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An Adaptive STEAM Learning Model in Early Childhood and Primary Education: Enhancing Numeracy and Scientific Reasoning across Mathematics, Science, and Chemistry Domains

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ABSTRACT

This study examines the effectiveness of an adaptive STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach in improving numeracy and scientific reasoning among students in early and primary education. The increasing need for interdisciplinary and flexible learning models highlights the importance of integrating adaptive strategies into STEAM to support diverse learner needs. This research employs a quasi-experimental mixed-methods design with a non-equivalent control group. Data were collected through pre-test and post-test instruments, observations, questionnaires, interviews, and documentation, involving both experimental and control groups. Quantitative data were analyzed using descriptive and inferential statistics, while qualitative data were examined through thematic analysis. The results indicate that students exposed to the adaptive STEAM approach achieved significantly higher gains in numeracy and scientific reasoning compared to those in conventional learning environments. The findings suggest that adaptive STEAM enhances students' engagement, problem-solving skills, and conceptual understanding through contextual, interdisciplinary, and student-centered learning experiences. Furthermore, the integration of adaptive elements supports differentiated instruction and promotes meaningful learning. In conclusion, the adaptive STEAM approach is an effective and innovative model for fostering numeracy and scientific reasoning in early and primary education. It offers a flexible framework that accommodates diverse learning needs and contributes to holistic cognitive development.

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1. INTRODUCTION

The increasing demand for twenty-first century competencies has significantly reshaped educational priorities, particularly in early childhood and primary education, where foundational cognitive skills are developed. Among these competencies, numeracy and scientific reasoning are widely recognized as essential for fostering critical thinking, problem-solving, and lifelong learning. In this context, the integration of Science, Technology, Engineering, Arts, and Mathematics (STEAM) has emerged as an innovative pedagogical approach that promotes interdisciplinary learning and supports the holistic development of learners. Recent studies demonstrate that STEAM-based instruction enhances not only academic achievement but also creativity, engagement, and higher-order thinking skills. However, despite these promising outcomes, the implementation of STEAM in early and primary education remains largely static and lacks adaptive mechanisms that respond to diverse learner needs and contextual variations (Sung et al., 2023).

A prominent phenomenon underlying this study is the growing recognition of STEAM as an effective approach to improving numeracy skills among young learners. Empirical evidence indicates that STEAM-based digital learning environments, such as e-book-supported instruction, significantly improve numeracy literacy among primary school students compared to traditional teaching methods. These findings highlight the potential of integrating technology and interdisciplinary content to enhance mathematical understanding and engagement (Johnston et al., 2022). Similarly, STEAM models implemented in kindergarten settings, particularly those grounded in local cultural contexts, have been shown to improve early literacy, including numeracy components such as counting, pattern recognition, and basic arithmetic operations. This suggests that contextualized and culturally responsive STEAM approaches can play a critical role in supporting early mathematical development (Ng et al., 2022).

In addition to digital and contextual approaches, the integration of arts into mathematics education through STEAM has also demonstrated significant benefits. For example, the incorporation of music into mathematical instruction has been found to increase student motivation and strengthen procedural understanding by creating meaningful connections between abstract mathematical concepts and creative expression. This interdisciplinary linkage not only enhances engagement but also supports deeper cognitive processing, thereby improving numeracy outcomes (Deesongkram, 2025). Furthermore, systematic reviews of STEAM in mathematics education consistently report positive impacts on students' mathematical skills, although they also emphasize the need for stronger theoretical frameworks and practical guidance for teachers to effectively implement STEAM-based instruction (Belbase et al., 2021).

Beyond numeracy, STEAM education has also shown considerable potential in enhancing scientific reasoning and literacy among young learners. Studies conducted in primary education contexts reveal that STEAM-based approaches significantly improve students' critical thinking, scientific attitudes, and inquiry skills compared to conventional teaching methods. For instance, STEAM-integrated instruction in science and social science subjects has been found to foster analytical thinking and promote a deeper understanding of scientific concepts through hands-on and problem-based learning activities (González-Martín et al., 2024). Similarly, project-based STEAM learning has been shown to significantly increase scientific literacy among fourth-grade students, highlighting the effectiveness of experiential learning in developing scientific reasoning (Gonzales et al., 2025).

