Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: https://www.science-gate.com/IJAAS.html

Effectiveness of virtual reality and simulation-based STEM instruction in developing students' soft skills: Evidence from a meta-analysis

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ARTICLE INFO

Article history:
Received 4 February 2026
Received in revised form
3 July 2026
Accepted 19 July 2026

Keywords:
Virtual reality
Simulation-based learning
STEM education
Soft skills
Meta-analysis

ABSTRACT

This study aims to evaluate the effectiveness of virtual reality (VR)- and simulation-based STEM instruction in developing students' soft skills through a systematic review and meta-analysis. The study was conducted in accordance with the PRISMA guidelines and employed a meta-analytic approach. Empirical studies published between 2015 and 2025 were identified from the Scopus, Web of Science, ERIC, and Google Scholar databases, and their quantitative data were analyzed using Comprehensive Meta-Analysis (CMA) software. The results indicate that VR- and simulation-based STEM instruction has a statistically significant, medium-to-high effect on the development of students' soft skills. In particular, virtual laboratories and problem-based simulation activities show a strong positive effect on communication, teamwork, and critical thinking skills. These findings support the use of VR and simulation technologies as evidence-based pedagogical tools for enhancing students' soft skills in STEM education and contribute to the advancement of digital STEM learning environments and curriculum innovation.

1. Introduction

In the context of globalization and digital transformation, the requirements placed on education systems are undergoing profound changes. In the 21st century, learners are expected not only to acquire subject-specific knowledge but also to develop soft skills, including critical thinking, problem-solving, communication, teamwork, creativity, and self-regulation. In this regard, the STEM (Science, Technology, Engineering, and Mathematics) education paradigm is regarded as an effective model aimed at the integrated development of students' cognitive and social competencies (Rizakhojayeva et al., 2025)

In recent years, virtual reality (VR) and digital simulations have gained particular importance in enhancing STEM instruction. These technologies provide learners with safe, interactive, and experience-based learning environments, expanding practical and social interaction opportunities that are often limited in traditional teaching approaches (Yang et al., 2024). Especially in engineering, natural science, and technical disciplines, tasks performed in virtual environments increase students' active engagement and foster their ability to make independent decisions and collaborate effectively (Cabrera-Duffaut et al., 2024).

Systematic reviews and meta-analyses empirically demonstrate the effectiveness of VR- and simulation-based STEM instruction in developing students' soft skills. Specifically, VR technologies have been shown to positively influence not only learners' practical competencies but also their professional responsibility, self-confidence, and communication skills (Animashaun et al., 2024). Moreover, immersive learning platforms enhance learning motivation and optimize cognitive load through the visualization of complex concepts (Tene et al., 2024). Contemporary studies indicate that the potential of virtual STEM environments extends

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beyond individual subject areas and is increasingly oriented toward the development of transversal competencies such as systems thinking, problem solving, and teamwork (Dossymov et al., 2026). Learning models based on robotic simulations and digital twins enable students to model real-world industrial and engineering processes, thereby supporting early professional orientation (Norambuena et al., 2025).

In this context, substantiating the effectiveness of VR- and simulation-based STEM instruction in developing students' soft skills through meta-analytical evidence represents a timely and significant scientific task. This line of research contributes to the improvement of educational practice based on evidence-informed findings and offers scientifically grounded solutions for the design of digital STEM learning environments.

2. Literature review

Over the past decade, virtual reality (VR), extended reality (XR), and immersive technologies have been extensively investigated as innovative instructional tools within the STEM education landscape. Research indicates that these technologies possess substantial potential for enhancing learners' cognitive, practical, and soft skills by transforming the learning process into an experience-based, interactive, and learner-centered format.

Elme et al. (2022) examined the impact of immersive virtual reality (IVR) on learning effectiveness and demonstrated that the use of IVR in STEM subjects improves learners' academic outcomes, while the integration of post-lesson self-explanation strategies facilitates deeper knowledge acquisition. These findings suggest that VR technologies function not merely as visual enhancement tools but also as mechanisms for fostering metacognitive skills.

