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Original Article

Integration of the steam approach in teaching linear algebra to engineering students

Integración del enfoque steam en la enseñanza de álgebra lineal para estudiantes de ingeniería

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Abstract

Introduction: this study examines the integration of the STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach and technological tools in teaching linear algebra, a fundamental subject in engineering education. Since a deep understanding of algebraic concepts is crucial for academic and professional success in engineering, the research explores how these innovative methodologies can enhance learning in this field.
Objetive: the aim of this study was to assess the effectiveness of integrating the STEAM approach and technological tools in teaching linear algebra to engineering students, with the goal of improving their academic performance and satisfaction with the implemented teaching strategies.
Methodology: a sequential explanatory mixed-methods design was used, combining standardized summative assessments (□ = 0.85) and open-ended evaluations, along with qualitative data from the Course Experience Questionnaire (CEQ, □ = 0.92). The participants were 29 engineering students selected through purposive sampling.
Results: the results revealed a significant improvement in students' academic performance, with a statistically significant difference ($p < 0.01$) and a large effect size ($d = 0.78$). Additionally, the participants expressed high satisfaction with the teaching strategies implemented, according to the course experience questionnaire results.
Conclusions: the integration of the STEAM approach and technological tools in teaching linear algebra shows promise in improving both conceptual understanding and practical application of the concepts in engineering contexts. The findings suggest that these methodologies can be an effective means of enhancing both academic performance and student satisfaction in technical disciplines.

Keywords: Linear Algebra, STEAM, Educational Technology, Engineering Education.

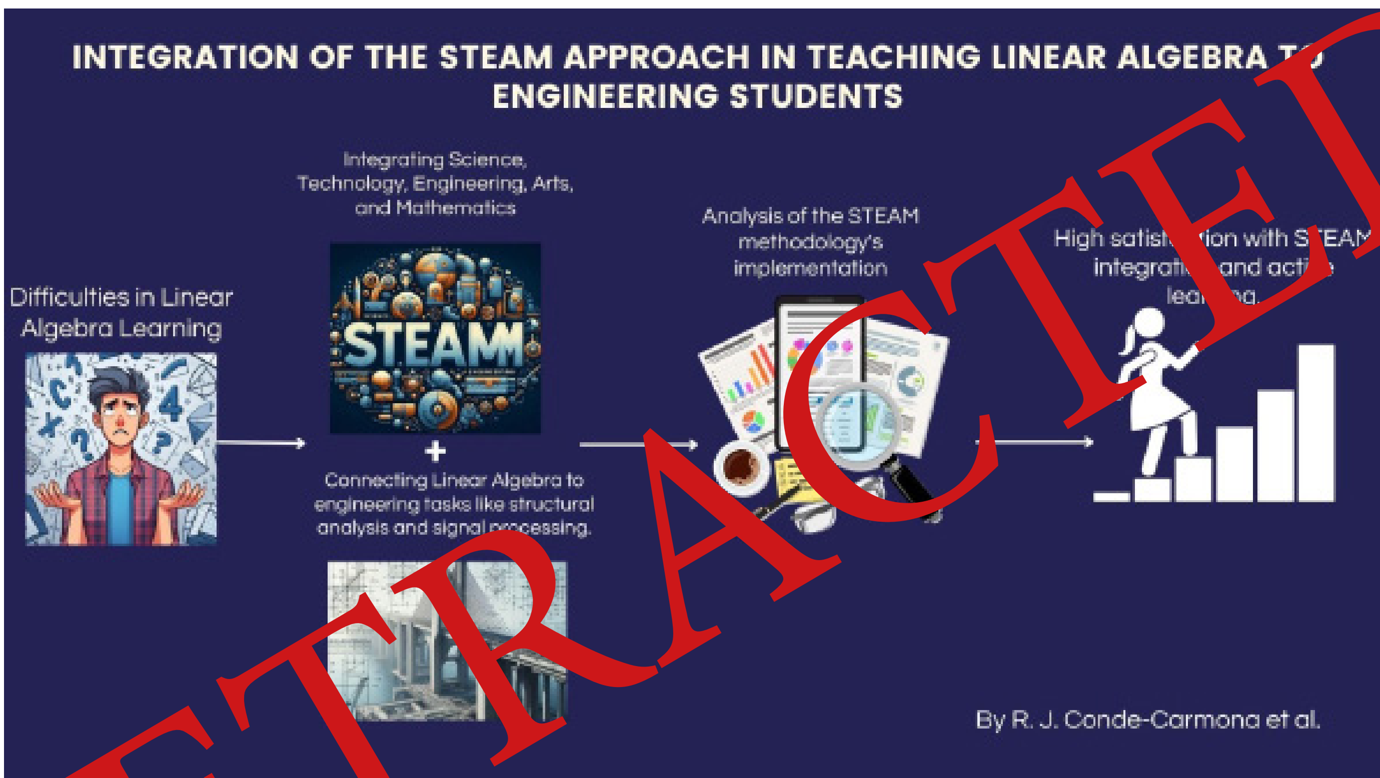
Resumen

Introducción: este estudio aborda la integración del enfoque STEAM (Ciencia, Tecnología, Ingeniería, Arte y Matemáticas) y herramientas tecnológicas en la enseñanza de álgebra lineal, una disciplina fundamental en los estudios de ingeniería. Dado que la comprensión profunda de los conceptos algebraicos es crucial para el éxito académico y profesional de los estudiantes de ingeniería, la investigación explora cómo estas metodologías innovadoras pueden mejorar el aprendizaje en este campo.
Objectivo: el objetivo de este estudio fue evaluar la eficacia de la integración del enfoque STEAM y las herramientas tecnológicas en la enseñanza del álgebra lineal a estudiantes de ingeniería, con el fin de mejorar su rendimiento académico y satisfacción con las estrategias pedagógicas implementadas.
Metodología: se empleó un diseño explicativo secuencial de métodos mixtos, que combinó evaluaciones sumativas estandarizadas (□ = 0.85) y evaluaciones abiertas, así como datos cualitativos obtenidos del Cuestionario de Experiencia del Curso (CEQ, □ = 0.92). Los participantes fueron 29 estudiantes de ingeniería seleccionados mediante muestreo intencional.
Resultados: los resultados indicaron una mejora significativa en el rendimiento académico de los estudiantes, con una diferencia estadísticamente significativa ($p < 0.01$) y un tamaño del efecto grande ($d = 0.78$). Además, los participantes expresaron una alta satisfacción con las estrategias pedagógicas implementadas, según los resultados del cuestionario de experiencia del curso.
Conclusiones: la integración del enfoque STEAM y el uso de herramientas tecnológicas en la enseñanza del álgebra lineal se muestra prometedora para mejorar la comprensión conceptual y la aplicación práctica de los conceptos en contextos de ingeniería. Los hallazgos sugieren que estas metodologías pueden ser una vía efectiva para aumentar tanto el rendimiento académico como la satisfacción estudiantil en disciplinas técnicas.