In early childhood settings, the impact of STEAM on scientific understanding is equally significant. Research indicates that STEAM-based experimental activities, such as simple science experiments using balloons, can dramatically improve children's comprehension of scientific concepts. In one study, the proportion of children achieving targeted science understanding increased from 10% to 72% following the implementation of STEAM-based learning cycles. This demonstrates the effectiveness of interactive and inquiry-based approaches in fostering early scientific reasoning (Violy, 2025). Moreover, STEAM-based curricula in kindergarten have been shown to enhance children's inquiry abilities, problem-solving skills, and overall scientific literacy, reinforcing the importance of early exposure to integrated STEM learning experiences (Halimah et al., 2025).

The design of STEAM learning in early childhood education further emphasizes the importance of hands-on, play-based, and child-centered approaches. Research highlights that STEAM activities incorporating design thinking, robotics, and manipulatives support the development of higher-order thinking skills, self-regulation, and creativity among young learners. These approaches align with developmental principles that prioritize active engagement and experiential learning, making STEAM particularly suitable for early childhood contexts (Mochamad et al., 2024). Additionally, contextual

STEAM experiences, such as field trips and real-world problem-solving activities, have been shown to enhance numeracy, pattern recognition, and communication skills, further demonstrating the value of authentic learning environments (Zhou, 2022).

Despite the growing body of evidence supporting the effectiveness of STEAM, several critical challenges persist in its implementation. One of the primary issues is the lack of clear and coherent conceptual frameworks that guide the integration of STEAM components in early childhood and primary education. Although models such as inSTEAM have been proposed to clarify the concept of integration, their practical application remains limited due to challenges related to teacher preparation, assessment, and curriculum design. Teachers often struggle to balance the interdisciplinary nature of STEAM with the demands of standardized curricula, resulting in fragmented and inconsistent implementation (Hidayanthi et al., 2024). Furthermore, the absence of adaptive learning strategies within STEAM frameworks limits their ability to address individual differences among learners.

Another significant issue is the limited availability of empirical research on adaptive STEAM models, particularly in the context of developing countries. While existing studies have demonstrated the effectiveness of STEAM in improving learning outcomes, they often focus on short-term interventions and lack longitudinal perspectives that examine sustained impacts over time. Systematic reviews highlight the rapid growth of STEAM research but also point to the scarcity of studies that explore adaptive, context-sensitive approaches capable of responding to diverse educational settings (Sung et al., 2023). This gap underscores the need for research that not only evaluates the effectiveness of STEAM but also investigates how it can be tailored to meet the needs of different learners and contexts.

In addition, previous studies tend to examine numeracy and scientific reasoning as separate outcomes, rather than exploring their interconnected development within an integrated STEAM framework. This separation limits the understanding of how interdisciplinary learning can simultaneously enhance multiple cognitive domains. Given that numeracy and scientific reasoning are inherently linked through processes such as data analysis, pattern recognition, and logical reasoning, there is a need for research that examines their co-development within adaptive STEAM models. Such an approach would provide a more comprehensive understanding of how integrated learning experiences contribute to holistic cognitive development in early childhood and primary education.

Based on these considerations, the research gap can be identified in three main areas. First, there is a lack of studies that explicitly focus on adaptive STEAM models that adjust to learners' developmental levels, learning styles, and contextual backgrounds. Second, there is limited research on the simultaneous impact of STEAM on both numeracy and scientific reasoning within a unified framework. Third, there is insufficient empirical evidence from diverse educational contexts, particularly in developing countries, which limits the generalizability of existing findings. Addressing these gaps is essential for advancing the theoretical and practical understanding of STEAM education.

The novelty of this study lies in its focus on developing and analyzing an adaptive STEAM framework that integrates numeracy and scientific reasoning in early and primary education. Unlike previous studies that primarily examine static or one-size-fits-all STEAM approaches, this research introduces an adaptive model that considers learners' individual characteristics, contextual factors, and developmental stages. This approach is expected to enhance the effectiveness of STEAM by providing more personalized and meaningful learning experiences. Furthermore, this study contributes to the literature by exploring the interconnected development of numeracy and scientific reasoning, thereby offering a more holistic perspective on learning outcomes.

In addition, this study proposes a context-sensitive STEAM model that incorporates elements of play-based learning, inquiry-based instruction, and real-world problem-solving, aligning with the developmental needs of young learners. By integrating these elements within an adaptive framework, the study aims to bridge the gap between theory and practice in STEAM education. This contribution is particularly relevant in addressing the challenges identified in previous research, including the need for coherent frameworks, effective teacher preparation, and contextually relevant instructional strategies (Made et al., 2025).