The methodological and ethical dimensions of integrating VR into education have also attracted scholarly attention. The EVRIM framework proposed by Geriş (2024) emphasizes the inclusive, ethical, and responsible implementation of virtual reality, which is particularly significant in STEM environments characterized by diverse learner populations. Similarly, Kumar and Priya (2025) highlighted that VR technologies enhance learners' engagement and broaden accessibility, thereby elevating experiential learning to a new level. Systematic literature reviews conducted in the field of engineering education indicate that virtual reality facilitates the comprehension of complex technical concepts and contributes to the development of spatial reasoning and problem-solving abilities (Muzata et al., 2024). Chiang and Liu (2023) further report that XR technologies lead to statistically significant improvements in STEM learners' engagement, motivation, and learning outcomes. Within the context of higher education, several studies have explored the effects of immersive technologies on academic achievement and learning motivation. Sviridova et al. (2023) found that virtual and immersive environments enhance students' academic performance and strengthen their emotional engagement in the learning process. These findings underscore the role of VR in developing soft skills, particularly self-regulation and learning motivation.

In engineering education, the application of VR technologies has been shown to improve students' spatial visualization, professional orientation, and problem-solving skills. Chasokela (2025) demonstrated that engineering tasks performed in virtual environments increase students' active participation and foster systems thinking. Moreover, Hmoud et al. (2025), focusing on the integration of artificial intelligence and XR, provided evidence that such environments support a transition from passive experience to active learner engagement.

Systematic reviews further indicate that immersive XR technologies are effective not only in STEM education but also in medical and engineering training contexts. Fugate et al. (2025) emphasized the high pedagogical potential of XR environments for skill acquisition and professional competence development. Likewise, Singh et al. (2020) reported that the application of virtual reality in biomedical engineering enables the safe and effective teaching of complex processes.

The theoretical foundations of immersive learning are systematized in the Theory of Immersive Collaborative Learning (TICOL) proposed by Makransky and Petersen (2023). This theory provides a comprehensive explanation of how cognitive load, emotional engagement, and social interaction within virtual environments influence learning outcomes. The TICOL framework offers a solid theoretical basis for understanding the mechanisms through which VR- and simulation-based STEM instruction contributes to the development of soft skills.

In summary, the reviewed literature demonstrates that STEM instruction grounded in virtual reality and immersive technologies is highly effective in fostering learners' cognitive, practical, and soft skills. However, the majority of existing studies focus on specific disciplines or isolated skill sets, highlighting the need for a comprehensive synthesis of evidence through meta-analysis to systematically evaluate the overall impact of virtual STEM environments on soft skills development.

3. Research methods

This study employed a comprehensive analysis of scholarly literature addressing the effectiveness of virtual reality (VR)- and simulation-based STEM instruction in developing learners' soft skills. The literature review was designed to establish the theoretical and methodological foundations of the research and to provide a scientific rationale for the pedagogical potential of digital STEM interventions in fostering soft skills.

Publication bias was assessed using the Begg and Mazumdar rank correlation test (Begg and Mazumdar, 1994), Egger's regression test (Egger et al., 1997), and the Duval and Tweedie Trim and Fill procedure (Duval and Tweedie, 2000). Effect sizes were expressed as standardized mean differences using Cohen's d (Cohen, 2013). Publication-bias robustness was additionally assessed using Rosenthal's fail-safe N (Rosenthal, 1979).

The literature search was conducted using the international scientific databases Web of Science, Scopus, and Google Scholar. These databases were selected due to their extensive coverage of high-quality, peer-reviewed publications related to virtual learning technologies, STEM education, simulation-based environments, immersive learning, and soft skills development.

Priority was given to international and national studies published between 2015 and 2025. During the search process, keywords relevant to the research topic were applied systematically. The primary search terms included "virtual reality," "simulation-based learning," "STEM education," "soft skills," "meta-analysis," "digital learning," "virtual laboratories," as well as their alternative and related variants.

The selection and screening of studies were conducted in accordance with the PRISMA methodology (Fig. 1). Specifically, the stages of study identification, screening, full-text assessment, and inclusion in the meta-analysis were structured based on clearly defined inclusion and exclusion criteria. As a result, the selected studies were incorporated into the meta-analysis, and their effect sizes were comparatively analyzed to assess the overall impact of VR and simulation-based STEM instruction on the development of learners' soft skills.

