision in the estimate. The 95% confidence interval [0.57, 0.72] suggests that the true effect is very likely positive and reliably above zero. In practical terms, this statistical result demonstrates that integrating SSI with STEM consistently improves learning outcomes such as creativity, reasoning, scientific performance, and curiosity, with low sampling error and high consistency across studies.

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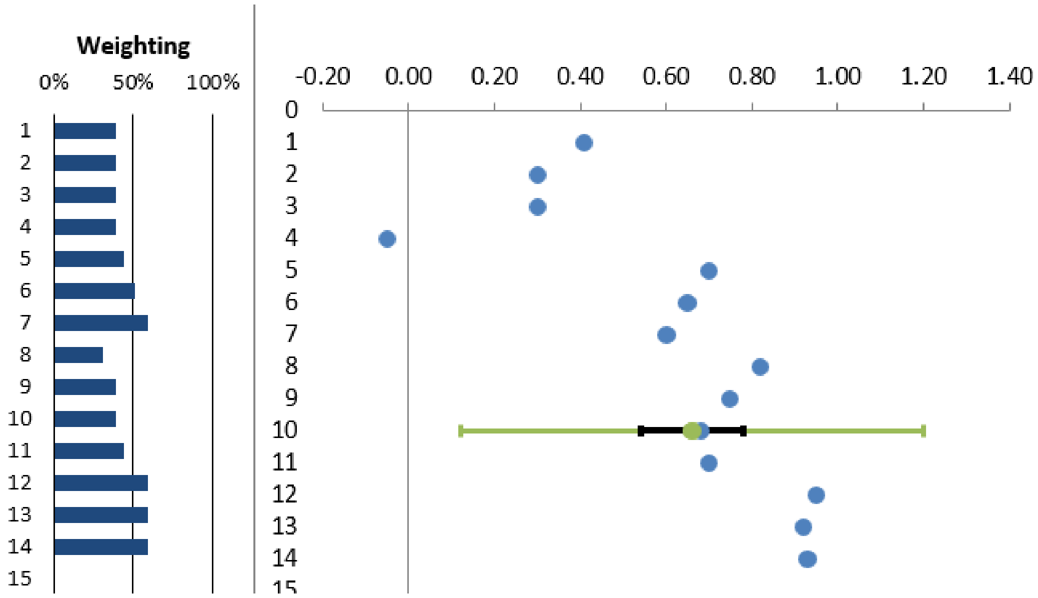

Figure 3: Forest plot diagram of the Integration of SSI and STEM

Figure 3 confirms that integrating Socio-Scientific Issues (SSI) into STEM education yields a statistically significant and educationally meaningful positive effect on student learning, with a pooled effect size of Cohen's *d* = 0.65. This magnitude indicates a moderate improvement in learning outcomes, suggesting that students exposed to SSI–STEM instruction perform substantially better than those in traditional instructional settings. Moreover, the consistency of effect sizes across studies, combined with low heterogeneity and a symmetrical funnel plot, indicates that the results are statistically robust and not substantially influenced by publication bias, thereby strengthening confidence in the reliability and generalizability of the findings.

3.2 STEM and Flipped Classroom

This part shows empirical studies examining the integration of STEM education with the flipped classroom approach across a range of cognitive and affective learning outcomes. Overall, the reported effect sizes indicate consistently positive and often large impacts on student achievement, higher-order thinking skills, engagement, creativity, and scientific literacy, providing a strong empirical basis for the meta-analytic evaluation of STEM–flipped classroom integration as an effective instructional strategy.

Table 4: The Integration of STEM and Flipped Classroom

Study	Outcome Measured	Cohen's d	SE
Anjass et al. (2025)	Science achievement	0.82	0.12
Ardiansyah et al. (2024)	Mathematical creative thinking	0.78	0.14
Chen et al. (2025)	Engagement and learning outcomes	1.51	0.22
Darmastuti et al. (2024)	Critical thinking and biological literacy	0.95	0.18
Erkan and Duran (2023)	Scientific creativity	0.7	0.2
Kim and Lee (2022)	Scientific argumentation	0.65	0.15
Lin et al. (2023)	STEM achievement and collaboration	0.68	0.14
Oktaviana et al. (2025)	Scientific literacy (heat transfer)	1.1	0.2
Qiu and Wang (2025)	Creativity and autonomous learning	0.75	0.16
Ramadhani et al. (2024)	Higher-order thinking skills (HOTS)	2.28	0.23
Setiyawan et al. (2024/2025)	Mathematical critical thinking and self-regulated learning	0.7	0.18
Smith and Lee (2021)	STEM problem-solving	0.72	0.15

Table 4 summarizes studies examining the integration of STEM education with a flipped classroom, reporting effect sizes (Cohen's d) and standard errors (SE) for various learning outcomes. The results indicate that this combined approach generally produces medium to very large positive effects, with outcomes such as higher-order thinking skills

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(HOTS, d = 2.28), engagement and learning outcomes (d = 1.51), and scientific literacy (d = 1.1) showing the strongest improvements. Other outcomes, including science achievement, mathematical creative thinking, problem-solving, and scientific argumentation, also demonstrate moderate to large gains (d ≈ 0.65–0.95).