Palabras clave: Álgebra Lineal, STEAM, Tecnología Educativa, Educación en Ingeniería.

Contribution to the literature

This study contributes to the literature by providing empirical evidence on the effectiveness of the STEAM approach and technological integration in teaching linear algebra, demonstrating significant improvements in academic performance and conceptual understanding. The innovative combination of quantitative and qualitative methods offers a comprehensive view of the impact of these pedagogical interventions, providing valuable insights for enhancing education in engineering and other STEAM disciplines.



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Introduction

Linear algebra is a fundamental and indispensable pillar in the education of engineers and STEAM professionals, providing essential conceptual foundations such as vector spaces, linear transformations, and matrices (1). However, several studies have compellingly evidenced the significant and persistent difficulties this course represents for many university students in engineering and science, who often find it a true hurdle in their academic journey (2-4).

Among the main challenges identified are the pronounced abstraction of the content, which can be overwhelming and discouraging for many students; the apparent disconnection with tangible real-world applications, which hinders the understanding of the relevance and usefulness of the concepts; and the inherent limitations of traditional expository methodologies, which often fail to actively engage students and foster deep and meaningful learning (5-7).

In the face of this pressing and complex issue, which threatens to undermine the education of a new generation of engineers and scientists, the strategic and deliberate integration of digital technologies, along with the adoption of the interdisciplinary STEAM approach (Science, Technology, Engineering, Arts, and Mathematics), emerge as highly promising and potentially revolutionary alternatives to innovate in the teaching of linear algebra. These strategies aim to promote truly meaningful, deep, and lasting learning for future generations of STEAM professionals.

Recent research has highlighted the enormous potential of cutting-edge technological resources such as dynamic geometry software (8), interactive applets (9), and augmented reality applications (10) to visualize abstract concepts tangibly and engagingly, effectively connecting them with relevant and authentic real-world applications. Additionally, the STEAM approach can make an invaluable contribution by integrating linear algebra with other disciplines through collaborative projects and carefully contextualized problems, thereby fostering the development of transversal skills and a more holistic and interconnected understanding of knowledge (11-12).

Given this challenging yet opportunity-filled landscape, the present study aimed to rigorously and deeply characterize the impact of integrating digital technologies through a STEAM approach in the learning of linear systems of equations among civil engineering students. This completed study has generated valuable, actionable, and transformative knowledge about the potential of innovative techno-pedagogical strategies to substantially improve a key component of linear algebra for future STEAM professionals, thus laying the foundations for cutting-edge education in this specific area.

The current challenges in teaching linear algebra and the potential of digital technologies and the STEAM approach suggest the need for in-depth research into these innovative pedagogical strategies. This study aims to explore how the integration of technological tools and the interdisciplinary STEAM approach can transform the learning experience of linear algebra for engineering students. The research seeks to provide valuable insights into how these pedagogical approaches can address persistent difficulties in linear algebra education, potentially paving the way for more effective and engaging educational methods in STEAM fields. In this context, the main objective guiding this research is to characterize the STEAM approach and the use of technological tools in teaching linear algebra to engineering students. The findings of this study could have significant implications for engineering and science education, contributing to the development of innovative pedagogical strategies that better prepare future STEAM professionals

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Theoretical framework

Teaching of linear algebra

Linear algebra is a fundamental branch of mathematics that focuses on the study of linear systems, vector spaces, linear transformations, and matrices (13). This course represents one of the main challenges in university mathematics education, particularly in engineering and science disciplines (3). The difficulties students face in learning linear algebra are primarily associated with three factors: the abstract nature of the concepts, the disconnect from real-world applications, and the use of procedural-focused methodologies (2,5).

The abstract nature of concepts in linear algebra, such as vector spaces and linear transformations, can be overwhelming for students, especially when presented in a decontextualized manner. Many students struggle to grasp the meaning and relevance of these abstract concepts, which hinders their learning (14). The lack of connection to real-world applications and concrete problems can make linear algebra seem irrelevant and uninspiring to students (15).

Furthermore, the excessive emphasis on procedures and algorithms over conceptual understanding is another factor contributing to student difficulties. When teaching focuses on memorization and mechanical application of formulas and algorithms, students may succeed in solving routine problems but often lack a deep understanding of the underlying concepts (15). This limits their ability to apply linear algebra to new situations and solve non-routine problems. In response to these challenges, there is an emphasis on the need for innovative pedagogical approaches that promote deep conceptual learning linked to context (6).

It is crucial that the teaching of linear algebra focuses on helping students build a solid understanding of fundamental concepts, rather than simply memorizing procedures. This involves using strategies that encourage visualization, exploration, and connection of abstract concepts to concrete situations and relevant applications for students (16).

Furthermore, it is important to create a learning environment that promotes active student participation, collaborative work, and mathematical discourse. Student-centered approaches such as problem-based learning and discovery learning can be effective in engaging students in the knowledge-construction process and developing critical thinking skills and problem-solving abilities (17).

In summary, teaching linear algebra presents significant challenges in university mathematics education, particularly in engineering and science disciplines. To address these challenges, it is necessary to adopt pedagogical approaches that promote deep conceptual learning linked to context and centered on the student. This involves using strategies that encourage visualization, exploration, connection to real-world applications, and collaborative work. By doing so, we can help students overcome difficulties associated with the abstract nature of concepts, disconnect from applications, and excessive focus on procedures, thereby promoting meaningful and lasting learning of linear algebra.

Teaching linear algebra through STEAM

The STEAM movement (acronym for Science, Technology, Engineering, Arts, and Mathematics) has emerged as a promising approach for mathematics education, including linear algebra. STEAM promotes the intentional integration of disciplines in education through contextualized activities, such as interdisciplinary projects (11,18). This approach aims to overcome traditional barriers between subjects and foster more authentic and meaningful learning. In the context of teaching linear algebra, integrating STEAM can bring significant benefits by linking abstract concepts with their applications in engineering, science, and the arts (12). By relating linear algebra to complex, real-world problems and situations in these disciplines, students can develop a more comprehensive understanding

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of the subject's relevance and applicability. This approach not only enhances their mathematical knowledge but also fosters the development of critical thinking and problem-solving skills within the context of their future professional fields, preparing them for the multidisciplinary challenges they will face in their careers.