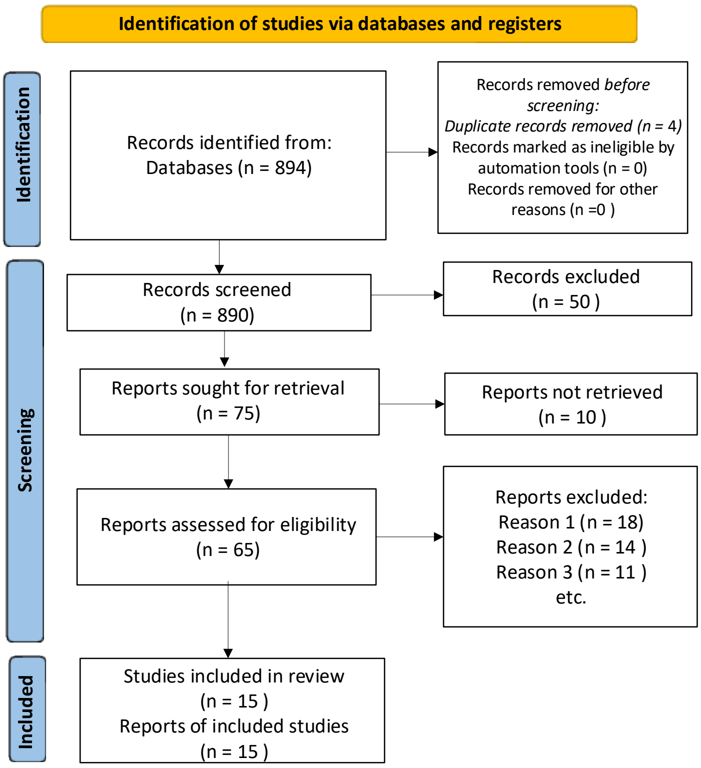

Fig. 1: PRISMA flow diagram of data collection

The obtained quantitative data were processed using the Comprehensive Meta-Analysis (CMA) software version 4.0. The analytical procedure included the estimation of the pooled effect size, the corresponding confidence intervals, and the degree of heterogeneity across studies. In addition, several statistical indicators were calculated, including the Z-statistic, Cochrane's Q, I^2, τ^2, and related parameters, to provide a comprehensive assessment of the pooled results.

The analysis was based on two main statistical components: the effect size and its associated standard error. The effect size was implemented as the standardized mean difference (Cohen's d), calculated to quantify the magnitude of the differences between comparison groups. The mathematical formula used for this calculation is given in Eq. 1.

$$Standardized\ difference = \frac{\overline{X_1} - \overline{X_2}}{S} \quad (1)$$

where, S represents the pooled standard deviation, which is a key parameter for determining the mean effect. It is derived from the standard deviations of the two comparison groups, as expressed in Eq. 2.

$$S = \sqrt{\frac{(n_1-1){S_1}^2 + (n_2-1){S_2}^2}{n_1+n_2-2}} \quad (2)$$

The standardized error values were calculated using the GraphPad online platform. After determining the effect sizes and standardized errors, the required data were entered into the Comprehensive Meta-Analysis (CMA) version 4.0 software to obtain the final meta-analytical results. In addition, Microsoft Office Excel (MS Excel) 2010 was used to calculate the prediction intervals of the data. Table 1 presents the quantitative data extracted from the studies included in the meta-analysis. For each study, key statistical indicators were systematically collected to ensure the accurate calculation of effect sizes. Specifically, the extracted data include the mean values (M_1 and M_2), standard deviations (SD_1 and SD_2), and sample sizes (N_1 and N_2) for the experimental and control groups.

In cases where direct descriptive statistics were not fully available, alternative reported indicators such as t-values or F-values were used to derive standardized mean differences following established meta-analytic procedures. All data were carefully verified and standardized prior to analysis to ensure consistency across studies.

Table 1: Extracted descriptive statistics from studies included in the meta-analysis

Reference	M_1	SD_1	N_1	M_2	SD_2	N_2
Budnarowski et al. (2025)	86.7	25.3	120	72.5	11.7	120
Radzi et al. (2020)	50	10	32	48.45	8	32
Osei Tutu et al. (2025)	0.79	0.12	21	0.70	0.10	21
Mørk et al. (2024)	4.23	1.09	140	4.39	1.01	146
Molek-Winiarska and Kawka (2024)	20.48	6.40	48	18.24	4.77	48
Lamiani et al. (2021)	3.7	0.69	71	4.1	0.58	71
Dell'Aquila et al. (2022)	3.45	0.72	16	2.99	0.78	19
Hassan and Abu Bakar (2025)	4.24	0.46	86	-	-	-
Lavi et al. (2021)	3.41	1.11	252	3.50	1.18	235
Holik et al. (2023)	4.62	1.17	208	4.73	1.28	208
Agbo et al. (2023)	50	10	49	45.8	10	49
Adefila et al. (2016)	8.48	1.73	54	9.10	1.65	54
Formosa et al. (2018)	136.42	28.24	50	208.88	25.63	50
Hamilton-Giachritsis et al. (2018)	3.0	1.0	26	2.4	0.7	51
Kurbanbekov et al. (2025)	6.985	1.24	110	8.765	1.097	112