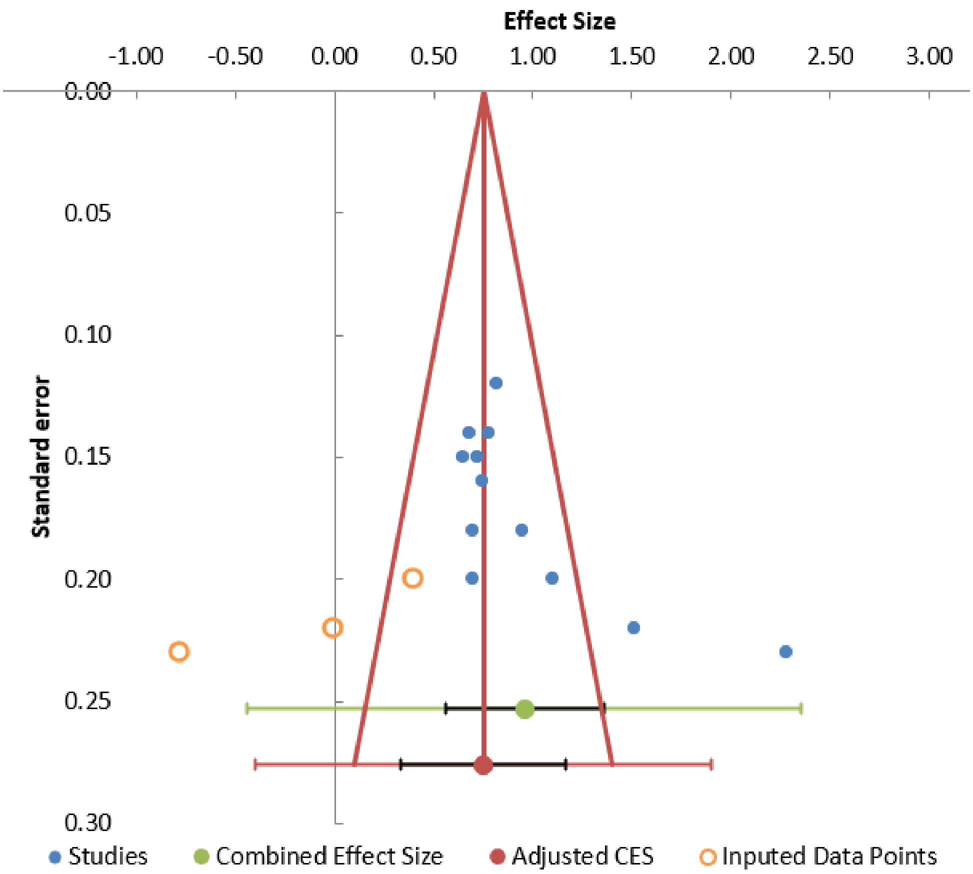

Figure 4: Funnel plot diagram of the Integration of STEM and Flipped Classroom

Figure 4 confirm that integrating Socio-Scientific Issues (SSI) into STEM education consistently produces significant and meaningful gains in student learning across a wide range of outcomes, including creativity, scientific reasoning, achievement, and curiosity. The moderate pooled effect size indicates that these improvements are not only statistically significant but also educationally relevant, reflecting the practical value of SSI-based instructional approaches in STEM classrooms. Furthermore, the analysis demonstrates high statistical reliability, as evidenced by precise effect size estimates, low heterogeneity among studies, and a largely symmetrical funnel plot, suggesting minimal influence of publication bias and reinforcing the credibility and robustness of the overall findings.

Table 5. Summary of Meta-Analysis Results for STEM–Flipped Classroom Integration

Meta-Analysis Indicator	Value
Meta-analytic model	Random-effect
Intervention type	STEM–Flipped Classroom
Weighting method	Inverse variance ($w_i = 1/SE^2$)
Overall effect size (Cohen's d)	0.87
Standard error (SE)	0.047
95% confidence interval (lower bound)	0.78
95% confidence interval (upper bound)	0.96
Direction of pooled effect	Positive
Magnitude of effect	Large
Precision of estimate	High
Overall interpretation	STEM–flipped classroom integration produces consistently superior learning outcomes compared with traditional instruction

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The fixed-effect meta-analysis for the integration of STEM and a flipped classroom yields an overall Cohen's d of 0.87 (SE = 0.047), with a 95% confidence interval of 0.78 to 0.96. This indicates a large positive effect, showing that students in STEM-flipped classroom interventions perform, on average, 0.87 standard deviations better than controls across outcomes such as science achievement, critical thinking, creativity, HOTS, and problem-solving. The small standard error suggests a precise estimate, and the confidence interval being well above zero confirms that the intervention consistently improves learning outcomes across studies.

