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Abstract

This meta-analysis synthesized 18 qualified studies, resulting in 29 effect sizes. This study involved a total sample of 1,280 students to evaluate the effectiveness of Engineering Design Process (EDP)-based instructional approaches in STEM education. Eligible studies were systematically selected through inclusion and exclusion criteria following the PRISMA protocol, and effect sizes were computed using Hedge's g , applying random-effect model due to substantial heterogeneity ($Q_e = 156.367$, $df = 28$, $p < 0.001$). The overall effect size ($ES = 1.168$) reflects a strong positive impact of EDP-based interventions on STEM learning. Meta-regression analysis further revealed that tertiary education level significantly moderated the effect size ($p=0.033$), while STEM competence type and implementation period did not yield statistically significant effects. The findings also revealed that scientific creativity and engineering-focused STEM integration were the most frequently enhanced STEM competence and instructional approach used on the reviewed studies respectively. These findings support the pedagogical strength of EDP in fostering inquiry-driven, higher-order thinking and suggest tailoring approaches based on learner's academic level to maximize impact.

Introduction

Engineering design process (EDP) has gained prominence for its potential to enhance students' competence to tackle real-world complex challenges (English et al., 2013; Purzer et al., 2015). Widely varied in definition, EDP is consistently described as a systematic and iterative problem-solving framework grounded in science, mathematics, and engineering. The National Aeronautics and Space Administration defines it as a step-by-step process involving asking, imagining, planning, creating, testing, and improving. On the other hand, the University of Colorado emphasizes the open-ended problem-solving and learning from failure nature of EDP. Dym et al. (2005) describe it as concept-driven development within constraints, and Mangold and Robinson (2013) highlight decision-making rooted on disciplinary knowledge.

EDP emerged to be one of the strategic educational tools for implementing STEM instruction (Hafiz & Ayop, 2019). The open-ended problem-solving and iterative learning feature of EDP enable students to grow from their

mistakes and develop creative, discipline-spanning solutions. As a pedagogical strategy, EDP enables learners to apply science, mathematics, and engineering knowledge in constructing optimal solutions (Hafiz & Ayop, 2019). Scholars classify EDP as a form of problem-based learning (Schnittka, 2009), given its shared emphasis on addressing real-world, ill-structured problems through design thinking (National Research Council, 2012). Furthermore, with its inclusion in the Next Generation Science Standards (NGSS), engineering design has been elevated to the same status as scientific inquiry across all grade levels, aiming to equip students with foundational skills to navigate future environmental and societal challenges (National Research Council, 2012).

EDP mirrors the real-world practices of engineers who collaboratively address societal problems through iterative design and decision-making (Dym et al., 1994). Unlike linear problem-solving models, EDP integrates cycle of planning, prototyping, testing, and revising, enabling the students to engage with complex challenges and constraints. EDP-based learning builds on this by embedding these practices into STEM education, fostering creativity and solution-driven thinking (Arik & Topcu, 2020). Compared to problem-based learning, EDP-based learning offers a more systematic, engineering-rooted framework. While scientists focused on inquiry and experimentation, engineers emphasize identifying constraints, generating ideas, and optimizing solutions (Zeid et al., 2014). This form of learning supports students in designing solutions that meet technical standards while encouraging reflective thinking and innovation across diverse STEM contexts.

Integrating EDP to STEM instruction has been shown to enhance both cognitive and non-cognitive aspects of the student learning. In terms of cognitive development, EDP improves scientific knowledge (Fan & Yu, 2017; Fan et al., 2017) thinking skills (Goktepe et al., 2018; McFadden & Roehrig, 2018), and academic performance (Strimmel et al., 2018). Non-cognitive benefits include development of practical skills (Barak & Assal, 2018; English & King, 2015), positive attitudes towards science (Hathcock et al., 2015), motivation (Jackson et al., 2018), and self-efficacy (Leonard et al., 2016). Moreover, Syukri et al. (2018) demonstrated that EDP enhances physics problem-solving skills, while Yildiz and Ozdemir (2018) found improved spatial abilities, and Capobianco et al. (2015) reported strength engineering identity among younger learners in elementary level. These findings established EDP as a prime strategy in STEM instructions.