4. Results

The results of the content-based and quantitative analyses of scientific studies examining the effectiveness of VR- and simulation-based STEM instruction in developing students' soft skills are summarized in Table 1. The reviewed studies comprehensively address the potential of virtual laboratories, immersive simulations, and digital modeling environments in STEM education to foster students' communication, teamwork, critical and engineering thinking, problem-solving, self-regulation, and creativity.

The majority of the studies indicate that VR- and simulation-based learning environments, when compared to traditional instructional approaches, significantly increase learners' engagement, support the personalization of the learning process, and enhance both cognitive and emotional capacities. In particular, collaborative VR environments, immersive technologies, simulation-based scenarios, and game-based elements contribute to improved quality of social interaction among students and promote the development of collaborative decision-making and engineering thinking skills (Fig. 2).

A number of studies examining experiential learning, simulation-based learning, and virtual experiential learning environments highlight the important role of experiential learning in developing soft skills in professional settings. These findings suggest that soft skills development should be understood not only from a socio-psychological perspective, but also as an important component that contributes to the overall quality and effectiveness of STEM education and workforce training.

Overall, the results summarized in Table 1 show that VR and simulation-based approaches, along with experiential learning technologies, have significant pedagogical potential to support soft skills development. These findings highlight the importance of incorporating such technologies into educational practice on a scientifically sound basis at various levels of education, including general, higher, and teacher education systems.

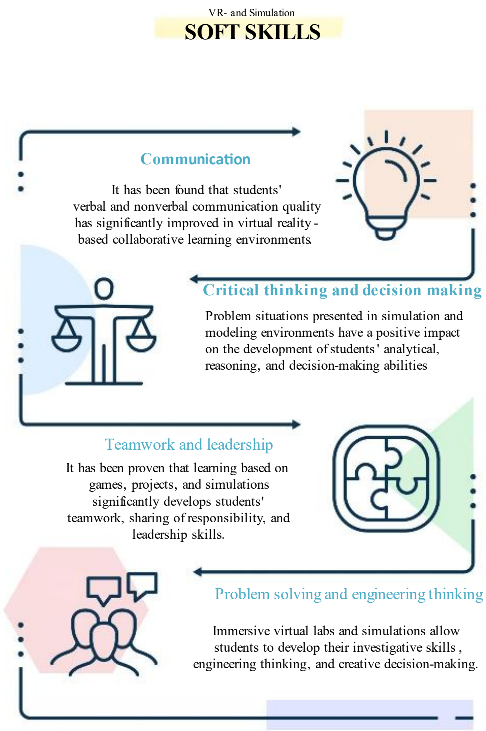

Fig. 2: Effectiveness of virtual reality- and simulation-based STEM instruction in developing soft skills

Meta-analysis serves as a rigorous methodological approach that combines quantitative results from multiple independent empirical studies into a single analytical framework. It allows for the application of statistical methods to aggregated data to draw generalized and substantiated conclusions.

In this study, data from selected literature were organized, standardized, and systematically presented in Table 2 to facilitate comparative analysis and synthesis.

Table 2: Meta-analysis results of the reviewed scientific studies

Reference	SMD	SE
Budnarowski et al. (2025)	0.71	0.139
Radzi et al. (2020)	0.155	0.064
Osei Tutu et al. (2025)	0.91	0.26
Mørk et al. (2024)	0.35	0.04
Molek-Winiarska and Kawka (2024)	0.68	0.22
Lamiani et al. (2021)	0.48	0.13
Dell'Aquila et al. (2022)	0.44	0.13
Hassan and Abu Bakar (2025)	2.66	0.25
Lavi et al. (2021)	0.29	0.09
Holik et al. (2023)	0.72	0.09
Agbo et al. (2023)	0.42	0.12
Adefila et al. (2016)	0.361	0.106
Formosa et al. (2018)	2.631	0.231
Hamilton-Giachritsis et al. (2018)	0.608	0.182
Kurbanbekov et al. (2025)	1.52	0.16

SMD: Standardized mean difference; SE: Standard error

Data from the included studies were analyzed using the Comprehensive Meta-Analysis (CMA) software version 4.0, which allowed for aggregated and robust conclusions. In the preliminary phase, selected empirical studies investigating the effectiveness of virtual reality (VR) and simulation-based STEM education in improving students' soft skills were systematically reviewed.