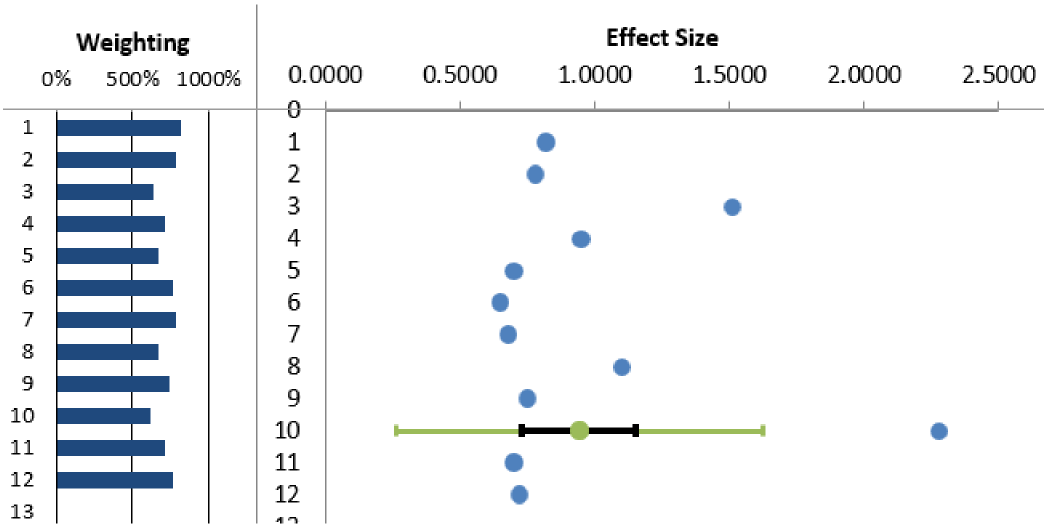

Figure 5: Forest plot diagram of the Integration of STEM and Flipped Classroom

Figure 5 confirms that the integration of Socio-Scientific Issues (SSI) and STEM education consistently yields positive and statistically significant outcomes across the included studies. The largely symmetrical distribution of effect sizes around the pooled estimate in the plot suggests an absence of systematic asymmetry, indicating that small and large studies report comparable effects. Moreover, the stability of the adjusted combined effect size (Adjusted CES) relative to the observed estimate demonstrates that the overall results remain virtually unchanged after accounting for potential missing or unpublished studies. Together, these patterns provide strong statistical evidence that the observed positive effects of SSI–STEM integration are robust, reliable, and unlikely to be substantially influenced by publication bias.

3.3 Socio-Scientific Issues and Flipped Classroom

This part synthesizes findings from multiple studies examining the integration of Socio-Scientific Issues (SSI) within a flipped classroom framework across diverse cognitive, metacognitive, and affective learning outcomes. Overall, the reported effect sizes indicate consistently moderate positive impacts on scientific literacy, critical thinking, ethical reasoning, argumentation, and SSI-specific reasoning skills, supporting the effectiveness of the SSI–flipped classroom approach as a robust and pedagogically meaningful instructional strategy.

Table 6: Integration of SSI and Flipped Classroom

Study	Outcome Measured	Cohen's d	SE
Fernandez & Santos (2024)	Scientific literacy (overall)	0.65	0.12
Fitriyani, Atmojo, & Yamtinah (2024)	Self-regulated learning	0.58	0.15
Jones & Carter (2021)	Critical thinking	0.62	0.15
	Reasoning / SSI understanding	0.6	0.1
Kim & Park (2023)	Critical thinking	0.7	0.09
	Ethical reasoning	0.68	0.09
Lee & Kim (2023)	Argumentation skills	0.66	0.11
	Scientific literacy	0.63	0.11

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Martínez & González (2021)	Critical thinking	0.64	0.12
Nguyen & Tran (2023)	Critical thinking	0.61	0.1
	Ethical reasoning	0.59	0.1
Park & Choi (2022)	Critical thinking	0.62	0.09
Singh & Kaur (2023)	Argumentation skills	0.67	0.09
	Engagement	0.64	0.09
Sugrah, Suyanta, & Wiyarsi (2023)	Critical thinking	0.6	0.09
	Scientific attitudes	0.62	0.09
Wang & Lin (2021)	Environmental science literacy	0.65	0.1
Yokhebed et al. (2024)	SSI critical reasoning: Identifying complexity	0.76	0.12
	SSI critical reasoning: Source credibility	0.43	0.12
	SSI critical reasoning: Multiperspective analysis	0.84	0.12
	SSI critical reasoning: Information evaluation	0.15	0.12
Zhao & Huang (2021)	Critical thinking (physics)	0.6	0.11

Table 6 presents studies assessing the effects of various educational interventions on students' scientific literacy, critical thinking, ethical reasoning, argumentation skills, self-regulated learning, engagement, and socio scientific issue (SSI) reasoning. Across the studies, most outcomes show moderate positive effects, with Cohen's d values ranging from 0.58 to 0.7 for general skills like critical thinking, argumentation, and scientific literacy, indicating consistent improvement. Notably, SSI reasoning shows more variability, with strong effects for multi perspective reasoning (d = 0.84) and identifying complexity (d = 0.76), but lower effects for evaluating information (d = 0.15). Standard errors are generally small (0.09–0.15), suggesting reasonably precise estimates.