For example, in engineering, linear algebra is applied in the analysis of electrical circuits, structural mechanics, and signal processing. Incorporating projects and activities that address these problems using concepts from linear algebra allows students to experience firsthand the relevance and utility of this branch of mathematics (19). This not only enhances their conceptual understanding but also develops important skills such as critical thinking, problem-solving, and the ability to apply mathematics in real contexts.

Similarly, in the sciences, linear algebra has applications in quantum physics, bioinformatics, and mathematical modeling of dynamic systems. The integration of STEAM enables exploration of these applications through interdisciplinary projects that combine mathematical concepts with scientific experiments and computational simulations (20). This provides students with a broader perspective on how linear algebra is used in scientific research and allows them to develop skills in modeling and data analysis.

Furthermore, incorporating art into the teaching of linear algebra through STEAM can foster creativity and mathematical visualization. Abstract concepts of linear algebra, such as linear transformations and vector spaces, can be explored through artistic and visual representations (21). For instance, students can create generative artworks using matrices and linear transformations or explore the geometry of vector spaces through the creation of three-dimensional sculptures. These artistic activities not only make learning more engaging and memorable but also help students develop a more intuitive and visual understanding of abstract concepts.

Technology plays a crucial role in effectively implementing STEAM in the teaching of linear algebra. Technological tools such as mathematical software, interactive applets, and augmented reality provide opportunities for students to visualize, explore, and apply concepts of linear algebra dynamically and interactively (8). For example, students can use software like MATLAB or GeoGebra to visualize and manipulate vectors, matrices, and linear transformations, allowing them to experiment with abstract concepts in a more tangible and concrete way, facilitating understanding and retention of knowledge. Moreover, augmented reality and virtual reality offer exciting possibilities for the teaching of linear algebra. These technologies enable students to immerse themselves in three-dimensional environments where they can interact with mathematical objects and visualize abstract concepts immersively (9-10). For instance, students can explore the geometry of linear transformations in a three-dimensional space using virtual reality devices, providing them with a more intuitive and memorable experience of the concept.

The integration of the STEAM approach into the teaching of linear algebra, particularly in the context of systems of linear equations, presents an opportunity to create more contextualized and potentially impactful learning experiences. This approach aligns mathematical instruction with the multidisciplinary nature of contemporary STEAM fields, particularly in civil engineering applications.

Teaching mathematics in engineering programs

Mathematics plays a crucial role in engineering education, providing the tools and concepts necessary to analyze and solve complex problems (22). Courses like linear algebra are essential for developing skills in logical reasoning, abstract thinking, and mathematical modeling, which are fundamental in engineering practice. However, engineering students often face significant challenges in learning mathematics, especially in advanced courses such as linear algebra. Research in engineering education has identified common

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difficulties, including understanding abstract concepts, algorithmic problem-solving without a solid conceptual understanding, and the disconnect between mathematics and its application in engineering problems (23).

One of the primary challenges is the abstract nature of linear algebra concepts. Many students struggle to grasp the relevance of concepts such as vector spaces, linear transformations, and eigenvalues, especially when presented in a decontextualized manner (14). This can decrease motivation and engagement with learning, as students fail to see the connection between abstract mathematics and their future professional practice.

Additionally, engineering students often focus on problem-solving using memorized algorithms and procedures, without a deep understanding of the underlying concepts. This approach can result in superficial learning and difficulties in applying mathematical concepts in new or non-routine situations (15). Lack of conceptual understanding can also hinder students' ability to model and solve engineering problems that require the application of mathematical concepts.

In response to these challenges, it is crucial to adopt pedagogical strategies that promote meaningful learning, increase student motivation, and facilitate the transfer of mathematical knowledge to engineering problems (24). Teaching mathematics in engineering should focus on helping students build a solid conceptual understanding rather than simply memorizing procedures and algorithms. An effective strategy is the integration of technology and interdisciplinary approaches, such as the STEAM approach. Technology, such as mathematical software and visualization tools, can help students explore and understand abstract concepts more concretely and visually (8). For example, using interactive applets and simulations can allow students to visualize linear transformations, eigenvalues, and eigenvectors, and experiment with different parameters to observe their effects on outcomes.

Furthermore, integrating interdisciplinary approaches like STEAM can contextualize mathematics and demonstrate its relevance in solving engineering problems. By linking mathematical concepts with applications in different engineering fields such as mechanics, electronics, or computer science, students can see the practical utility of mathematics and develop skills to transfer knowledge across disciplines (11).

Another important strategy is to foster active and collaborative learning in the engineering mathematics classroom. Student-centered approaches, such as problem-based learning and discovery-based learning, can engage students in the knowledge construction process and develop critical thinking and problem-solving skills (17). By working in collaborative groups on projects and problem-solving activities, students can share ideas, discuss concepts, and learn from each other, promoting deeper and more meaningful learning.

In summary, integrating the STEAM approach into the teaching of linear algebra offers an innovative perspective to address traditional challenges associated with this subject. By connecting abstract concepts with real-world applications and promoting interdisciplinary and technological learning, STEAM has the potential to transform how engineering and science students engage with and apply linear algebra. This approach, as suggested by the literature, may foster a more comprehensive understanding of the subject, enhancing students' ability to connect mathematical concepts with their future professional practice. The integration of STEAM in linear algebra education presents an opportunity to create more contextualized and potentially impactful learning experiences, aligning mathematical instruction with the multidisciplinary nature of contemporary STEAM fields.

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Methodology

This study adopted a mixed-methods approach, combining quantitative and qualitative methods to provide a comprehensive understanding of the impact of the STEAM approach in teaching linear algebra. According to Hernández-Sampieri et al. (25), integrating both methods allows for a more complete and detailed insight into the research problem, leveraging the strengths of each approach. This approach is particularly valuable in educational studies, where the goal is not only to measure outcomes but also to understand participants' experiences and perceptions.

Consequently, the study employed a sequential explanatory design consisting of three sequential phases, where the results of one phase inform and guide subsequent stages (26). This design was ideal as it allowed for describing and understanding phenomena while also enabling the generation of changes and improvements in specific contexts (25).

The study combined standardized summative assessments and open-ended assessments to measure performance and conceptual understanding in linear algebra, providing an objective view of the impact of the implemented pedagogical strategies (8). Additionally, qualitative feedback from students was gathered through Course Experience Questionnaires (CEQ), offering a deep understanding of their experiences and perceptions regarding the teaching strategies (10). Triangulating quantitative and qualitative results allowed for the identification of convergent and divergent patterns, enhancing the validity and reliability of findings and providing a more comprehensive interpretation of the studied phenomenon (23, 27).