At present, there remains a limited scholarly literature that systematically reviews the EDP as an instructional approach in STEM education using meta-analysis as a model of inquiry. Hafiz and Ayop (2019) conducted a systematic review highlighting EDP's potential as a core strategy in STEM teaching and learning. Similarly, Winarno et al. (2020) critically examined EDP-related literature to identify key project themes, educational benefits, and implementation outcomes. Sudrajat et al. (2022) expanded this work through a comprehensive bibliometric analysis, offering broad foundations for future EDP research.

Lammi et al. (2018) contributed further by clarifying EDP conceptualization in pre-college STEM contexts. Building on these studies, the present study aimed at providing a critical review based on empirical findings regarding the effectiveness of EDP in STEM context. It further sought to establish the potential of EDP as a pedagogical intervention and learning approach towards improved learning outcomes.

Research Questions

The following research questions were framed to guide the current meta-analysis:

1. What is the effectiveness of EDP-based instructional approaches in enhancing STEM competence?
2. Do the type of STEM competence, implementation period, and academic level significantly moderate the effectiveness of EDP-based instructional approaches on STEM competence outcomes across obtained studies?
3. What are the EDP-based instructional approaches utilized in the obtained studies?
4. What are the specific STEM competencies examined in the studies obtained?

Method

Research Design

This study employed a meta-analysis as research design to address the research questions. This process involved systematic methods to locate, select, and evaluate pertinent research, and to extract and analyze data from the studies that formed part of the review (Khan et al., 2003). It is a statistical method that synthesizes results from multiple studies to identify the overall trend (McKenzie et al., 2019). The present study adapted the protocols based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) in conducting systematic reviews. The PRISMA is an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses.

Inclusion and Exclusion Criteria

The present meta-analytic review included journal articles that were written in English language published from 2016 to present year, 2025. The eligible articles are empirical studies that investigated the quantitative impact of EDP as an instructional intervention to improve students' learning outcomes in STEM both at school and classroom level. Likewise, the dependent variables set in the selected studies must be considered as STEM competence. In terms of research designs, only studies that incorporated true- or quasi-experiment method were considered. In addition, the journal articles that formed part of the review contained sufficient statistical information such as effect size, standard deviation, posttest mean values, and the sample size. The studies may also include t-value and F-value. For the exclusion criteria, journal articles that are not situated in the context of STEM teaching and learning were not considered. Articles which employed correlational, pre-experimental, single-subject, and qualitative research were also removed from the review.

Data Gathering Procedure

The information sources of this study included Google Scholar, ERIC, Scopus, and Web of Science databases. The search strategy was conducted using the Publish or Perish (PoP) software to obtain relevant articles from ERIC, Google Scholar, Scopus, and Web of Science (WoS) databases. To initiate search, the following keywords were used singly and in combination: "engineering design process", "engineering design", "STEM education".

Figure 1 shows the PRISMA flowchart of the present meta-analysis.

Data Analysis

This meta-analysis utilized JASP 0.19.3.0 software, where Hedge's g was computed to determine the overall effect size of EDP-based instructional approach to STEM competence using random-effect model. Moderator variables such as type of STEM competence, implementation period, and academic level were tested using meta-regression with Knapp and Hartung adjustment. The heterogeneity was assessed using Q , τ , τ^2 statistics, which serve as groundwork for moderation analysis. Forest plot was generated to visualize individual and pooled effect sizes of the reviewed studies. Following Cohen's (1998) guidelines, effect sizes were interpreted as small ($g \leq 0.2$), moderate ($0.2 < g \leq 0.5$), and large ($g > 0.5$), enabling meaningful understanding of the effect of intervention.