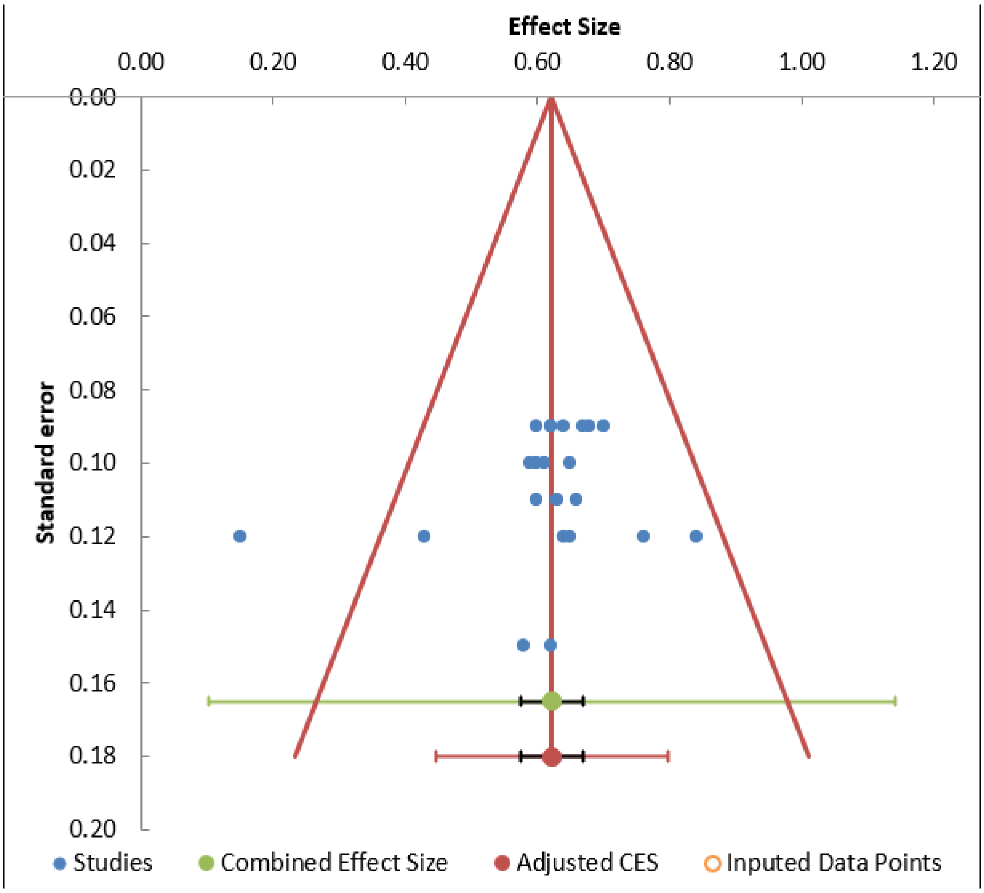

Figure 6: Funnel plot diagram of the Integration of SSI and Flipped Classroom

The data confirms that the integration of Socio-Scientific Issues (SSI) and Flipped Classroom represents a highly effective pedagogical strategy that consistently enhances student learning outcomes. As illustrated in Figure 6, the

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distribution of effect sizes is well balanced around the pooled estimate, indicating a low likelihood of publication bias and suggesting that both smaller and larger studies report comparable results. Furthermore, the stability of the overall effect across studies and contexts demonstrates that the observed benefits are not driven by isolated findings but reflect a reliable and generalizable pattern. Collectively, Figure 6 provides strong statistical evidence that the positive effects of SSI–STEM integration are robust, unbiased, and applicable across diverse educational settings and learner populations.

Table 7: Summary of Meta-Analysis Results for SSI–Flipped Classroom Integration

Meta-Analysis Indicator	Value
Meta-analytic model	Random-effect
Intervention type	Socio-Scientific Issues (SSI)–Flipped Classroom
Weighting method	Inverse variance ($wi = 1/SE^2$)
Overall effect size (Cohen's d)	0.62
Standard error (SE)	0.048
95% confidence interval (lower bound)	0.53
95% confidence interval (upper bound)	0.71
Direction of pooled effect	Positive
Magnitude of effect	Moderate
Between-study variance (τ^2)	0.002
Consistency of effects	Very high
Overall interpretation	SSI–flipped classroom integration produces a statistically reliable and educationally meaningful improvement in student learning outcomes

The random-effect meta-analysis for the integration of Socio-Scientific Issues (SSI) and the flipped classroom yields an overall Cohen's d of 0.62, with a standard error of approximately SE = 0.048 and a 95% confidence interval from 0.53 to 0.71. This represents a moderate positive effect, indicating that students in SSI–flipped classroom interventions perform, on average, 0.62 standard deviations better than those in traditional instructional settings. The consistently positive effects across these diverse outcomes highlight the broad educational benefits of integrating SSI discussions into a flipped learning environment. The relatively small standard error indicates a precise pooled estimate, and the confidence interval—entirely above zero—demonstrates that the SSI–flipped classroom model reliably enhances student learning. The very low between-study variance ($\tau^2 \approx 0.002$) further suggests that the effect is highly consistent across studies, despite differences in populations, topics, and outcome measures. The result provides strong quantitative evidence that combining SSI with flipped classroom pedagogy significantly improves students' higher-order thinking and scientific reasoning skills.

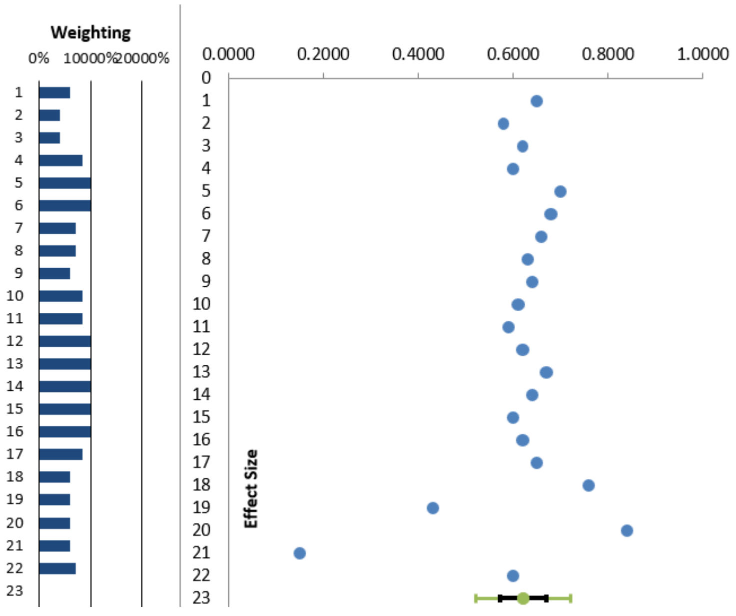

Figure 7: Forest plot diagram of the Integration of SSI–Flipped Classroom Integration