The triangulation of quantitative and qualitative data was conducted through a systematic process of convergent parallel analysis. Specifically, we compared the statistical results from the standardized assessments with the thematic analysis of the CEQ responses. For instance, when quantitative data showed a significant improvement in students' performance on matrix operations, we corroborated this with qualitative feedback from students describing their enhanced understanding of matrix concepts through STEAM activities. This integration allowed us to not only verify the consistency of findings across methods but also to provide a more nuanced interpretation of the results.

The selection of questions for both standardized and open-ended assessments was guided by a comprehensive content validity process. A panel of experts in linear algebra and engineering education reviewed each question to ensure alignment with the study's objectives and the STEAM approach. For standardized assessments, we included questions that required application of linear algebra concepts in engineering contexts. For example, one question asked students to solve a system of linear equations representing current flow in an electrical circuit. In open-ended assessments, we included questions that prompted students to explain their problem-solving process and reflect on the real-world applications of the concepts. An example of such a question was: 'Describe how you would use matrix transformations to analyze the stress distribution in a bridge structure, and explain the relevance of this application in civil engineering.' This approach ensured that the assessments effectively evaluated both conceptual understanding and practical application of linear algebra in engineering contexts.

In summary, the methodology of this study, based on a sequential explanatory design, allowed for a comprehensive characterization of the impact of the STEAM approach in teaching linear algebra. The combination of quantitative and qualitative data offered a rich and holistic perspective of the studied phenomenon, facilitating the identification of factors conducive to the improvement and effective implementation of the STEAM methodology in the educational context.

Mixed-methods sequential explanatory study. Participants: 29 engineering students (7 female, 22 male), selected through purposive sampling. Instruments: Standardized

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summative assessments: 16 multiple-choice questions on key course concepts ($\alpha = 0.85$, content validity by expert judgment). Open-ended assessments: 3 questions requiring demonstration of understanding and application of concepts, evaluated with a validated rubric ($\kappa = 0.81$). CEQ: 20 items on student experiences and perceptions ($\alpha = 0.92$, construct validity by confirmatory factor analysis). Data Analysis: Quantitative: Paired t-tests to compare pre- and post-intervention performance. Effect sizes (Cohen's d) and 95% confidence intervals. Qualitative: Thematic analysis of open-ended responses from CEQ, with independent coding by two researchers (agreement > 85%). Integration: Triangulation of quantitative and qualitative results for a more comprehensive understanding. Results: Significant improvement in academic performance: Increase in scores on standardized summative assessments (pre: $M = 65.8$, $SD = 14.2$; post: $M = 84.5$, $SD = 10.1$; $t(28) = 6.84$, $p < 0.001$, $d = 0.78$, 95% CI [0.42, 1.14]). High satisfaction with implemented strategies: Emergent themes from CEQ included "Increased engagement and motivation," "Better understanding of abstract concepts," and "Appreciation of applicability in engineering contexts."

Research phases

The study procedure was developed in three distinct phases:

Initial Quantitative Phase: in this phase, we assessed academic performance through a diagnostic evaluation, identifying strategies and challenges in the teaching and learning of linear algebra among engineering students. Standardized tests and summative assessments were employed to measure both performance and conceptual understanding of students in the linear algebra course. These quantitative data provided an objective insight into the impact of the pedagogical strategies implemented (8).

STEAM Implementation and Ongoing Assessment Phase: building on the insights from the initial phase, we designed and implemented a STEAM-based didactic sequence that meticulously integrated all five disciplines:

- Science: incorporated through physics and chemistry problems related to linear systems.
- Technology: leveraged via GeoGebra, interactive HTML5 videos, and matrix calculators.
- Engineering: highlighted through problems in structural analysis, circuit design, and data processing.
- Arts: integrated through creative visualizations of mathematical concepts, design of infographics explaining complex ideas, and analysis of symmetry and transformations in artistic works.
- Mathematics: formed the core, focusing on linear algebra principles.

Students engaged in various activities, such as creating digital art pieces using matrix transformations, analyzing geometry in architectural designs, and producing short explanatory videos on linear algebra concepts.

During this phase, we conducted ongoing assessments, including:

- Formative assessments integrated into learning activities (problem-solving sessions, group presentations of STEAM projects, digital portfolio submissions)
- A mid-term summative assessment to gauge progress
- The first application of the Course Active Assessment (CAA) survey to capture initial student perceptions of the STEAM approach

This combination of continuous evaluation and perception analysis allowed us to monitor student progress and adjust our teaching strategies in real-time, ensuring the effectiveness of the STEAM integration.

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Final Qualitative and Integration Phase: in this phase, we conducted a deeper analysis of the STEAM methodology's implementation. We explored students' perceptions and experiences regarding the integration of the STEAM approach through surveys and content analysis, using the Course Active Assessment (CAA) survey. This qualitative approach provided a deeper understanding of students' experiences with the teaching strategies, technological tools used, and their overall satisfaction with the course (10).

Finally, we integrated the quantitative and qualitative results through a triangulation process. Findings from both phases were compared and contrasted to identify convergent and divergent patterns (27). This triangulation approach strengthened the validity and reliability of the results, allowing for a more comprehensive and nuanced interpretation of the studied phenomenon (23). The combined results from all phases were used to propose evidence-based improvements, aiming to foster educational transformation in engineering disciplines by optimizing the teaching of linear algebra and promoting more meaningful and enduring learning experiences.

Population and sample

This study involved 29 civil engineering students enrolled in a linear algebra course at a private university in Barranquilla, Colombia. The participants comprised 7 females (24.1%) and 22 males (75.9%), reflecting the current gender distribution in the civil engineering program. All participants were in their second year of studies and had completed prerequisite mathematics courses. The sample was selected through convenience sampling, a method deemed appropriate when subject accessibility and availability are crucial factors for the research (28). Selection criteria included active enrollment in the linear algebra course during the study period and willingness to participate in all phases of the study, from quantitative data collection to qualitative activities. This approach ensured continuous and committed participation, essential for the validity and reliability of the results obtained.

Criteria for defining the sample were based on the active enrollment of students in the linear algebra course during the study period. Additionally, students' willingness to participate in all phases of the study, from quantitative data collection to qualitative activities, was considered. This approach ensured continuous and committed participation of the subjects, which is essential for the validity and reliability of the results obtained

Instruments for data collection

Data collection involved both quantitative and qualitative instruments. The quantitative instruments included:

A standardized summative assessment developed by linear algebra experts, consisting of 16 multiple-choice questions covering key course concepts. This assessment was administered at the beginning and end of the course to measure performance improvement. Its reliability and validity were established through peer review and pilot testing (8).
A series of open-ended summative assessments administered throughout the course. These required students to demonstrate their understanding of linear algebra concepts by solving problems and justifying their responses (16).