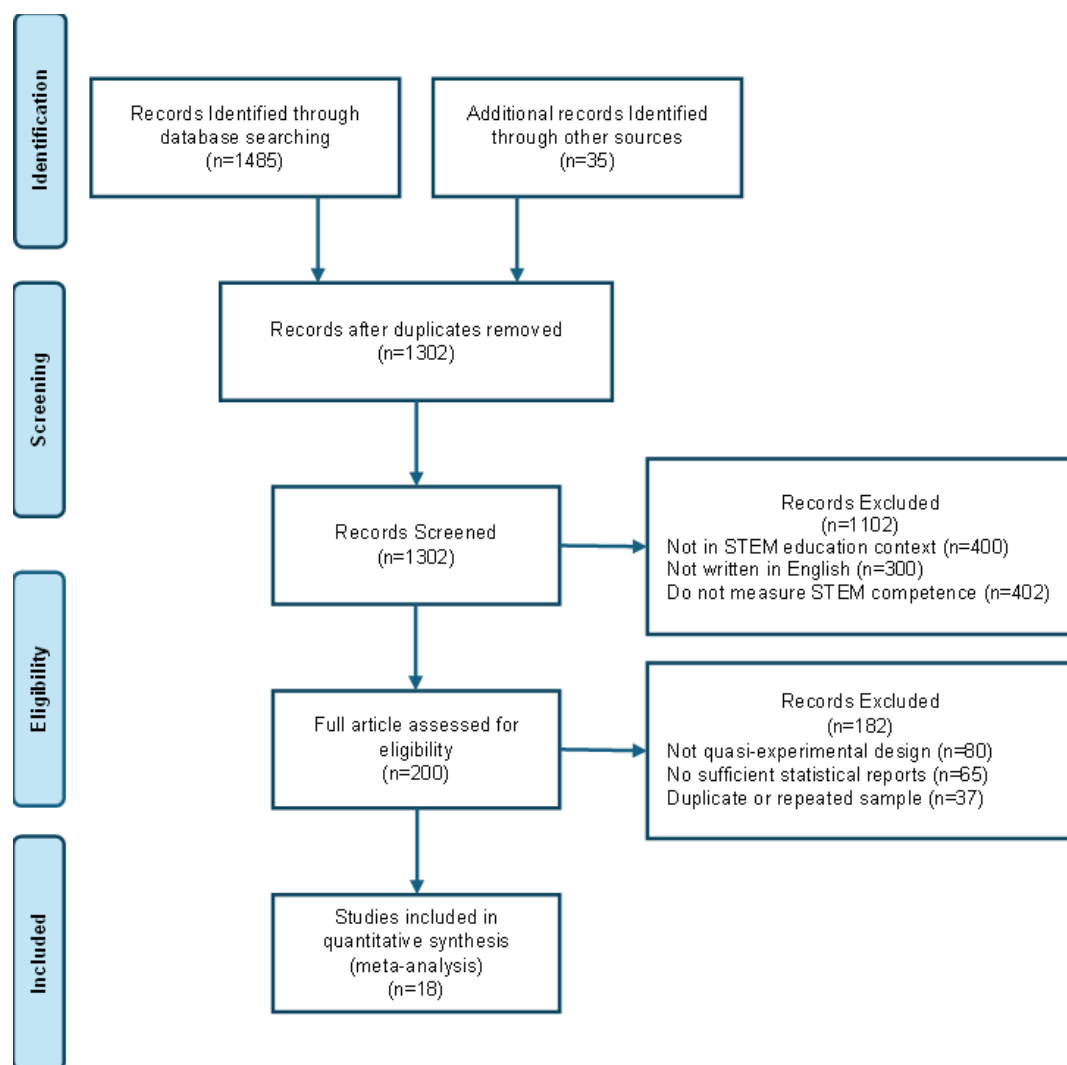


Figure 1. PRISMA Flowchart of the Study

Results

This meta-analysis included 18 qualified studies, resulting in 29 effect sizes derived from a total sample of 1,280

students who participated in either EDP or non-EDP instructional interventions. The studies were analyzed based on various characteristics, including the specific STEM competence addressed, duration of implementation, academic level, STEM discipline, and country of origin. These variables were systematically coded. Table 1 summarizes the moderating variables incorporated in the analysis, along with the distribution of the studies across each category.

Table 1. Distribution According to Moderating Variables

Moderating Variable	Frequency (k=29)	Percent
STEM Competence		
STEM Knowledge	9	31.034
STEM Skills	14	48.276
STEM Attitude	6	20.690
Implementation Period		
Not Reported	5	17.241
1 to 4 Weeks	6	20.690
5 to 8 Weeks	12	41.379
9 to 12 Weeks	4	13.793
13 to 16 weeks	2	6.897
Academic Level		
Primary	6	20.690
Secondary	21	72.414
Tertiary	2	6.897

Table 1 shows that the 29 effect sizes analyzed in this meta-analysis were primarily focused on STEM skills (48.28%), followed by STEM knowledge (31.03%) and attitude (20.69%). Most interventions lasted to 5 to 8 weeks (41.38%), while durations over 8 weeks were less common. In terms of academic level, most of the studies were conducted at the secondary level (72.41%), with fewer at the primary and tertiary level. This distribution reflects a strong emphasis on mid-length interventions targeting skill development among secondary students.