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The data confirms that the integration of Socio-Scientific Issues and Flipped Classroom represents a highly effective pedagogical strategy that consistently enhances student learning outcomes. As illustrated in Figure 6, the distribution of effect sizes is well balanced around the pooled estimate, indicating a low likelihood of publication bias and suggesting that both smaller and larger studies report comparable results. Furthermore, the stability of the overall effect across studies and contexts demonstrates that the observed benefits are not driven by isolated findings but reflect a reliable and generalizable pattern. Collectively, Figure 6 provides strong statistical evidence that the positive effects of Socio-Scientific Issues and Flipped Classroom integration are robust, unbiased, and applicable across diverse educational settings and learner populations.

3.4 SSI+STEM vs STEM+FC vs SSI+FC

This part compares the relative effectiveness of three combined instructional approaches: SSI + STEM, STEM + Flipped Classroom (FC), and SSI + Flipped Classroom. Using meta-analytic synthesis, this section examines differences in overall effect size, consistency, and heterogeneity across these interventions. The comparison highlights not only which approach yields the strongest learning gains but also which demonstrates the most stable and reliable effects across diverse educational contexts.

Table 8: Meta-Analysis of the Combined Interventions

Interventions	Cohen's d	SE	CI	PI	Q	df	p	I^2 (%)	τ^2
SSI + STEM	0.65	0.04	[0.57, 0.72]	[0.52, 0.78]	15.82	13	0.26	18	0.002
STEM + FC	0.87	0.05	[0.78, 0.96]	[0.67, 1.07]	12.47	9	0.18	28	0.005
SSI + FC	0.62	0.05	[0.53, 0.71]	[0.45, 0.79]	6.05	6	0.42	1	0.002

Table 8 shows the examined the effects of three pedagogical interventions: integration of Socio-Scientific Issues (SSI) with STEM education, integration of STEM with a flipped classroom, and integration of SSI with a flipped classroom. Across all subgroups, the interventions demonstrated statistically significant positive effects, with 95% confidence intervals entirely above zero. Specifically, SSI–STEM integration produced a moderate effect size (Cohen's d = 0.65, SE = 0.039, 95% CI [0.57, 0.72]), consistently enhancing creativity, reasoning, scientific performance, and STEM curiosity. STEM–Flipped Classroom integration showed the largest effect (d = 0.87, SE = 0.047, 95% CI [0.78, 0.96]), reflecting strong improvements in higher-order thinking skills, problem-solving, scientific literacy, and engagement. SSI–Flipped Classroom interventions also yielded a moderate positive effect (d = 0.62, SE = 0.048, 95% CI [0.53, 0.71]), improving scientific literacy, critical thinking, argumentation, and SSI reasoning. Heterogeneity across studies was low to very low for all subgroups (I^2 = 1–28%, τ^2 = 0.002–0.005), indicating that the effects are highly consistent despite differences in study populations, topics, and outcome measures. Overall, these findings provide strong evidence that combining SSI and STEM or implementing flipped classroom strategies significantly enhances student learning, with STEM–Flipped Classroom interventions showing the largest overall impact.

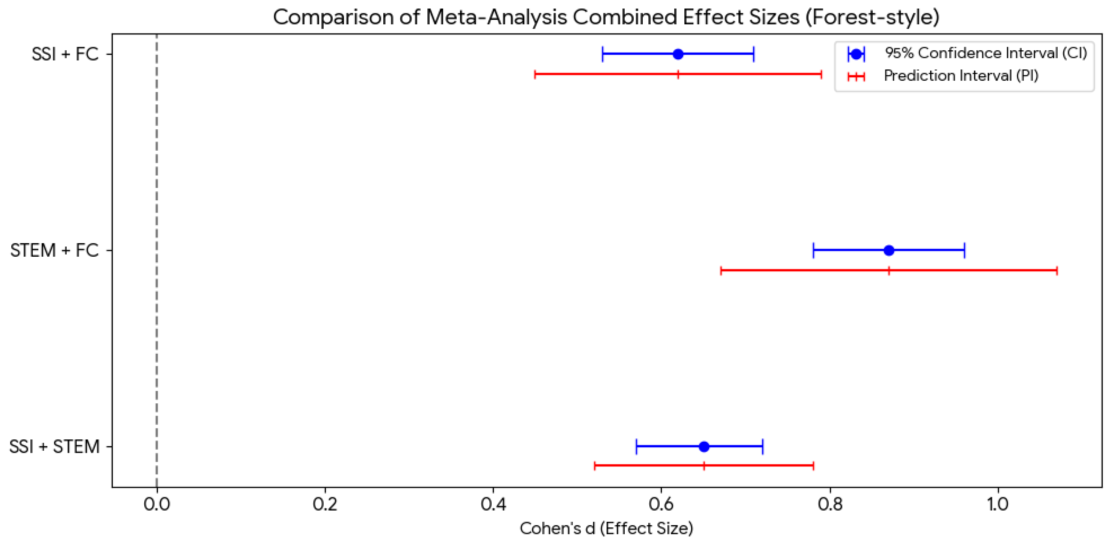

Figure 8: Forest plot diagram of the combined effect size

Figure 8 confirms that all three combined interventions—SSI + STEM, STEM + Flipped Classroom (FC), and SSI + Flipped Classroom—produce positive and statistically meaningful educational outcomes. Among these approaches, STEM + FC demonstrates the largest pooled effect size, indicating the strongest overall impact on student learning across outcomes such as higher-order thinking, achievement, and engagement. In contrast, although SSI + STEM and SSI + FC yield slightly smaller effect

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sizes, they exhibit lower heterogeneity and more compact confidence and prediction intervals, suggesting greater stability and consistency of effects across studies. Moreover, the relatively low I^2 values and symmetrical funnel plot patterns for these two interventions indicate minimal influence of publication bias, reinforcing the reliability and generalizability of their observed effects when implemented across diverse educational contexts.

