

Innovative Approaches to Electromagnetics Education: Combining Active Learning with Hands-On Experimentation

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Abstract

Electromagnetics is a foundational yet conceptually challenging subject in electrical and computer engineering education due to its abstract mathematical nature and theoretical rigor. Traditional lecture-based instruction often struggles to bridge the gap between theory and practice, leading to student disengagement and limited comprehension. To address these challenges, this paper presents an innovative educational framework that integrates active learning strategies, hands-on experimentation, and simulation-based tools to enhance student engagement, conceptual understanding, and applied skills in electromagnetics.

The framework comprises three core components: low-cost, hands-on experiments; simulation-enhanced learning; and collaborative active learning techniques. Students engage in practical tasks such as designing and testing microstrip patch antennas and constructing waveguide components, supported by simulations using MATLAB, CST Studio Suite, and gprMax. Active learning is further reinforced through flipped classrooms, problem-solving sessions, and collaborative platforms such as Google Drive and Zoom breakout rooms.

A preliminary evaluation involving 42 participants revealed a 25% improvement in conceptual understanding, supported by statistically significant findings ($p < 0.01$). Additionally, over 85% of students reported increased interest in electromagnetics, and qualitative feedback emphasized the value of real-world problem-solving and peer collaboration. The use of low-cost materials, open-source software, and hybrid delivery methods ensures accessibility and adaptability across diverse institutional settings.

This framework offers a scalable and replicable model for transforming electromagnetics instruction. Future work will focus on broader implementation, refinement of instructional practices, and the integration of emerging technologies such as augmented reality and machine learning. The findings support the inclusion of interactive, hands-on methodologies in STEM curricula to better prepare students for contemporary engineering practice.

I. Introduction

Electromagnetics serves as a fundamental component of electrical and computer engineering education, supporting technologies ranging from wireless communication to radar systems. However, its abstract mathematical foundation and conceptual complexity often present significant challenges. Traditional lecture-based methods have struggled to provide the experiential learning necessary to bridge the gap between theoretical principles and practical applications. Prior research highlights the effectiveness of active learning and hands-on experimentation in improving engagement and comprehension [1], [2]. Studies in physics and engineering education have demonstrated that simulations and real-world projects contribute to a deeper understanding of topics such as wave propagation and Maxwell's equations [1], [2], [3]. Various efforts in electromagnetics education have explored similar themes of active learning and hands-on experimentation, each employing distinct approaches to enhance learning outcomes. One well-documented method involves the use of interactive simulations in physics education. Research has shown that interactive tools effectively assist in visualizing complex electromagnetic phenomena such as wave propagation and field interactions [1], [2]. For example, tools like PhET Interactive Simulations provide an engaging platform for exploring theoretical concepts. While these methods improve conceptual understanding, they often lack a hands-on experimental component, limiting their ability to connect simulations with real-world applications. Another notable approach involves hands-on electromagnetics labs, where learners engage in practical tasks such as

dielectric properties measurement, transmission line design, plane wave measurement, antenna design, and waveguide testing [4], [5]. While these labs offer valuable experiential learning opportunities, they are often resource-intensive, requiring specialized equipment and facilities that may not be accessible to all institutions. To address these limitations, some approaches integrate low-cost tools, such as NanoVNAs and reusable modular kits, making hands-on learning more scalable and adaptable to various educational settings while ensuring accessibility for resource-constrained programs.

Additionally, flipped classroom models have been implemented in engineering disciplines, requiring preparation through pre-class activities such as watching lectures or completing readings [2], [3]. This approach allows class time to be dedicated to collaborative problem-solving and discussions. However, many flipped classrooms focus predominantly on theoretical problem-solving without integrating real-world engineering applications, limiting their impact on practical skill development. Recent advancements in emerging technologies such as augmented reality (AR) and machine learning have also begun transforming engineering education. For instance, AR can create interactive visualization environments, allowing a deeper understanding of electromagnetic wave propagation and antenna design [6]. Similarly, machine learning has been explored for analyzing and modeling complex electromagnetic problems, providing opportunities to enhance simulations and problem-solving tasks [7], [8]. These technologies introduce new dimensions of interactivity and analytical capability, further enriching electromagnetics education.