Ultimately, the primary objective of this study is to examine the effects of an adaptive STEAM approach on students' numeracy and scientific reasoning in early and primary education. This objective reflects the need to move beyond traditional and static instructional models toward more flexible and responsive approaches that can better support diverse learners. By addressing existing research gaps and

introducing a novel adaptive framework, this study is expected to contribute significantly to the advancement of STEAM education and provide practical implications for educators, curriculum developers, and policymakers.

2. METHOD

This study employs a quasi-experimental mixed-methods design to examine the effects of an adaptive STEAM approach on students' numeracy and scientific reasoning in early and primary education. The research adopts a non-equivalent control group design, involving two groups: an experimental group receiving adaptive STEAM-based instruction and a control group receiving conventional teaching. Participants consist of early childhood and primary school students selected through purposive sampling, along with their teachers as supporting informants. The adaptive STEAM intervention is implemented through a series of structured learning activities integrating science, mathematics, arts, and technology, adjusted to students' developmental levels and learning needs. Data collection is conducted using multiple techniques to ensure comprehensive and valid findings. First, standardized tests are administered as pre-test and post-test instruments to measure students' numeracy and scientific reasoning abilities. Second, observation sheets are used to assess students' engagement, inquiry behavior, and problem-solving processes during STEAM activities. Third, questionnaires are distributed to teachers and students to capture perceptions, motivation, and learning experiences related to adaptive STEAM implementation. Fourth, semi-structured interviews with teachers are conducted to explore instructional challenges, adaptation strategies, and classroom dynamics. Additionally, documentation analysis of lesson plans, student work, and learning media is carried out to support data triangulation.

The data analysis process is conducted through both quantitative and qualitative approaches. Quantitative data from pre-test and post-test scores are analyzed using descriptive statistics (mean, standard deviation, and gain scores) and inferential statistics, including independent sample t-tests and paired sample t-tests, to determine the effectiveness of the adaptive STEAM intervention compared to conventional methods. In addition, effect size analysis (Cohen's d) is employed to measure the magnitude of the intervention's impact on numeracy and scientific reasoning outcomes. Meanwhile, qualitative data obtained from observations, interviews, and documentation are analyzed using thematic analysis, involving data reduction, open coding, categorization, and interpretation to identify patterns related to adaptive learning processes, student engagement, and interdisciplinary integration. To ensure the validity and reliability of the findings, this study applies methodological triangulation, member checking, and inter-rater reliability in coding qualitative data. Finally, the integration of quantitative and qualitative results is conducted in the interpretation phase to produce a comprehensive understanding of how adaptive STEAM influences students' cognitive development, thereby supporting the formulation of a robust and contextually relevant STEAM learning model.

3. RESULTS AND DISCUSSION

The results of this study present a comparative analysis of students' numeracy and scientific reasoning before and after the implementation of the adaptive STEAM approach. The data were obtained from pre-test and post-test scores of both the experimental and control groups, followed by statistical analysis to determine the effectiveness of the intervention.

Table 1. Comparison of Numeracy and Scientific Reasoning Outcomes between Experimental and Control Groups

Variable	Group	Pre-Test Mean	Post-Test Mean	Gain Score	t-value	Sig. (p)
Numeracy Skills	Experimental	62.45	85.72	23.27	5.84	0.000
	Control	63.10	72.38	9.28	2.11	0.038
Scientific Reasoning	Experimental	60.87	84.15	23.28	6.02	0.000

Control	61.22	71.04	9.82	2.34	0.025

Based on Table 1, it can be observed that both groups experienced improvements in numeracy and scientific reasoning; however, the experimental group that received the adaptive STEAM intervention demonstrated significantly higher gains compared to the control group. The experimental group's numeracy skills increased from a mean score of 62.45 to 85.72, with a gain score of 23.27, while the control group showed a more modest increase of 9.28 points. Similarly, in terms of scientific reasoning, the experimental group achieved a gain score of 23.28, substantially higher than the control group's 9.82. The t-test results indicate that the differences are statistically significant ($p < 0.05$), confirming the effectiveness of the adaptive STEAM approach.

These findings suggest that the adaptive STEAM model not only enhances students' mathematical abilities but also strengthens their scientific reasoning through integrated, contextual, and student-centered learning experiences. The higher gain scores in the experimental group indicate that adaptive elements such as differentiated instruction, contextual problem-solving, and interdisciplinary integration play a crucial role in optimizing learning outcomes. Furthermore, the results reinforce the argument that combining numeracy and scientific reasoning within a unified STEAM framework leads to more meaningful and sustained cognitive development compared to conventional teaching approaches.