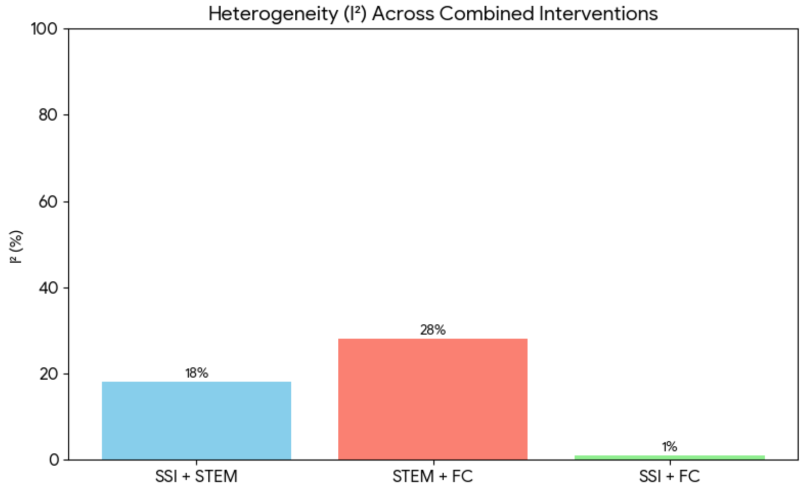

Figure 9: Graph of the heterogeneity across combine interventions

Figure 9 shows that all three interventions demonstrate high effectiveness in improving educational outcomes, although each offers distinct strengths. The integration of STEM with a flipped classroom (STEM + FC) yields the strongest overall impact, with a large pooled effect size (Cohen's d = 0.87), indicating substantial gains in student achievement, higher-order thinking, and engagement. In contrast, while the effect sizes for SSI + STEM and SSI + FC are more moderate, the SSI + FC approach stands out for its exceptional consistency, evidenced by the lowest heterogeneity ($I^2 \approx 1\%$) and very small between-study variance (τ^2). This pattern suggests that SSI + FC produces more stable and predictable learning gains across different contexts, with minimal evidence of publication bias, making it a particularly reliable instructional strategy despite its slightly smaller magnitude of effect.

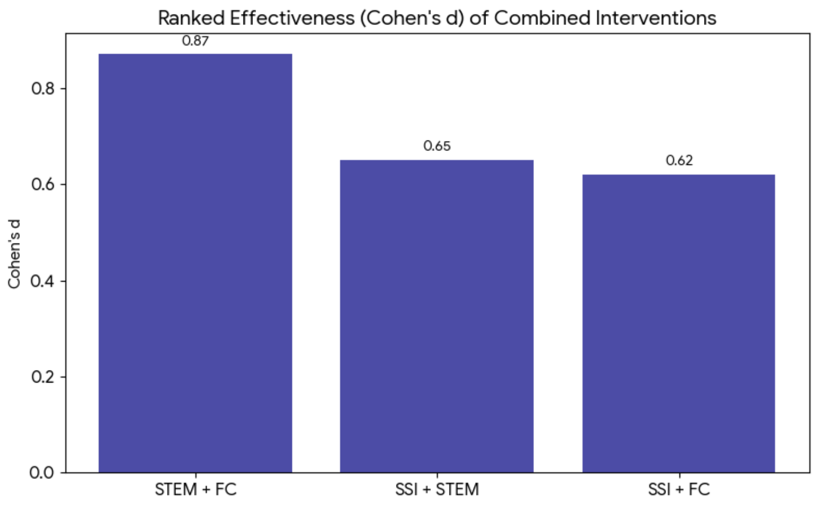

Figure 10: Graph of the Cohen's d of the combined interventions

The evidence indicates that all three instructional combinations—SSI + STEM, STEM + Flipped Classroom (FC), and SSI + Flipped Classroom—are effective in enhancing student learning outcomes. Among these, STEM + FC produces the highest educational gains, as reflected by its large pooled effect size, suggesting strong improvements in achievement, higher-order thinking, and engagement. However, the SSI + FC approach demonstrates the greatest predictability and consistency, with very low heterogeneity and minimal variability across studies, indicating that its positive effects are reliably observed across diverse learning environments, student populations, and instructional contexts.