Table 2. Meta-Analytic Estimates of the EDP in Enhancing STEM Competence

	Estimate	95% CI		95% PI		Residual Heterogeneity Test		
		Lower	Upper	Lower	Upper	Q _e	df	p
Effect Size	1.168	0.893	1.443	-0.265	2.602	156.367	28	< .001
τ	0.687	0.481	0.947					
τ^2	0.472	0.232	0.897					

Table 2 shows the meta-analysis yielded a significant overall effect size of 1.168, with 95% confidence interval

from 0.893 to 1.443, indicating that EDP-based interventions had a strong positive impact on the students' STEM competence. This suggests that learners exposed to EDP instruction consistently performed better in STEM-related domains compared to those who were not. However, wide prediction interval (-0.265 to 2.602) implies variability in outcomes across different contexts or study conditions.

Table 2 further revealed that significant residual heterogeneity ($Q_e = 156.367$, $df = 28$, $p < 0.001$), suggesting meaningful difference across included studies. The heterogeneity estimates ($\tau = 0.687$, $\tau^2 = 0.472$) confirm substantial variability, reinforcing the need to explore moderating variables that may explain differential effectiveness. These findings emphasize both the robust potential of EDP interventions and the importance of contextual factors in shaping their impact.

The forest plot in Figure 2 displays the 29 effect sizes across 18 studies assessing the effect of EDP interventions on STEM competence. Most studies reported positive effects, with individual effect sizes ranging 0.187 to 3.581. The largest effect size ($g = 3.581$) was demonstrated by the study of Muslihah et al. (2024), which focused on improving the students view about the nature of science. On the other hand, the smallest effect size ($g = 0.187$) was observed from the study of Korur et al. (2015)b addressing the students' attitude towards simple machines. Furthermore, the pooled estimate is statistically significant ($t(28) = 8.70$, $p < 0.001$), supporting the overall effectiveness of EDP. However, substantial heterogeneity is present indicating considerable between-study variability as also supported by Table 2.