For qualitative data, we employed the Course Active Assessment (CAA) survey, an online feedback tool allowing students to express their opinions about the course, teaching strategies, and technological tools used. The CAA was administered at two key points: midway through the course implementation and at the end, to capture the evolution of students' perceptions (10).

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Results

Pilot test

In the first phase of the study, we administered a comprehensive diagnostic test to assess both the performance and conceptual understanding of students in linear algebra. This test, consisting of 16 items, also gathered data on students' perceptions of conventional teaching, recognition of difficulties, and performance in prerequisite knowledge. Analysis of these multifaceted results yielded a Cronbach's alpha reliability coefficient of 0.901, indicating high internal consistency of the instrument. Figure 1.

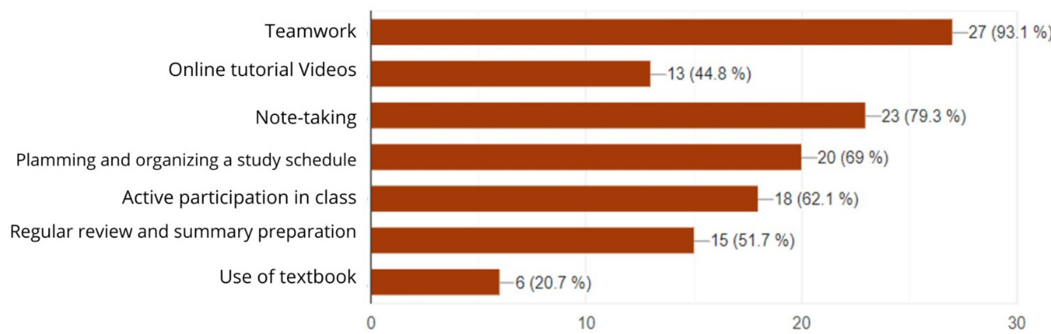

Figure 1. Students' perception of the diagnostic test regarding favorable strategies in their learning process.

First, the recognition of more favorable strategies and the availability of technological resources in students' learning processes are examined. Primarily, it is highlighted that 93.1% of students identify teamwork, and 79.3% note-taking as the most beneficial strategies for their learning. Teamwork allows them to address questions within a discussion context and share diverse perspectives, thereby promoting individual accountability through collaboration. Secondly, students recognize the importance of keeping track of class progress for future reviews. This facilitates reviewing algorithms, formulas, problem-solving processes, pattern identification, and other crucial study elements, supported by a 69% approval rate. A third relevant aspect is planning and organization, as shown in Figure 1 illustrating students' perceptions of favorable strategies in their learning processes. This not only reflects how they manage their own learning process but also the classroom dynamics organization by educators, which sometimes may not be clearly visible or communicated to students.

In the second part of the results, a correlational analysis of students' prior knowledge related to the prerequisites for the Linear Algebra course was conducted. The sample, comprising fewer than 29 observations, underwent a normality test using the Shapiro-Wilk test. The results of this test, with a significance value greater than 0.05, indicated that the data followed a normal distribution, allowing for the use of a parametric Pearson correlation test to explore relationships between the selected variables, suitable for this context.

Analysis conducted in the SPSS software (Table 1) revealed a Pearson correlation coefficient of 0.598 between the perception of the effects of traditional education and the demonstrated performance in prior knowledge, with this correlation being statistically significant. This suggests that increased student interest and motivation, along with organized teaching focused on future courses or applications in their field, correlate with better academic outcomes.

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Table 1. Result of parametric correlation test in SPSS

		Prior knowledge	Difficulties	Traditional education and its effects	Epistemological analysis of content
Prior knowledge	Pearson correlation	1	,164	,598**	,690**
	Sig. (two-tailed)		,395	,001	,000
	N	29	29	29	29

** The correlation is significant at the 0.01 level (two-tailed).

Furthermore, a strong and significant correlation of 0.690 was evidenced between the epistemological analysis of content and the prerequisite knowledge required for the Linear Algebra course. This highlights the importance of designing and implementing clear and understandable teaching processes in mathematical education courses, demonstrating to students the practical relevance of mathematical concepts in their daily lives and future careers, particularly in engineering.

The epistemological analysis of content was conducted using the methodology proposed by Sierpinska (2) for linear algebra. This method involves identifying and analyzing the fundamental concepts, their historical development, and their interconnections within the field of linear algebra. The analysis focused on systems of linear equations, examining students' understanding of key concepts such as variables, coefficients, and solution sets. The process included a review of historical problems that led to the development of linear systems, an examination of different representation systems (algebraic, geometric, and matrix), and an analysis of common misconceptions and difficulties associated with these concepts. This epistemological approach provided a robust framework for assessing students' prior knowledge and conceptual understanding, informing the design of the STEAM-based didactic sequences.

The pre-knowledge assessment (Figure 2) administered to the 29 students before starting the Linear Algebra course revealed an average performance below 50%, especially in competencies such as formulating and solving problems in mathematical contexts involving equation formulation and operationalization of algebraic expressions when analyzed by competencies. These findings underscore the urgent need to focus on these areas to promote a deeper understanding of algebraic principles and enhance the ability to solve mathematical problems more effectively.

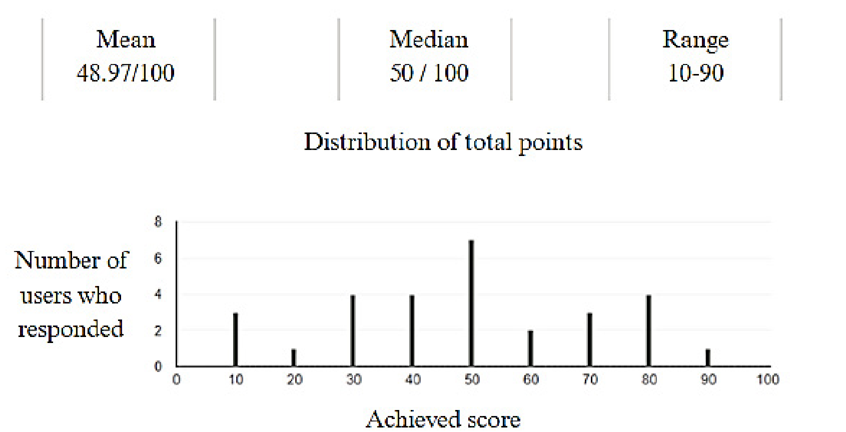

Figure 2. Previous knowledge diagnostic result

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In conclusion, the findings reveal a generally positive perception regarding the clarity and relevance of linear algebra content among engineering students. However, they identify specific areas for improvement, particularly concerning the practical application of knowledge and the impact of pedagogical methods on the development of critical thinking. The high availability of technological resources among students represents an advantage for implementing innovative educational approaches, though a renewed focus on strengthening the connection between academic theory and practical applicability is recommended to enhance the overall educational experience.