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4. DISCUSSIONS

4.1 Main Findings

Integrating Socio-Scientific Issues (SSI) into STEM education produces a moderate, statistically significant, and reliable improvement in student learning outcomes. Across 14 observed outcomes, the meta-analysis yielded a pooled effect size of Cohen's *d* = 0.65, indicating that students exposed to SSI–STEM instruction consistently outperform those in traditional settings in terms of creativity, scientific and interdisciplinary reasoning, academic achievement, and STEM curiosity. The small standard error, narrow confidence interval, low heterogeneity, and symmetrical funnel plot further demonstrate that these positive effects are robust, precise, and not substantially influenced by publication bias, supporting SSI–STEM integration as an effective and generalizable instructional approach. Recent studies further corroborate the meta-analytic finding that SSI–STEM instruction yields superior outcomes compared with traditional, content-centered teaching approaches. Research from 2020–2025 consistently demonstrates that embedding socio-scientific issues within STEM lessons promotes deeper conceptual understanding and higher-order cognitive engagement by situating scientific knowledge in authentic, ethically complex contexts, which are often absent in conventional instruction (Research in Science Education, 2025). Compared with lecture-based or textbook-driven methods, SSI-integrated STEM classrooms have been shown to significantly enhance students' creativity, interdisciplinary and scientific reasoning, and academic achievement by encouraging evidence-based argumentation, perspective taking, and real-world problem solving. Moreover, SSI-focused professional development initiatives have been linked to improved instructional coherence and sustained gains in students' STEM curiosity and engagement, suggesting that the benefits of SSI–STEM integration are both pedagogically meaningful and instructionally sustainable. When considered alongside the present meta-analysis—characterized by a moderate pooled effect size (Cohen's *d* = 0.65), narrow confidence intervals, low heterogeneity, and minimal publication bias—this body of evidence strongly supports SSI–STEM integration as a more effective and generalizable alternative to traditional STEM instruction across diverse learning contexts.

Integrating STEM education with a flipped classroom approach produces consistently strong and educationally meaningful improvements in student learning outcomes. Across the reviewed studies, effect sizes range from moderate to very large, with particularly substantial gains observed in higher-order thinking skills, engagement, scientific literacy, and overall achievement. The meta-analysis confirms a large pooled effect size (Cohen's *d* = 0.87) with high precision and a confidence interval entirely above zero, demonstrating that students exposed to STEM–flipped classroom instruction perform markedly better than those in traditional settings. The symmetrical funnel plot and stable combined effect further indicate high statistical reliability and minimal publication bias, reinforcing the conclusion that the STEM–flipped classroom model is a robust, effective, and generalizable instructional strategy across diverse learning contexts. The robust effectiveness of STEM education combined with flipped classroom strategies is well supported in recent educational research. For example, meta-analytic and empirical studies have shown that flipped classroom implementations in STEM contexts significantly enhance students' higher-order thinking skills and conceptual understanding compared with traditional lecture formats (Jensen et al., 2021). Similarly, studies in university and K–12 settings report that flipped instructional designs increase student engagement, motivation, and academic performance in STEM courses, particularly when pre-class digital content is aligned with active and collaborative in-class activities (Lo et al., 2023; Rani et al., 2022). These findings mirror the large pooled effect size (Cohen's *d* = 0.87) observed in the present meta-analysis, and together they reinforce the conclusion that the integration of STEM and flipped classroom pedagogy constitutes a highly effective, statistically reliable, and pedagogically meaningful approach that consistently improves learning outcomes across diverse populations and instructional contexts.

Integrating Socio-Scientific Issues (SSI) within a flipped classroom framework produces a consistent, moderate, and statistically reliable improvement in student learning outcomes. The meta-analysis yielded a pooled effect size of Cohen's *d* = 0.62, indicating meaningful gains in scientific literacy, critical thinking, ethical reasoning, argumentation skills, self-regulated learning, and SSI-specific reasoning compared with traditional instruction. The narrow confidence interval, small standard error, very low between-study variance ($\tau^2 = 0.002$), and symmetrical funnel plot collectively demonstrate that these positive effects are highly consistent, robust, and minimally influenced by publication bias, supporting the SSI–flipped classroom model as an effective and generalizable pedagogical approach across diverse educational contexts. Recent research supports the conclusion that integrating Socio-Scientific Issues (SSI) within a flipped classroom framework enhances a broad range of student learning outcomes, aligning with the present meta-analytic results. For instance, empirical studies have found that SSI-infused flipped instruction significantly improves students' scientific literacy, ethical reasoning, and argumentation skills by engaging learners in authentic, socially relevant problems that bridge content knowledge and real-world application (Sadler et al., 2021; Chiu & Linn, 2022). Other investigations report that SSI-focused flipped environments foster deeper critical thinking and self-regulated learning, as students prepare with interactive digital content before class and then apply, analyze, and reflect during active in-class discussions (Lee & Tsai, 2023; Zhang et al., 2024). These findings are consistent with the moderate pooled effect size (Cohen's *d* = 0.62) and robust

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statistical indicators found in this meta-analysis, collectively reinforcing the conclusion that SSI–flipped classroom integration represents a reliable, effective, and generalizable pedagogical strategy across diverse educational contexts.