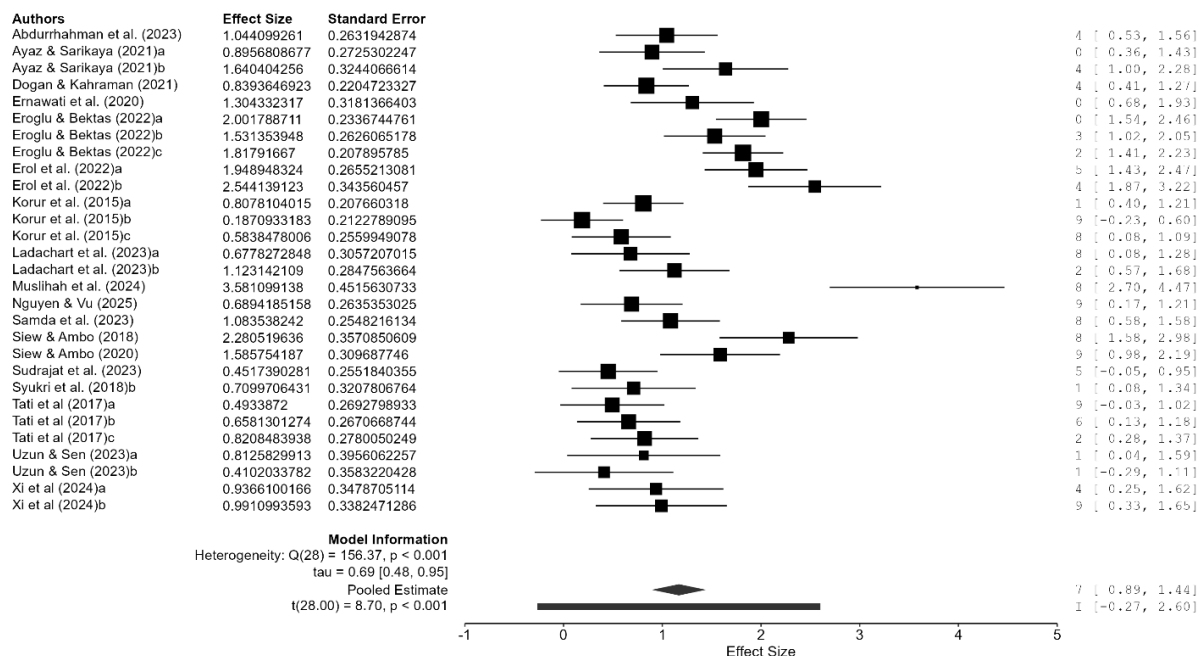


Figure 2. Forest Plot of Effect Sizes Derived from 18 Qualified Studies

The results in Table 3 presents the meta-regression test evaluating whether the three identified moderating variables in the study significantly influence the variability in effect sizes. Academic level approached significance ($F(2,21) = 2.955$, $p = 0.074$), suggesting potential trend worth further exploration. However, STEM

competence type ($p = 0.2210$) and implementation period ($p = 0.959$) were not statistically significant. These results indicate that variation in the effect size is not strongly explained by these moderators when using the Knapp and Hartung adjustment. These findings suggest that the effectiveness of EDP-based interventions appears relatively stable across different implementation periods and types of STEM competence, which supports the generalizability of such approaches.

Table 3. Effect Size Meta-Regression Terms Tests for Moderating Variables

	F	df₁	df₂	p
Academic Level	2.955	2	21.000	0.074
STEM Competence	1.622	2	21.000	0.221
Implementation Period	0.100	3	21.000	0.959

Note. Fixed effect tested using Knapp and Hartung adjustment.

Table 4 presents the meta-regression estimates examining how academic level, STEM competence focus, and intervention duration moderate the effect of EDP interventions on STEM competence. The intercept value of 0.781 represents the predicted effect size for the reference group, which are studies at primary level, focused on STEM knowledge, with unreported implementation duration. Most predictors, including secondary level, STEM skills, and STEM attitude, and the 1-12 weeks of implementation groups, did not show statistically significant differences compared to the reference, as indicated by p-values greater than 0.05 and confidence interval that included zero. It should also be noted that 13 to 16 weeks was not included in the analysis due to small sample size.

Table 4. Meta-Regression Estimates for Moderating Variables

	Estimate	Standard Error	t	df	p	95% CI	
						Lower	Upper
Intercept	0.781	0.706	1.106	21.000	0.281	-0.688	2.250
Secondary Level	0.354	0.456	0.776	21.000	0.446	-0.594	1.301
Tertiary Level	1.988	0.870	2.285	21.000	0.033	0.179	3.798
STEM Skills	0.181	0.398	0.454	21.000	0.655	-0.647	1.008
STEM Attitude	-0.602	0.490	-1.228	21.000	0.233	-1.620	0.417
1 to 4 Weeks	0.174	0.494	0.353	21.000	0.728	-0.853	1.201
5 to 8 Weeks	0.035	0.389	0.090	21.000	0.929	-0.774	0.844
9 to 12 Weeks	-0.116	0.576	-0.201	21.000	0.843	-1.313	1.082

Note. Fixed effect tested using Knapp and Hartung adjustment.

Table 4 further revealed that only the tertiary predictor yielded a significant result with estimate of 1.988 ($p=0.003$), suggesting stronger impact of EDP interventions at the college or university level compared to primary

education. This indicates the potential effectiveness of EDP models for advanced learners, possibly due to their increased capacity for abstract reasoning and independent problem-solving. These findings underscore the value of tailoring EDP design to academic maturity.