Implementation and evaluation of the proposal

In the qualitative phase of implementing the proposal, based on diagnostic results and a review of literature on effective strategies for teaching linear algebra, the team of instructors designed three didactic sequences focused on integrating the STEAM approach and utilizing technological tools. These sequences specifically targeted the second unit of the syllabus, focusing on teaching Systems of Linear Equations, which are crucial due to their wide applicability in engineering problems.

The didactic sequences were carefully designed to integrate all STEM disciplines. For instance, science concepts were incorporated through physics problems related to linear systems. Technology was seamlessly integrated via the use of GeoGebra and interactive HTML5 videos. Engineering applications were highlighted through problems in structural analysis and circuit design. Mathematical concepts formed the core of the sequences, with a focus on abstract linear algebra principles. Additionally, we incorporated artistic elements by having students create visual representations of mathematical concepts and design aesthetically pleasing infographics to explain complex ideas. This comprehensive approach ensured a true STEAM integration, enhancing student engagement and understanding.

For example, in one of the didactic sequences focused on systems of linear equations, students were presented with a civil engineering problem involving the design of a truss bridge. They used GeoGebra to visualize the structure and model the forces as a system of linear equations. The engineering application was highlighted through discussions on load distribution and structural stability. Students then used matrix calculators to solve the system, linking the mathematical solution to the physical implications for the bridge design. This approach integrated the STEAM elements: Science (physics of forces), Technology (software tools), Engineering (bridge design), Arts (visual representation and design aesthetics), and Mathematics (systems of linear equations).

The didactic sequences were conceived based on collaborative work and contextualization of mathematical concepts in realistic situations. Carefully selected resources such as GeoGebra, interactive HTML5 videos, and matrix calculators were chosen for their ability to visualize abstract concepts, encourage dynamic exploration, and facilitate the resolution of complex problems. Prior to implementation, teachers participated in an intensive 16-hour workshop spread over four weekly sessions. During this workshop, they became familiar with STEAM strategies, the use of selected technological tools, and best practices for integrating them into the classroom. They also reviewed the initial diagnostic results and made adjustments to the didactic sequences to address specific needs, such as including reviews of previous concepts and enhancing practical application in engineering.

The expert team that designed the didactic sequences consisted of five members: two mathematics professors with over 10 years of experience in teaching linear algebra, one civil engineering professor specializing in structural analysis, one educational technology expert, and one pedagogy expert with a focus on STEAM education. This diverse team ensured that the sequences were mathematically rigorous, relevant to civil engineering applications, technologically enhanced, and pedagogically sound.

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The implementation of the didactic sequences took place during weeks 6 to 10 of the Linear Algebra course, totaling 15 in-person hours spread over three weekly hours. Each sequence followed a consistent structure: activation of prior knowledge, collaborative exploration with technological tools, discussion and formalization of concepts, and application to contextualized problems.

In the first sequence, the concept of systems of linear equations was introduced through an engineering application problem in civil engineering. Students worked in pairs to graphically represent the problem using GeoGebra and discuss solutions. Subsequently, the instructor formalized the concepts and guided students in the algebraic resolution of the problem. The second sequence focused on methods for solving linear systems, exploring the Gaussian elimination method and Cramer's rule through interactive HTML5 videos with comprehension questions and immediate feedback. They then applied these methods to solve a concrete mixing problem in civil engineering. In the third sequence, the matrix representation of linear systems of equations and the use of the matrix calculator for their resolution were addressed. Students collaborated in groups to solve a traffic flow problem, modeling the system of equations and using the matrix calculator to find the solution.

At the conclusion of the three sequences, students underwent two summative assessments: a standardized test with multiple-choice questions (20% of the grade), as shown in Figure 3 depicting the results obtained in the second academic assessment, previously designed and validated by a team of expert instructors, and an open-ended test requiring justification of the procedures used (10% of the grade). During implementation, greater participation and commitment from students were observed compared to traditional classes. Teachers reported increased student interest in contextualized problems and appreciated the opportunity to explore concepts using interactive technological tools. However, challenges arose such as the need to support students less familiar with the software used and effective time management to cover all planned content.

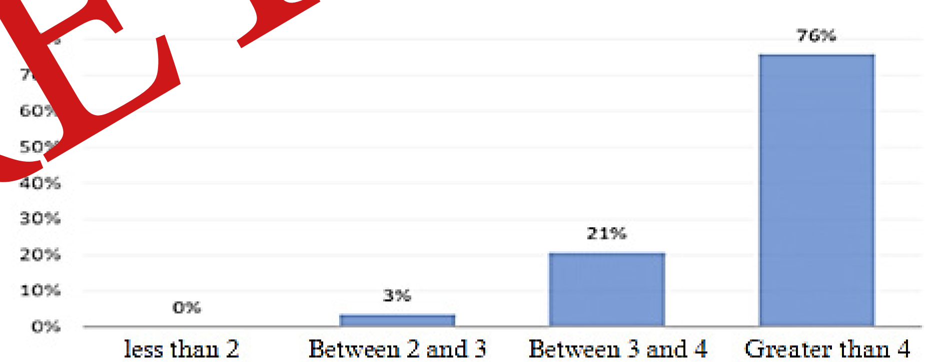

Figure 3. Summative assessment results at the end of the academic period

Note: The percentages of students in each of the four scales from 0 - 2, 2 - 3, 3 - 4, and 4 - 5.

To assess the effectiveness of the intervention, various data sources were employed, including summative assessments and the Course Active Assessment (CAA). The assessments demonstrated a significant improvement in student performance, with a high percentage achieving above satisfactory levels in both standardized tests and open-ended questions. Additionally, the CAA revealed high satisfaction among students with the implemented strategies, highlighting positive feedback on collaborative activities, use of technological tools, and the relevance of engineering problems addressed.

The CAA covered aspects such as the effectiveness of teaching strategies, usefulness of technological tools, relevance of addressed problems, and overall satisfaction with the course. Summative assessment results indicated a significant increase in student

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performance compared to previous semesters: 80% of students scored above satisfactory levels in the standardized test, while this percentage was 75% in the open-ended question test. Moreover, there was a reduction in the number of students receiving grades below the minimum required level.