A funnel plot was constructed to assess the potential for publication bias (Fig. 3). This graphical representation shows the relationship between individual study effect sizes and their corresponding standard errors, allowing for an assessment of the symmetry in the distribution of results.

The use of this method provided visual and analytical tools for assessing the stability and reliability of reported effects, thus supporting a more rigorous interpretation of the effects of VR and simulation-based STEM interventions on developing soft skills. As presented in Table 3, the presence of publication bias in the meta-analysis was examined using multiple complementary statistical procedures. The results of the Begg and Mazumdar rank correlation test were not statistically significant (Kendall's τ = 0.18, p = 0.162), suggesting no clear indication of publication bias across the included studies. In line with this, the Egger regression analysis did not reveal evidence of small-study effects (intercept = 1.57, p = 0.121).

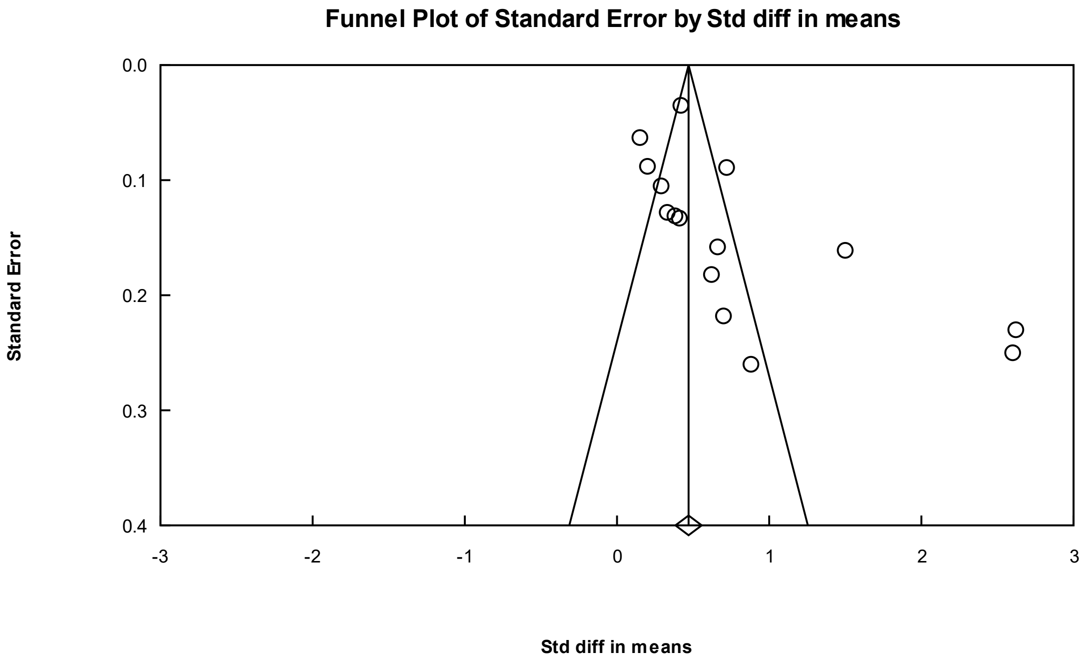

Fig. 3: Funnel plot constructed based on the aggregated scientific data

Table 3: Results of the assessment of publication bias

Method	Indicator	p-value	Interpretation
Begg & Mazumdar	Kendall's τ = 0.18	0.162 (1-tailed)	No evidence of publication bias detected
Egger test	Intercept (B_0) = 1.57	0.121 (1-tailed)	No small-study effect detected
Trim & Fill	ES: 0.46 → 0.43	-	Effect size did not change substantially
Fail-safe N	1840	-	Results are highly robust
Number of studies	k = 15	-	Included in the meta-analysis

Furthermore, the application of the Duval and Tweedie Trim and Fill procedure demonstrated only a minimal change in the pooled effect size (ES: 0.46 to 0.43), indicating that the overall findings remain stable even after adjusting for potential missing studies. The robustness of the results is also supported by the high Rosenthal fail-safe N value (N = 1840), which implies that a substantial number of additional null-result studies would be required to reduce the overall effect to non-significance.