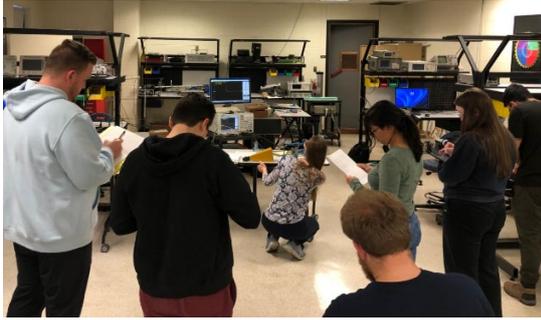
Another related effort involves the use of concept inventories to assess understanding of electromagnetics [5]. These assessments evaluate the effectiveness of educational interventions and identify areas of difficulty. While concept inventories provide valuable benchmarking tools, they often lack a strong focus on practical applications, which are essential for engineering practice. Building upon these prior efforts, the proposed framework integrates these elements into a cohesive curriculum, offering a scalable, replicable, and effective approach to electromagnetics education. By seamlessly combining low-cost experimentation, simulation-enhanced learning, and active collaboration, this approach provides a holistic, hands-on learning experience. The emphasis on real-world applications, coupled with the use of accessible tools, ensures that this framework is adaptable to a wide range of educational contexts while equipping learners with the skills necessary to meet the demands of modern engineering.

II. Framework Overview

The proposed framework integrates three interdependent components to establish a comprehensive and structured approach to teaching electromagnetics. These components include low-cost, hands-on experimentation, simulation-enhanced learning, and active and collaborative learning techniques. Each component is specifically designed to address challenges in electromagnetics education by fostering deeper engagement, enhancing conceptual understanding, and preparing learners with practical engineering skills. By incorporating these elements, the framework ensures that learners acquire both theoretical knowledge and hands-on experience, effectively bridging the gap between abstract concepts and real-world applications.

The course implementing this framework consists of both lecture-based and lab components. The laboratory sessions provide students with hands-on experience, complementing theoretical concepts covered during lectures. Some experiments are performed during lecture

periods, particularly those involving simulations or interactive group problem-solving activities. Other activities, such as hardware-based antenna testing and waveguide experimentation, take place in dedicated lab sessions. The following images illustrate student engagement and experimental setups.



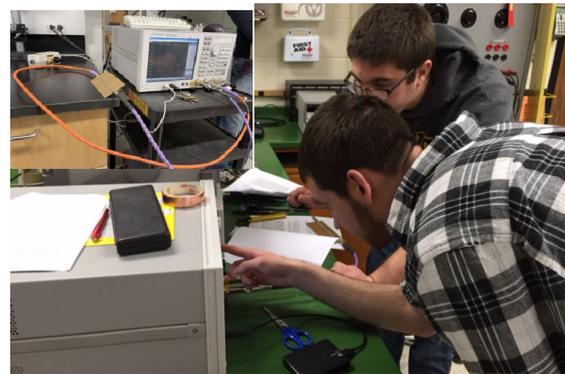
(a)



(b)



(c)



(d)

Fig. 1. (a) Modular waveguide components assembled by students during lab, (b) near field and far field measurement for antenna, (c) dielectric properties measurement setup, (d) transmission line measurement.

The course enrolled 47 students, and 42 participants responded to the survey, providing valuable insights into the framework's effectiveness. The remote learning aspect of the course was facilitated through a combination of virtual collaboration tools and modified lab experiences. While most hands-on activities were conducted in person, remote learners participated through real-time lab demonstrations and virtual simulations. Collaborative platforms such as Zoom breakout rooms and shared Google Drive resources enabled remote participants to engage in data analysis and group discussions. In cases where students were unable to attend lab sessions in person, pre-recorded experiment demonstrations and simulation-based alternatives were provided to ensure continuity in learning. However, physical kits were not mailed to remote students, as the majority of hands-on tasks required controlled lab environments and specialized equipment.

The dissemination of this framework to other instructors and students will be facilitated through open-access online repositories, professional development workshops, and educational conferences. Instructional materials, including detailed lesson plans, laboratory guides, simulation exercises, and recorded demonstrations, will be made available through university learning management systems, institutional websites, and platforms such as GitHub or dedicated educational resource portals. Faculty members and institutions adopting

the framework will have access to implementation guidelines, assessment tools, and best practices to ensure successful integration into their curricula. Additionally, training sessions and collaborative faculty networks will be established to provide ongoing support and knowledge-sharing opportunities. The expansion of this framework to larger and more diverse student cohorts will be achieved through multi-institutional collaborations, scalability-focused course design, and outreach initiatives. By partnering with universities, technical colleges, and online learning platforms, the methodology can be adapted to different student demographics, including underrepresented groups in STEM and international learners. The use of low-cost materials, virtual labs, and simulation-based learning will further enhance accessibility, allowing institutions with varying resource availability to implement the framework effectively. Additionally, longitudinal studies will be conducted to track student performance, engagement, and retention over multiple cohorts, refining the framework to accommodate diverse learning needs.