The CAA tool proves valuable for teachers seeking to reflect on and improve their pedagogical practice, conducted in real-time during the completion of the second phase of the course, demonstrating teachers' capacity for self-critique and commitment to continuous improvement. This data collection allowed for a comprehensive and detailed insight into students' perception of the implemented educational strategy. Figure 4 presents the evaluation of the didactic strategies implemented in the Linear Algebra class, in terms of an organized, formalized procedure aimed at achieving a set goal.

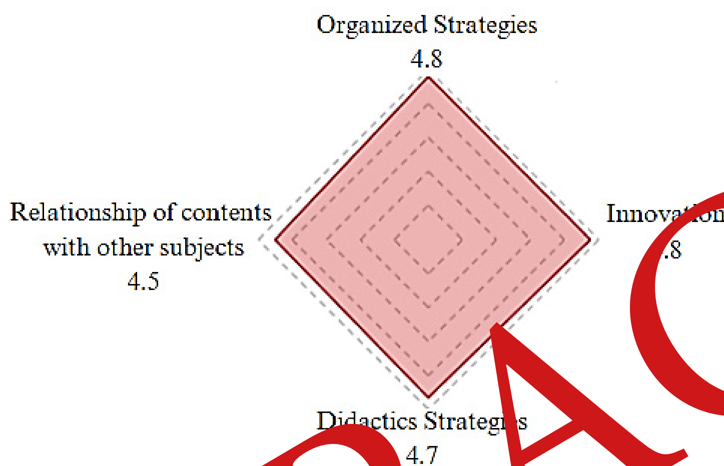

Figure 4. Students assessment of classroom actions related to organization, innovation, and implementation of Didactics strategies.

In summary, these results indicate that the integration of the STEAM approach and technological tools, alongside the adaptation of instructional sequences based on initial diagnostics, had a positive impact on the learning and motivation of engineering students in the Linear Algebra course. This combined approach of student-centered strategies, interactive resources utilization, and contextualization of concepts in real engineering problems appears to have significantly contributed to enhancing conceptual understanding and the ability to apply acquired knowledge.

Integration of Quantitative and Qualitative Data

To assess the effectiveness of the implemented educational intervention, multiple sources of data were employed to provide a comprehensive view of its impact on student learning. Quantitative evaluations revealed significant improvements in the academic performance of participating students. In standardized tests, 80% of students exceeded the satisfactory level, while in open-ended assessments, this percentage was 75%. These numerical results underscore the success of the applied educational strategies, validating the effectiveness of the designed instructional sequences and the integration of technological tools such as GeoGebra and matrix calculators.

On the other hand, qualitative data collected through the Course Experience Questionnaire (CEQ) complemented these quantitative findings by providing a more detailed perspective on students' learning experiences. The CEQ revealed high satisfaction among participants with the implemented strategies. Specifically, 85% of students highlighted those collaborative activities and the use of technological tools significantly contributed to a better understanding of mathematical concepts. Moreover, a notable 90% positively valued the contextualization of

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problems in engineering contexts, emphasizing the practical relevance of linear algebra in their academic and professional development. The Figure 5 shows the satisfaction level of the lass.

These combined results underscore the importance of evaluating both the quantitative and qualitative aspects of student learning. While numerical metrics objectively validate the improvement in academic performance and proficiency in key mathematical skills, students' qualitative perceptions provide a deep understanding of how educational strategies influenced their motivation, engagement, and conceptual understanding. This comprehensive approach not only supports the effectiveness of implemented pedagogical interventions but also informs future improvements in the teaching of linear algebra, aimed at promoting more meaningful and applicable learning within the context of engineering.

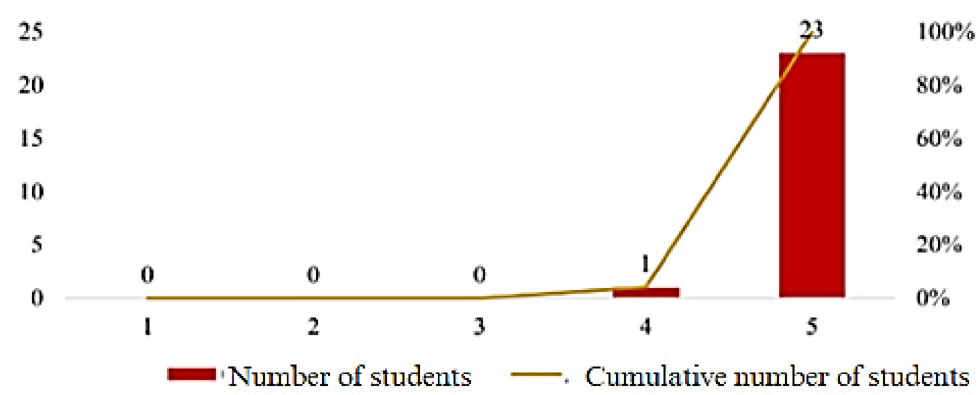

Figure 5. Institutional CAA. Student satisfaction level regarding the development of the class.

Discussion

To analyze and discuss the findings of this study and highlight their significance for mathematics education, as well as their contributions to higher education and the enhancement of professional preparation, it is crucial to consider how educational strategies based on technology and innovative pedagogical approaches can transform learning in university contexts. This mixed-methods study has provided substantial evidence supporting the effectiveness of integrating the STEAM (Science, Technology, Engineering, Arts, Mathematics) approach and advanced technological tools in the teaching of linear algebra for engineering students.

The quantitative and qualitative results highlight several key aspects. Firstly, the significant improvement in students' academic performance, as measured by standardized summative assessments and open-ended tests, underscores how the implementation of innovative pedagogical strategies can enhance conceptual understanding and practical application of mathematical knowledge (8-9). This finding is consistent with prior literature suggesting that integrating technology and active methodologies can improve learning quality in higher mathematics and related disciplines (10, 23).

Furthermore, positive feedback obtained through Course Experience Questionnaires (CEQ) indicates that students are not only satisfied with the implemented educational strategies but also value the use of technological tools such as GeoGebra and HTML5-based interactive videos to facilitate their learning (10, 23). This aspect is crucial as student motivation and satisfaction are determinant factors in academic success and persistence in STEAM disciplines.

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The personalized approach used in this study, which included an initial diagnostic assessment to tailor teaching strategies to individual student needs, also underscores the importance of considering prior knowledge and specific learning difficulties of each student (14, 16). This approach not only promotes autonomous and collaborative learning but also develops critical skills necessary for solving real-world problems in engineering, thus preparing students for future challenges in their professional careers.

The strategic integration of technological tools such as dynamic geometry software, interactive applets, and augmented reality not only enhances visualization and understanding of abstract mathematical concepts but also facilitates practical application of this knowledge in engineering contexts (8-9). This aspect is crucial given the increasing emphasis on training professionals who can use advanced technologies to solve complex problems in professional practice.