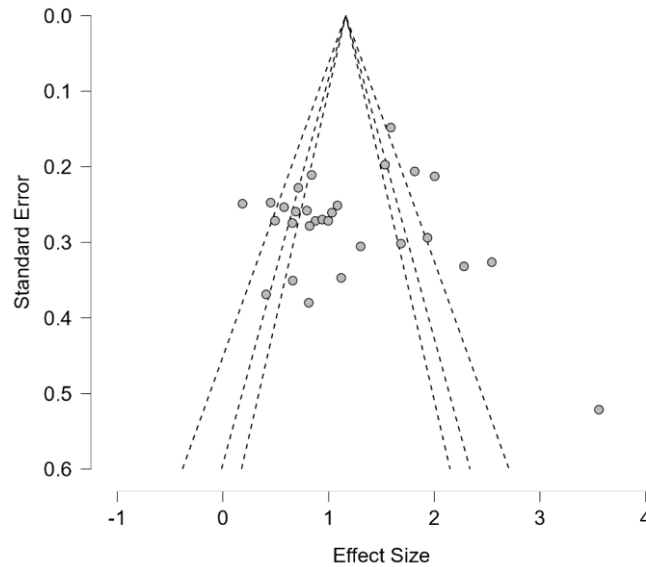


Figure 3. Funnel Plot Assessing Publication Bias among Included Studies

The meta-regression test for funnel plot asymmetry, based on 29 estimates, yielded a z-value of 1.565 with p-value of 0.118, indicating no statistically significant asymmetry. Furthermore, the limit estimate was 0.334, with 95% confidence interval. Since the p-value exceeds 0.05 at the confidence interval includes zero, the result suggests that there is insufficient evidence of publication bias in the included studies. This is consistent with the funnel plot shown in Figure 3, which appears mostly symmetrical and lacks major outliers, visually reinforcing the absence of small-study effects or bias. This supports the reliability of the meta-analytic findings indicating that the results are not meaningfully distorted by unpublished or selectively reported studies.

Table 5 shows the distribution of instructional approaches grouped according to four clusters. The Engineering-Integrated approach cluster was most prevalent, accounting for 58.63%, emphasizing the strong focus on EDP and engineering-driven models. The 5E-based Learning Models followed, representing 20.69% of the total, followed further by STEM-oriented Project-based Learning and STEAM and Creative Approaches each comprised of 13.80% and 6.90% respectively. This suggests that there is a diverse method that integrate creativity and inquiry into EDP. It further reflects a varied yet engineering-centered, instructional designs within the reviewed studies.

Table 5. Clusters of Instructional Approaches Implemented from the Obtained Studies

Cluster	Instructional Approach	f	%
5E-based Learning Models	5E Learning Model	2	6.90
	5E STEM-based Learning	3	10.34
	5E-EDP Model	1	3.45

Cluster	Instructional Approach	f	%
Engineering-Integrated Approaches	Engineering-focused STEM integration	9	31.03
	Engineering-focused STEM integration with DIGIER Model	1	3.45
	STEM Activity with EDP	2	6.90
	Problem-based Learning with Engineering is Elementary Model	1	3.45
	Conceive-Design-Implement-Operate (CDIO) model with EDP	2	6.90
	EDP-based with Project-based Learning	2	6.90
STEM-oriented Project-based Learning Approaches	STEM-focused Project-based Learning	2	6.90
	Project-based Learning with STEM Integration	2	6.90
STEAM and Creative Approaches	STEAM Education with Tales	2	6.90
Total		29	100

Figure 4 shows the distribution of STEM competence enhanced in the reviewed studies. Scientific creativity emerged to be the most frequently targeted STEM competence across the studies, appearing 9 out of 29 effect sizes. Other moderately emphasized outcomes included Scientific Achievement, Scientific Understanding, Science Problem-Solving Skills,