Taken together, these outcomes suggest that the influence of publication bias is either absent or negligible, thereby supporting the reliability and validity of the synthesized effect size estimates.

The meta-analytic results illustrate the distribution of true effects, reflecting the variability of effect sizes across the included studies (Fig. 4). The pooled standardized mean difference was estimated at d = 0.81, indicating a moderate-to-large effect. The corresponding 95% confidence interval (0.58 to 1.05) suggests a consistent and positive overall impact of VR- and simulation-based STEM instruction on students' soft skills.

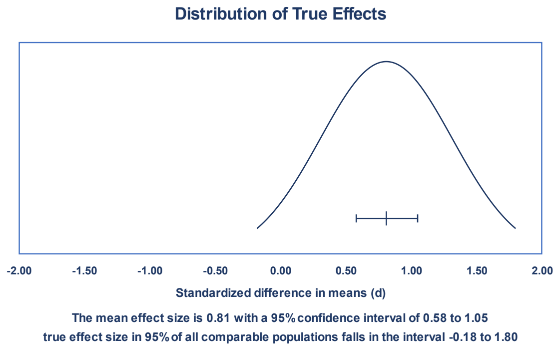

Fig. 4: Distribution of true effects

In addition, the 95% prediction interval ranged from −0.18 to 1.80, demonstrating that while effect sizes vary across different study conditions, most of the observed effects remain within the positive range. This variability implies that the effectiveness of the interventions is influenced by contextual factors such as instructional design, implementation conditions, and participant characteristics, while still maintaining an overall beneficial tendency.

Taken together, the distribution of true effects provides evidence that VR- and simulation-based STEM instruction yields a statistically reliable and practically meaningful contribution to the development of soft skills.

Furthermore, the impact of these interventions is visually summarized through a forest plot (Fig. 5), which presents both individual study effects and the aggregated effect size within a unified graphical framework. This visualization allows for the comparison of effect magnitudes, their confidence intervals, and the degree of heterogeneity among studies.

The forest plot indicates that the majority of studies report positive and statistically significant effects, thereby reinforcing the conclusion that VR- and simulation-based STEM approaches are generally effective in enhancing soft skills outcomes.

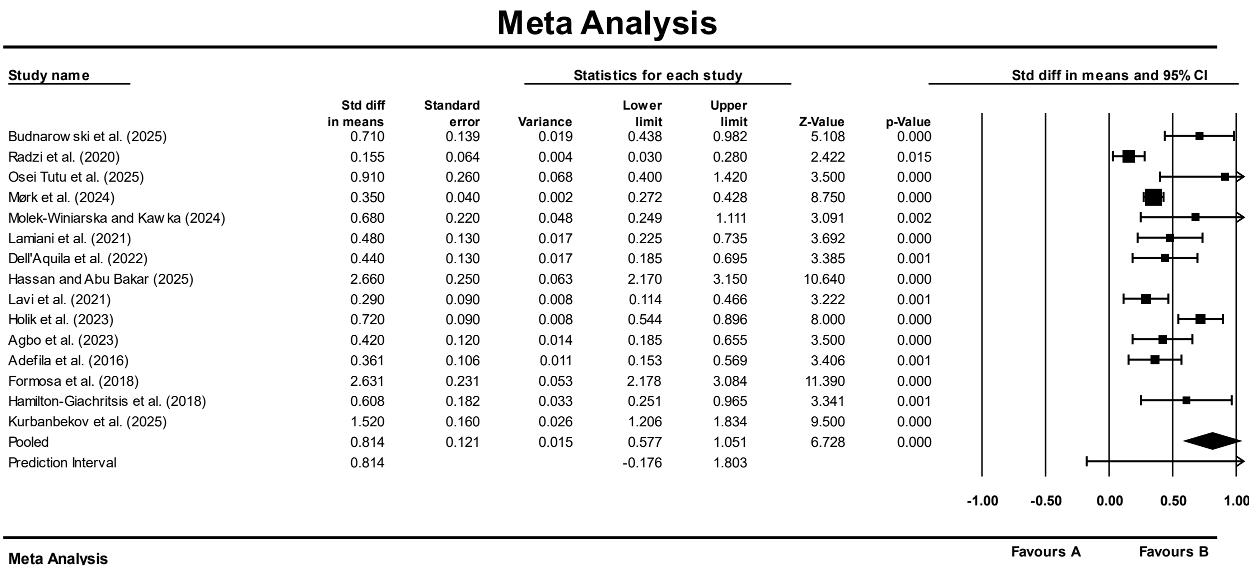

Fig. 5: Graphical representation of the meta-analysis results

Overview: The meta-analysis was conducted based on data obtained from fifteen independent studies. The standardized mean difference (Cohen's d) was adopted as the primary indicator of effect size to ensure comparability across studies.