In terms of higher education, this study emphasizes the urgent need to establish instructional processes that link technology, autonomous learning, collaborative learning, and critical thinking in the teaching of mathematics and other STEAM disciplines. Researchers such as Creswell and Plano Clark (27) advocate for data triangulation and the integration of mixed methods approaches to gain a more comprehensive understanding of educational phenomena, thus supporting the validity and relevance of this study.

Despite promising results, it is crucial to acknowledge the study's limitations, such as the relatively small sample size and restriction to a specific educational context. Future research could expand this approach to other educational institutions and STEAM disciplines to assess its generalizability and replicability. Moreover, longitudinal studies could explore the long-term impact of these educational strategies on professional development and student success in their careers.

The adaptability of the STEAM strategies presented in this study warrants deeper consideration across diverse educational contexts. While our research focused on engineering students taking linear algebra, it's important to consider how these strategies could be modified for application at different levels and disciplines. For instance, in mathematics courses for first-year students, the STEAM approach could be simplified to introduce basic linear algebra concepts through less complex interdisciplinary projects, such as analyzing simple structures in civil engineering or basic circuits in electrical engineering. At more advanced levels, such as in graduate courses, STEAM strategies could be expanded to address more complex problems, integrating advanced simulations and big data analysis.

In related disciplines like physics or computer science, STEAM strategies for teaching linear algebra could be adapted by emphasizing field-specific applications. For example, in physics, linear transformations could be explored in the context of quantum mechanics, while in computer science, emphasis could be placed on applications of linear algebra in computer graphics or machine learning. These adaptations would not only maintain the essence of the STEAM approach but also ensure the relevance and specificity necessary for each discipline.

It is important to acknowledge the limitations of our study and how these might affect the generalization of results. The relatively small sample size (n=29) and focus on a single institution limit the direct generalization of our findings. Additionally, the 15-hour implementation period may not be sufficient to fully evaluate the long-term effects of STEAM strategies. Future research should consider longitudinal studies and larger, more diverse samples to validate and expand our results. It would also be valuable to explore how cultural differences and diverse educational systems might influence the effectiveness of these strategies in a global context.

In terms of scalability, the STEAM approach shows promise for application in more advanced engineering courses beyond basic mathematics. For example, in fluid dynamics, students could use computational fluid dynamics (CFD) software to visualize complex

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flow patterns, integrating principles from physics, computer science, and advanced mathematics. In control systems engineering, the STEAM approach could involve designing and simulating control systems for renewable energy plants, incorporating elements of electrical engineering, environmental science, and advanced algebra. These extensions of the STEAM approach to higher-level courses could foster a more integrated and application-oriented understanding of complex engineering concepts, potentially enhancing students' preparedness for real-world engineering challenges.

In conclusion, this study provides a solid foundation for improving the quality of higher education in mathematics and related disciplines, highlighting how the effective integration of technology and innovative pedagogical approaches can strengthen learning, student motivation, and professional preparation. These findings underscore the importance of continuing to refine and adapt instructional processes that promote meaningful and applicable learning, thereby preparing future professionals to tackle emerging challenges in their respective fields (14, 23).

Conclusions

This study provides empirical evidence for the effectiveness of integrating the STEAM approach and technological tools in teaching linear algebra to engineering students. The results suggest that these strategies can significantly enhance students' conceptual understanding, academic performance, and satisfaction. These findings have practical implications for mathematics education in higher education, highlighting the importance of adopting interdisciplinary approaches and leveraging technology to promote deeper and more applied learning. Educators and institutions are encouraged to consider implementing these strategies to improve the quality of mathematics education in engineering programs.

The integration of technology, such as GeoGebra and HTML5-based interactive videos, has proven crucial in facilitating deeper and more applicable learning of mathematics. These tools not only strengthen theoretical understanding but also equip students with critical and analytical skills essential for their future careers in engineering.

In the context of higher education, these findings emphasize the importance of continuously adapting pedagogical methods to meet contemporary educational demands. Educational quality is enriched when technologies promoting autonomous, collaborative, and critical learning are incorporated, essential for shaping competent professionals prepared to tackle global challenges.

In summary, this study not only validates the effectiveness of integrating advanced technology in mathematics education but also highlights its fundamental contribution to enhancing educational quality in higher education institutions. The conclusions presented here provide a solid foundation for continued innovation and improvement in educational processes, ensuring comprehensive and competitive preparation of students in the fields of science and engineering.

In conclusion, the findings of this study offer promising perspectives for the application and adaptation of the STEAM approach in various educational contexts within higher engineering education. The integration of STEAM strategies and technological tools in teaching linear algebra is not only applicable to this specific course but also presents an adaptable model for other fundamental mathematics courses in engineering. For example, the principles of contextualization and visualization used in this study could be extended to courses in calculus, differential equations, or numerical methods, adapting technological tools and interdisciplinary projects to the specific objectives of each course. Furthermore, the focus on active learning and contextualized problem-solving could be applied in more advanced engineering courses, fostering a deeper understanding of how fundamental mathematical concepts apply in real-world situations. Future studies could explore the

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implementation of these strategies in different engineering institutions and programs, evaluating their effectiveness in diverse cultural and educational environments, thus contributing to a broader understanding of how to optimize mathematics education in engineering at a global level.

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CRediT authorship contribution statement

Robinson Junior Conde Carmona: conceptualization-ideas, data curation, formal analysis, funding acquisition, research, methodology, project management, resources, software, supervision, validation, visualization-preparation, writing-original draft-preparation, writing-revision and editing-preparation. Stiven Díaz: conceptualization-ideas, data curation, formal analysis, funding acquisition, research, methodology, project management, resources, software, supervision, validation, visualization-preparation, writing-draft original-preparation, writing-revision and editing-preparation. José Luis Gómez Muñoz: conceptualization-ideas, data curation, formal analysis, funding acquisition, research, methodology, resources, software, supervision, validation, visualization-preparation, draft-writing, original draft-preparation, writing-revision and editing-preparation. Maura Alejandra Jiménez Consuegra: conceptualization-ideas, data curation, formal analysis, funding acquisition, research, methodology, resources, software, supervision, validation, visualization-preparation, writing-original draft-preparation, writing-revision and editing-preparation. Yina Ospino Buelvas: conceptualization-ideas, data curation, formal analysis, funding acquisition, research, methodology, resources, software, supervision, validation, visualization-preparation, draft-writing, draft-original-preparation, writing-revision and editing-preparation.

Conflict of interest

The authors no declare.

Ethical implications

The authors do not have any type of ethical involvement that should be declared in the writing and publication of this article.

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