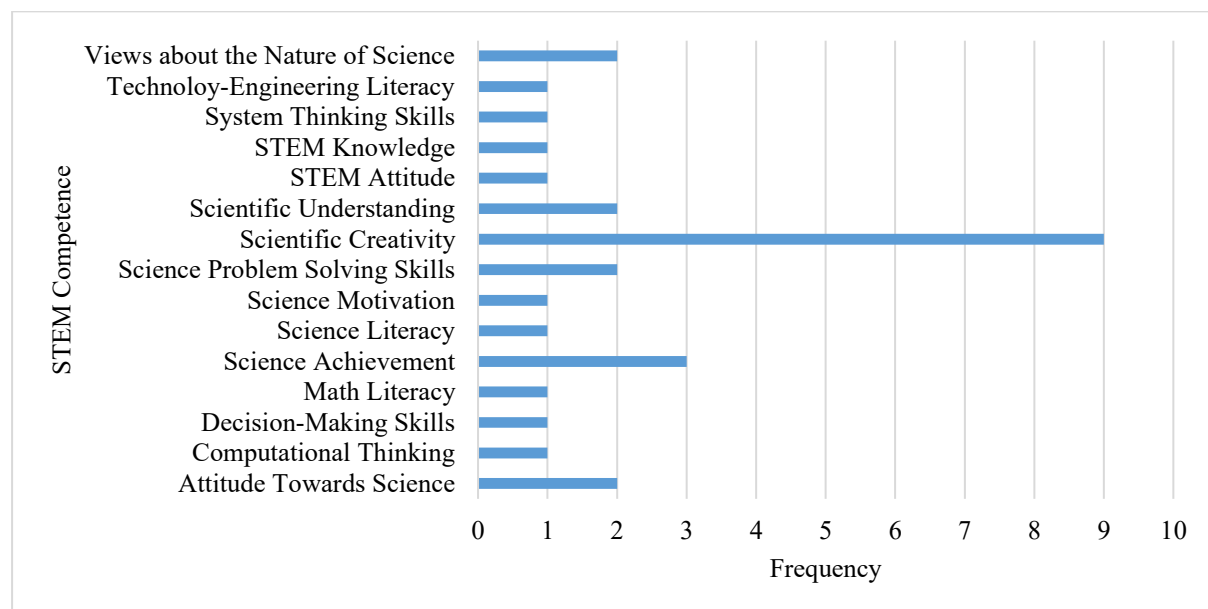


Figure 4. Distribution of STEM Competence Examined from the Obtained Studies

Views about the Nature of Science, and Attitude Towards Science, each addressed twice from the obtained studies. The remaining competencies such as Technology-Engineering Literacy down to Computational Thinking, were only highlighted once. This distribution suggests that a strong research focus on fostering creative and inquiry-driven thinking, while more technical or specific skill sets were explored less frequently in the context of EDP-based interventions.

Discussion

The EDP has emerged as one of the most widely used and effective pedagogical strategies for implementing STEM education (Abdurrahman et al., 2023; Hafiz & Ayop, 2019). While its application in STEM instruction has expanded, there remains limited meta-analytic research evaluating the effectiveness in enhancing students learning outcome. This study addresses that gap by synthesizing existing empirical evidence. The findings provide deeper insights into pedagogical value of EDP and inform future directions for instructional practices and research in STEM education.

The results shows that EDP is widely used in enhancing STEM skills (e.g., Abdurrahman et al., 2023; Ayaz & Sarikaya, 2021; Dogan & Kahraman, 2021; Ernawati et al., 2020; Eroglu & Bektas, 2022; Erol et al., 2022; Nguyen & Vu, 2025; Samad et al., 2023; Siew & Ambo, 2018; Siew & Ambo, 2020; Sudrajat et al., 2023; Syukri et al., 2018), typically implemented for 5 to 8 weeks (Xi et al., 2024; Samad et al., 2023; Uzun & Sen, 2023; and was applied frequently to secondary level (Korur et al., 2015; Ladachart et al., 2023; Samad et al., 2023). This meta-analysis of 18 experimental studies obtained from 2015 to 2025 involving 1280 students yielded to an effect size of 1.160, which denotes a large and positive effect size. This strong effect proved the potential of EDP as an effective instructional strategy in STEM education as revealed in the literature (Panergayo & Prudente, 2024). Its consistent positive influence across studies reinforces the relevance of incorporating EDP in STEM curriculum planning and teaching practices to elevate learning outcomes (Ali & Tse, 2023).

Examining each study involved, majority of the studies demonstrated large effect size including Abdurrahman et al. (2023), Ayaz & Sarikaya (2021)a/b, Eroglu & Bektas (2022)a/b/c, Korur et al. (2015)a, Ladachart et al. (2023)b, Muslihah et al. (2024), Samad et al. (2023), Uzun & Sen (2023)a, Tati et al. (2017)c, Erol et al. (2022)a/b, Dogan & Kahraman (2021), Siew & Ambo (2018/2020), Ernawati et al. (2020), Xi et al. (2024)a/b. while other studies demonstrated a moderate effect, as observed in the studies by Korur et al. (2015)c, Ladachart et al. (2023)a, Syukri et al. (2018)b, Tati et al. (2017)b, Nguyen & Vu (2025). On the other hand, small effect size were computed for the studies Korur et al. (2015)b, Tati et al. (2017)a, Uzun & Sen (2023)b, Sudrajat et al. (2023). Based on the findings, majority of the studies shows large effect sizes, confirming the strong impact of EDP on STEM education. The presences of smaller effect sizes prompt contextual differences, supporting the need for moderator analysis to guide the implementation. This is consistent with the test of residual heterogeneity ($Q_e = 156.367$, $df = 28$, $p < 0.001$), suggesting meaningful difference across included studies.