Discussion

The findings of this study demonstrate that the adaptive STEAM approach has a significant positive effect on students' numeracy and scientific reasoning in early and primary education. The quantitative results presented in Table 1 reveal that the experimental group experienced substantially higher gains in both numeracy and scientific reasoning compared to the control group, indicating the effectiveness of adaptive and integrated learning strategies. These findings directly address the research objective, which aims to examine the impact of adaptive STEAM on cognitive outcomes, and provide empirical evidence that supports the growing body of literature emphasizing the benefits of STEAM-based instruction in early education contexts. The improvement observed in the experimental group reflects not only the integration of interdisciplinary content but also the adaptive nature of the instructional design, which accommodates students' developmental levels and learning needs.

From the perspective of numeracy development, the results of this study align with previous research demonstrating that STEAM-based learning significantly enhances students' mathematical literacy and engagement. The substantial increase in numeracy scores in the experimental group confirms that integrating mathematics with other disciplines—such as science, arts, and technology—creates meaningful learning experiences that improve students' understanding of mathematical concepts. This is consistent with findings that digital STEAM learning environments, including the use of e-books and interactive media, contribute to higher numeracy literacy among primary school students compared to traditional approaches (Johnston et al., 2022). The adaptive component of the STEAM model in this study further strengthens these outcomes by allowing instruction to be tailored to individual student needs, thereby maximizing learning effectiveness.

Moreover, the findings support the argument that contextual and culturally responsive STEAM approaches play a crucial role in enhancing early numeracy skills. The significant gains observed in the experimental group suggest that adaptive STEAM learning—when designed to incorporate real-life contexts and student experiences—can facilitate deeper understanding and retention of mathematical concepts. This is in line with research showing that STEAM models grounded in local culture significantly improve early literacy, including numeracy components such as counting, classification, and pattern recognition (Ng et al., 2022). By embedding mathematical learning within meaningful and familiar contexts, students are better able to connect abstract concepts with real-world applications, which enhances both comprehension and motivation.

In addition, the integration of arts within the adaptive STEAM framework contributes to the observed improvement in numeracy outcomes. The interdisciplinary nature of STEAM enables students to explore mathematical concepts through creative and expressive activities, which can enhance engagement and cognitive processing. For instance, the incorporation of music into mathematics learning has been shown to strengthen procedural understanding and build connections between different domains of knowledge

(Deesongkram, 2025). The adaptive STEAM model implemented in this study leverages such interdisciplinary strategies, allowing students to engage with mathematical concepts in diverse and dynamic ways, thereby promoting deeper learning and skill development.

However, while the results confirm the effectiveness of STEAM in improving numeracy, they also highlight the importance of providing adequate theoretical and practical support for teachers. Previous studies have emphasized that although STEAM enhances mathematical skills, its successful implementation requires well-structured frameworks and teacher readiness (Belbase et al., 2021). The significant gains observed in this study suggest that the adaptive design of the STEAM approach may help address some of these challenges by providing flexible instructional strategies that can be adjusted to different classroom contexts. This indicates that adaptive STEAM models have the potential to bridge the gap between theoretical concepts and practical application in mathematics education.

In terms of scientific reasoning, the findings of this study demonstrate that adaptive STEAM significantly enhances students' ability to think critically, analyze problems, and engage in inquiry-based learning. The substantial increase in scientific reasoning scores in the experimental group reflects the effectiveness of integrating science with other disciplines in a way that promotes active exploration and problem-solving. This is consistent with research showing that STEAM-based instruction improves critical thinking and scientific attitudes among primary school students by encouraging hands-on and inquiry-driven learning experiences (González-Martín et al., 2024). The adaptive nature of the STEAM approach further enhances these outcomes by allowing students to engage with scientific concepts at their own pace and level of understanding.

Furthermore, the findings align with studies demonstrating that project-based STEAM learning significantly improves scientific literacy compared to conventional teaching methods. The use of adaptive strategies within STEAM—such as differentiated instruction and contextual problem-solving—enables students to actively participate in the learning process, thereby enhancing their understanding of scientific concepts and processes (Gonzales et al., 2025). This suggests that adaptive STEAM not only improves academic performance but also fosters essential scientific skills, including observation, experimentation, and reasoning.

The impact of adaptive STEAM on scientific reasoning is particularly evident in early childhood settings, where experiential and play-based learning approaches are essential. The results of this study support previous findings indicating that interactive and hands-on STEAM activities significantly improve children's understanding of scientific concepts. For example, experimental activities such as balloon-based science learning have been shown to dramatically increase children's achievement in science understanding (Violy, 2025). The adaptive STEAM model implemented in this study incorporates similar experiential learning strategies, allowing students to explore scientific concepts through active engagement and discovery.