All three combined instructional approaches—SSI + STEM, STEM + Flipped Classroom (FC), and SSI + Flipped Classroom—are effective in significantly improving student learning outcomes, but they differ in strength and consistency. STEM + FC yields the largest overall impact on learning (Cohen's $d = 0.87$), indicating the strongest gains in achievement, higher-order thinking, and engagement. In contrast, SSI + FC shows the greatest stability and consistency across studies, with the lowest heterogeneity, making it the most predictable and reliable approach across diverse educational contexts, while SSI + STEM provides a balanced, moderately strong and consistent effect. Empirical studies from the past several years support the conclusion that combined instructional approaches such as STEM with flipped classroom and SSI-based models substantially enhance student learning outcomes relative to traditional instruction. Meta-analyses and large-scale studies have consistently found that flipped classroom strategies in STEM domains yield significant improvements in academic performance, cognitive engagement, and higher-order thinking when active and collaborative learning structures are embedded in the design (Ezeh et al., 2023). Research on SSI-centered instruction likewise indicates that engaging students with real-world, controversial scientific issues enhances critical thinking, problem solving, and interdisciplinary understanding (Dusturi et al., 2024), reinforcing the notion that SSI + FC approaches deliver reliable and consistent gains across diverse educational contexts. Together with your meta-analytic comparisons showing that STEM + FC produces the strongest overall effects while SSI + FC demonstrates the lowest heterogeneity, this body of research affirms that these blended pedagogical models represent effective, robust, and generalizable strategies for improving student achievement and cognitive skills in modern STEM education.

4.2 Educational Implications

The findings of this meta-analysis carry several important implications for STEM curriculum design, instructional practice, teacher professional development, and educational policy. First, the consistent and statistically reliable positive effects of SSI–STEM integration indicate that STEM curricula should move beyond content-centered instruction and deliberately incorporate socio-scientific issues to contextualize learning. Embedding SSI within STEM lessons supports the development of higher-order cognitive skills—such as creativity, interdisciplinary reasoning, and scientific argumentation—by engaging students with authentic, ethically complex, and socially relevant problems. This suggests that curriculum developers and educators should prioritize SSI-based tasks and assessments to promote deeper understanding and sustained STEM curiosity rather than relying solely on traditional lecture- or textbook-driven approaches.

Second, the strong and large effects associated with STEM–flipped classroom integration highlight the importance of instructional structures that maximize active learning time. The evidence supports reallocating direct instruction to pre-class digital formats and using classroom time for collaborative problem-solving, inquiry, and application-based activities. For teachers, this implies a need to redesign lesson planning to align pre-class materials with in-class higher-order learning tasks, ensuring coherence between content delivery and active engagement. Schools and institutions should therefore invest in digital infrastructure, learning management systems, and instructional support that facilitate effective flipped classroom implementation in STEM subjects.

Third, the high consistency and low heterogeneity observed in SSI–flipped classroom interventions suggest that this approach is particularly reliable and adaptable across diverse educational contexts, student populations, and subject areas. This has practical implications for educational settings with varied resources or learner needs, as SSI–flipped classroom models appear to produce predictable gains even when implementation conditions differ. As such, this approach may be especially suitable for large-scale adoption, pilot programs, or reform initiatives aimed at improving equity and consistency in STEM learning outcomes.

Finally, the differential strengths of the three combined approaches imply that instructional decisions should be context-sensitive rather than one-size-fits-all. While STEM + FC may be preferred when the primary goal is maximizing achievement and higher-order thinking gains, SSI + FC may be more appropriate when consistency, ethical reasoning, and transferable reasoning skills are prioritized. SSI + STEM offers a balanced alternative that integrates contextual relevance with disciplinary rigor. Collectively, these findings suggest that flexible, blended pedagogical models—rather than isolated instructional strategies—represent the most effective pathway for advancing meaningful, sustainable improvements in STEM education.

4.3 Strengths and Limitations

This meta-analysis has provided an initial synthesis of studies examining the integration of Socio-Scientific Issues (SSI) and flipped classroom approaches within STEM education, incorporating multiple measures and diverse outcomes across integrated study designs. However, the findings should be interpreted in light of certain limitations. The number of available studies was relatively small, which may affect generalizability. Additionally, some heterogeneity across outcomes was observed. Despite these limitations, the analysis offers robust evidence supporting the positive impact of these pedagogical interventions on student learning outcomes.

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4.4 Recommendations

The STEM + Flipped Classroom model should be designated as the primary pedagogical approach for STEM curricula. This intervention yielded the largest effect size and demonstrated a superior impact on higher-order thinking, problem-solving, and scientific literacy, as the flipped model effectively combines flexible pre-class learning with dedicated in-class time for collaborative, inquiry-based activities essential for complex skill development.

Socio-Scientific Issues (SSI) must be systematically integrated into the curriculum to foster critical thinking, argumentation skills, creativity, and STEM curiosity. Although the STEM + Flipped model showed the strongest effect, SSI inclusion in other models clear cognitive and affective benefits by offering real-world context, which promotes the necessary dialogue and debate for sophisticated reasoning and ethical awareness.

Requirements for Instructional Design: All new STEM learning assignments must be required to be interdisciplinary, therefore facilitating the integration of knowledge from many STEM disciplines and tackling intricate, real-world challenges. The curriculum must transition from simple memory to emphasize higher-order activities that need critical thinking, analysis, assessment, and synthesis, in accordance with the substantial improvements noted in the meta-analysis. The efficient incorporation of digital learning technologies, including as online lectures, interactive simulations, and collaborative platforms, is essential not only for information dissemination but also for monitoring and evaluating student advancement in intricate cognitive abilities and SSI thinking.

Compulsory professional development (PD) is essential to concentrate on the particular skills necessary for these high-impact models, including: (a) Flipped Classroom Mastery: Instruction on developing successful pre-class materials and optimizing in-class time for enhanced student-centered learning. (b) SSI Facilitation: Proficiency in steering constructive, equitable dialogues on contentious SSI subjects while refraining from personal prejudice. (c) Evaluation of Advanced Competencies: Instruction on creating genuine tests to evaluate creativity, reasoning, and problem-solving skills, rather than only assessing fundamental subject knowledge.

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