The meta-regression results indicate that none of the tested moderators such as academic level, STEM competence, or implementation period significantly influence the effect sizes, as all p-values exceeded the 0.05 threshold. While academic level approached significance, it did not reach conventional criteria. These findings suggests that the impact of EDP on STEM learning outcomes remains generally consistent across various contexts, though further research might clarify the potential effects of academic level. This further suggests that duration of implementation alone does not ensure quality, it is the design, context, and implementation strategies often have greater impact on STEM learning outcomes than time. Meta-Regression estimates, however, revealed that tertiary academic level predictor yielded a significant result with estimate of 1.988 ($p=0.003$), suggesting stronger

impact of EDP interventions at the college or university level compared to primary and secondary education levels. This suggests that EDP interventions appear significantly more effective at the tertiary level, indicating their stronger impact at collegiate science education settings (Ayaz & Sarikaya, 2021).

The reviewed studies reveal a diverse range of instructional strategies used to integrate the EDP into STEM education, including 5E models, project-based learning, STEAM-oriented storytelling, and various engineering-integrated approaches. The variety reflects the versatility of EDP across pedagogical frameworks (Dym et al., 2005; Mumba et al., 2023). Likewise, there is an emerging trend favoring engineering-focused STEM integration models, suggesting growing preference for approaches that situate EDP within authentic, design-driven problem-solving. This is consistent with the study of Abdurrahman et al. (2023) and Panergayo and Prudente (2024) suggesting that STEM-EDP is gaining momentum toward embedding EDP within real-world, design-based learning, making STEM-EDP approaches highly relevant in the current scientific and technological advancement. This indicates a shift toward instructional strategies that closely exemplify real-world engineering practices. This trend toward engineering-focused integration reflects growing recognition of its ability to cultivate critical thinking, innovation, and applied problem-solving skills essential for 21st century STEM learners. As this preference emerges, it suggests a need for teacher training programs and curriculum developers to align instructions with real-world engineering practices.

The results, moreover, put emphasis on fostering scientific creativity through EDP-based intervention suggests a promising foundation on nurturing divergent thinking and innovative problem-solving (Ayaz & Sarikaya, 2021; Ernawati et al., 2020; Nguyen & Vu, 2025; Siew & Ambo, 2018) Siew & Ambo, 2020; Sudrajat et al., 2023). While STEM knowledge and attitude were also commonly addressed, more technical competencies such as computational thinking and engineering literacy were rarely emphasized. Abdurrahman et al. (2023) argued that STEM-integrated EDP with simple technology can foster systems thinking and computational thinking through real-world problem-solving. This suggests a need to broaden the application of EDP to encompass underrepresented areas of STEM competence. Investigating differentiated impacts across educational levels and contexts could yield insights into optimizing EDP frameworks. Moreover, studies comparing various instructional pairings with EDP may clarify which combinations most effectively promote comprehensive STEM competence.

Conclusion and Recommendations

This meta-analysis confirms that EDP-based instruction exerts a strong positive influence on STEM education, with majority of the reviewed studies reporting large effect sizes. However, substantial heterogeneity and the diversity of instructional approaches suggests varied implementation across educational settings. This variability reflects both the flexibility and the challenges of adapting EDP in practice. Furthermore, although scientific creativity was frequently emphasized, other critical STEM competence was notably underrepresented, revealing significant gaps that warrant further academic and pedagogical attention.

This study encountered several limitations that should be acknowledged. First, the relatively small number of studies in some subgroups may have limited the statistical power to detect significant moderator effect. Second,

the variability in how EDP was operationalized across studies introduces potential inconsistencies, complicating direct comparison. Third, reliance on published studies may have led to publication bias, overestimating the true effectiveness of EDP-based instruction. Lastly, the limited representation of certain STEM competencies constrains the generalizability of findings across full spectrum of STEM learning outcomes. In line with the findings and limitations of the study, the following were recommended: First, future studies should aim to explore how EDP can effectively cultivate underemphasized STEM competencies, particularly those aligned with 21st century technical demands. Second, investigating potential moderators other than those considered in this study can illuminate the conditions under which EDP is mostly effective. The moderators may include STEM discipline, curriculum design, and the specific EDP model used. Third, comparative studies on various instructional pairings with EDP could help identify models that foster more comprehensive STEM competence. This can provide insightful inputs for a more inclusive and context-responsive understanding of EDP towards advancing evidence-based STEM education.

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