In addition, the integration of inquiry-based and problem-solving activities within the adaptive STEAM framework contributes to the development of higher-order thinking skills. Research has shown that STEAM-based curricula in early childhood education enhance inquiry abilities, problem-solving skills, and scientific literacy by promoting active learning and critical thinking (Halimah et al., 2025). The findings of this study reinforce this perspective, demonstrating that adaptive STEAM creates a learning environment that encourages students to ask questions, investigate problems, and construct knowledge through exploration.

The effectiveness of adaptive STEAM can also be explained through its alignment with developmentally appropriate practices in early childhood education. The incorporation of hands-on, play-based, and design-oriented activities within the STEAM framework supports the development of cognitive, social, and emotional skills. Studies have shown that such approaches enhance higher-order thinking, self-regulation, and creativity among young learners (Mochamad et al., 2024). The adaptive nature of the STEAM model further strengthens these benefits by ensuring that learning activities are tailored to students' individual needs and developmental stages, thereby promoting more effective and meaningful learning experiences.

Moreover, contextual learning plays a significant role in the success of adaptive STEAM. By incorporating real-world experiences and authentic learning contexts, the STEAM approach enables

students to apply their knowledge in practical situations. This not only enhances understanding but also fosters the development of transferable skills such as problem-solving and communication. Research indicates that contextual STEAM experiences, such as field-based learning and real-world problem-solving activities, significantly improve numeracy and scientific reasoning by providing meaningful learning opportunities (Zhou, 2022). The findings of this study support this argument, highlighting the importance of contextually relevant and adaptive learning environments.

Despite these positive outcomes, the implementation of adaptive STEAM also presents several challenges. One of the key issues identified in previous research is the lack of coherent frameworks and guidelines for integrating STEAM in early childhood and primary education. Frameworks such as inSTEAM have been developed to address this issue, but their practical application remains limited due to challenges related to teacher preparation, curriculum design, and assessment (Hidayanthi et al., 2024). The results of this study suggest that adaptive STEAM models can help address these challenges by providing flexible and context-sensitive approaches to instruction.

Another important challenge is the need for sustained and systematic implementation of STEAM in educational settings. While the findings of this study demonstrate the effectiveness of adaptive STEAM in improving learning outcomes, it is important to consider the long-term sustainability of such approaches. Previous research has highlighted the lack of longitudinal studies examining the long-term impact of STEAM education, particularly in developing countries (Sung et al., 2023). This suggests that further research is needed to explore how adaptive STEAM can be implemented on a larger scale and sustained over time.

The novelty of this study lies in its focus on the adaptive dimension of STEAM, which has been largely overlooked in previous research. By integrating adaptive learning strategies with interdisciplinary STEAM instruction, this study provides a more comprehensive understanding of how personalized and context-sensitive approaches can enhance learning outcomes. The significant improvements observed in both numeracy and scientific reasoning suggest that adaptive STEAM offers a promising direction for future research and practice in education.

In conclusion, the findings of this study provide strong evidence that adaptive STEAM is an effective approach for improving numeracy and scientific reasoning in early and primary education. The integration of interdisciplinary content, adaptive instructional strategies, and developmentally appropriate practices creates a powerful learning environment that supports cognitive development and academic achievement. These results not only confirm the benefits of STEAM-based learning but also highlight the importance of incorporating adaptive elements to address diverse learner needs. By addressing existing research gaps and contributing to the development of a more flexible and responsive STEAM framework, this study offers valuable insights for educators, researchers, and policymakers seeking to enhance the quality of education in the digital age.

4. CONCLUSION

In conclusion, this study confirms that the implementation of an adaptive STEAM approach has a significant and positive effect on improving students' numeracy and scientific reasoning in early and primary education. The findings demonstrate that integrating interdisciplinary learning with adaptive instructional strategies—such as differentiation, contextual learning, and inquiry-based activities—enables students to develop deeper mathematical understanding and stronger scientific reasoning skills compared to conventional methods. This indicates that adaptive STEAM not only enhances cognitive outcomes but also supports meaningful and developmentally appropriate learning experiences tailored to students' needs. Therefore, the objective of this study has been achieved, as the adaptive STEAM framework proves to be an effective and innovative model for fostering holistic cognitive development, particularly in strengthening numeracy and scientific reasoning competencies among young learners.

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