Statistical Model: A random-effects model was applied, assuming that the included studies represent a random subset of a broader population of potential research. This approach allows the findings to be generalized beyond the analyzed sample and accounts for variability between studies.

Mean Effect Size: The aggregated effect size was estimated at d = 0.814, with a 95% confidence interval ranging from 0.577 to 1.051. This interval indicates that the overall effect is positive and that the true mean effect size is likely to lie within this range.

The statistical significance of the pooled effect was evaluated using the Z-test. The obtained value ($Z = 6.728$, $p < 0.001$) led to the rejection of the null hypothesis at $\alpha = 0.05$, confirming that the mean effect size differs significantly from zero.

Heterogeneity Analysis: To assess variability among studies, Cochran's Q-test was applied. The results ($Q = 86.765$, $df = 14$, $p < 0.001$) indicate that the assumption of a common effect size is not supported, suggesting substantial heterogeneity across studies. The I^2 statistic was calculated at 75%, demonstrating that a large proportion of the observed variance is attributable to real differences between studies rather than random sampling error.

Overall Interpretation: The findings of the meta-analysis provide evidence that VR- and simulation-based STEM instruction is associated with a positive and statistically significant improvement in students' soft skills, including communication, collaboration, critical thinking, problem solving, engineering thinking, empathy, and self-regulation.

The evaluation of publication bias further supports the robustness of these findings, as no substantial bias was detected. The high fail-safe N value indicates that a considerable number of additional null-result studies would be required to invalidate the observed effect. However, it is important to note that the magnitude of the effect is not uniform across studies. The results suggest that the effectiveness of VR- and simulation-based instruction is influenced by contextual factors, such as instructional design, learning environment, and characteristics of the participants.

To further investigate the sources of this variability, a meta-regression analysis was performed (Table 4). Meta-regression allows for the examination of how study-level characteristics, referred to as moderator variables, contribute to differences in effect sizes, thereby offering a deeper understanding of the conditions under which these interventions are most effective.

Table 4: Results of the moderator analysis of the effects of instructional format and intervention duration (random-effects model)

Covariate	Coefficient	SE	95% lower	95% upper	Z-value	Two-sided p-value
Intercept	1.0866	0.1815	0.7309	1.4423	5.99	0
format and duration: 2	-0.4914	0.2436	-0.968	-0.014	-2.02	0.0437

Test of the model: Simultaneous test that all coefficients (excluding the intercept) are zero: Q = 4.07, df = 1, p = 0.0437; Goodness of fit: τ^2 = 0.1956, τ = 0.4423, I^2 = 75.51%, Q = 86.73, df = 13, p = 0.0000; Comparison of Model 1 with the null model: Total between-study variance (intercept only): τ^2 = 0.1952, τ = 0.4418, I^2 = 75.63%, Q = 86.76, df = 14, p = 0.0000; Proportion of total between-study variance explained by Model 1: R^2 analog = 0.00

To further explore the sources of heterogeneity, a meta-regression analysis was conducted using study-level characteristics as moderator variables. In the present study, a composite moderator combining instructional format and intervention duration was included in the model.

During the meta-regression analysis, a composite moderator combining instructional format and intervention duration was introduced. The results indicated that this moderator exerted a statistically significant influence on the effect size related to soft skills development. Compared with the baseline category, the effect size for format and duration: level 2 was significantly lower (β = −0.491; SE = 0.244; Z = −2.02; p = 0.0437; 95% CI [−0.968; −0.014]). This finding suggests that changes in the organizational format and duration of the intervention are associated with meaningful variations in pedagogical effectiveness.

The overall significance of the model further confirmed the moderating role of this composite variable. Specifically, the null hypothesis that all regression coefficients (excluding the intercept) are equal to zero was rejected (Q = 4.07; df = 1; p = 0.0437). This result indicates that the combined moderator plays a statistically significant role in explaining differences in effect sizes across studies.

At the same time, a moderate-to-high level of heterogeneity remained among the included studies (I^2 = 75.51%; τ^2 = 0.196), suggesting that variability in effect sizes cannot be explained solely by instructional format and duration. Comparisons with the null model also revealed that the inclusion of the moderator did not substantially reduce the overall between-study variance (R^2 analog = 0.00). This implies that additional factors—such as learning context, research design, participant characteristics, and assessment instruments—may also contribute to variations in effect sizes.

However, the proportion of between-study variance explained by the model was negligible (R^2 analog = 0.00). This indicates that, although the moderator was statistically significant, it did not substantially account for the observed heterogeneity across studies. A moderate-to-high level of heterogeneity remained (I^2 = 75.51%; τ^2 = 0.196), suggesting that variability in effect sizes cannot be explained solely by instructional format and intervention duration. Therefore, the remaining unexplained variance may be attributed to additional moderators, such as learning context, research design, participant characteristics, type of VR technology, and assessment instruments.

5. Discussion

The meta-analysis conducted in this study demonstrates that VR- and simulation-based STEM instruction has a statistically significant moderate-to-high effect on the development of learners' soft skills. These findings are fully consistent with recent empirical and review studies reported in the literature.

In particular, research by Lebert and Vilarroya (2025) showed that the effectiveness of simulation-based learning increases substantially when combined with prior textual or theoretical preparation. This finding helps explain one of the key results of the present meta-analysis—namely, the high heterogeneity (elevated I^2 values). The effectiveness of VR and simulations depends not only on the technology itself but also on the pedagogical scenarios in which it is embedded and the level of learners' prior preparation. Thus, soft skills development is closely linked to the structural organization of the intervention.

The multidimensional pedagogical model proposed by Mikkonen et al. (2025) suggests that combining traditional classroom instruction with high-fidelity simulation and extended reality (XR) supports the sustained development of soft skills. This result is consistent with the meta-regression findings of the present study, which demonstrated that instructional format and duration, when considered as a combined moderator, significantly influence effect sizes. Consequently, long-term, systematically organized VR-based interventions appear to be more effective than short-term or fragmented implementations.

In addition, the scoping review conducted by Owolabi et al. (2025) highlights that simulation-based learning in medical and biomedical education enhances not only domain-specific knowledge but also confidence, professional communication, and decision-making skills. This observation provides a broader interpretive context for the present findings, as simulations in STEM education similarly create authentic, profession-oriented environments that support soft skills development in realistic contexts.

Taken together, both the reviewed literature and the results of the present meta-analysis indicate that the effectiveness of VR- and simulation-based STEM instruction in developing soft skills depends not solely on the immersive nature of the technology, but also on pedagogically sound instructional design, intervention duration, and learning context. This underscores the importance of adopting methodologically grounded, long-term, and integrated models when implementing VR and simulation technologies in education.

6. Conclusion

The results of this meta-analysis indicate that VR- and simulation-based STEM instruction generally has a statistically significant and positive effect on the development of learners' soft skills. In particular, these approaches appear to support the development of competencies such as communication, teamwork, problem solving, and critical thinking.

However, the findings also suggest that the magnitude of this effect varies depending on contextual factors, including instructional design, intervention duration, learning environment, and participant characteristics. This variability is further supported by the observed heterogeneity and the limited explanatory power of the moderator analysis.

Therefore, while VR and simulation technologies represent promising and pedagogically valuable tools, their effectiveness should be understood as context-dependent rather than universally consistent. Future research should focus on identifying additional moderating factors and optimizing instructional conditions for maximizing their impact.

List of abbreviations

AI	Artificial intelligence
CI	Confidence interval
CMA	Comprehensive Meta-Analysis
ERIC	Education Resources Information Center
ES	Effect size
IVR	Immersive virtual reality
I^2	I-squared (heterogeneity statistic)
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SD	Standard deviation
SE	Standard error
SMD	Standardized mean difference
STEM	Science, technology, engineering, and mathematics
TICOL	Theory of Immersive Collaborative Learning
VR	Virtual reality
WoS	Web of Science
XR	Extended reality
Z-test	Z statistical test
τ^2	Tau-squared (between-study variance)

Acknowledgment

This research was supported by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan under Grant No. BR28713097.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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