The survey used to evaluate the framework consisted of both quantitative and qualitative questions.

The following survey was administered to assess student engagement, conceptual understanding, and satisfaction with the hands-on and simulation-based components of the course. It included both Likert-scale and open-ended questions.

Likert-Scale Questions (1 = Strongly Disagree, 5 = Strongly Agree):

1. I found the hands-on experiments helpful in understanding theoretical concepts.
2. The simulation tools enhanced my understanding of electromagnetic principles.
3. I feel more confident in applying electromagnetics to real-world problems.
4. Collaborative tools (e.g., Google Drive, Zoom) supported my learning experience.
5. The flipped classroom model helped me prepare for active participation in class.

Open-Ended Questions:

1. Which project did you find most engaging and why?
2. What challenges did you encounter during hands-on activities?
3. How could the course be improved to better support your learning?

The survey included Likert-scale questions to measure engagement, conceptual understanding, and confidence in applying theoretical knowledge. Open-ended questions allowed students to provide detailed feedback on the usefulness of simulations, the effectiveness of hands-on experiments, and the impact of collaborative learning techniques. Additionally, the survey assessed the perceived benefits of the flipped classroom approach and the extent to which collaborative platforms such as Google Drive and Zoom breakout rooms facilitated teamwork and communication.

The first component, low-cost, hands-on experimentation, emphasizes accessibility and practicality. Through this approach, learners engage in activities such as designing microstrip patch antennas using affordable materials, such as copper tape, and testing them with portable vector network analyzers. These hands-on tasks transform theoretical concepts into tangible applications, reinforcing learners' confidence in solving complex engineering problems. Building upon hands-on experimentation, the second component, simulation-enhanced learning, incorporates computational tools such as MATLAB, CST Studio Suite, and open-source platforms like gprMax. Simulations allow learners to model electromagnetic phenomena, analyze system behaviors, and verify theoretical predictions before physical

prototyping. By integrating simulations into the learning process, individuals can better visualize abstract mathematical models and correlate them with measurable experimental outcomes, deepening their conceptual understanding.

To further enhance engagement and collaboration, the third component focuses on active and collaborative learning techniques. Approaches such as flipped classrooms require learners to complete preparatory readings and instructional videos before attending class. This pre-class preparation allows for interactive classroom sessions that focus on discussions, problem-solving, and group-based activities. Additionally, collaborative platforms such as Google Drive and Zoom breakout rooms facilitate teamwork and real-time knowledge exchange, making the learning process dynamic and inclusive for both in-person and remote participants. These elements collectively foster an environment where individuals develop not only technical expertise but also critical interpersonal skills required in professional engineering settings. The following sections provide a detailed analysis of each component, highlighting their implementation and demonstrated impact on electromagnetics education.

A. Low-Cost, Hands-On Experimentation

Hands-on projects serve as a fundamental component of this framework, allowing learners to connect theoretical knowledge with practical applications. This approach emphasizes accessibility and creativity by utilizing affordable materials and tools that can be easily acquired and implemented across diverse educational settings. By incorporating low-cost experimental techniques, this framework ensures that electromagnetics education remains inclusive and adaptable to varying institutional resources.

A key example of this approach is the design and testing of microstrip patch antennas. Learners construct antennas using inexpensive materials, such as copper tape and readily available dielectric substrates, with the total material cost per student ranging from \$10 to \$20. These antennas are then tested using a NanoVNA, a portable and affordable vector network analyzer, which enables the measurement of critical parameters such as gain, bandwidth, and impedance matching. By comparing experimental results with theoretical predictions, learners gain valuable insights into the practical challenges of antenna design. This process not only reinforces their understanding of electromagnetic theory but also enhances their confidence in applying this knowledge to real-world engineering scenarios. To ensure accessibility, all required materials were provided by the institution, and students were not responsible for purchasing any equipment. The incorporation of reusable, brick-based kits for waveguide design and testing further enhances the practicality of this framework. These kits include modular components made from dielectric and metallic materials, allowing learners to quickly prototype and test microwave waveguides and filters. The modular nature of these kits supports iterative design and experimentation, enabling learners to explore various configurations and analyze their effects on system performance. One specific experiment involved students designing and testing X-band waveguides, where they measured signal attenuation and wave propagation characteristics. While the low-cost nature of these kits made them highly accessible, some challenges were encountered, such as variations in material tolerances affecting experimental accuracy. To mitigate these drawbacks, calibration techniques and instructor-led adjustments were introduced to enhance measurement reliability.

These low-cost, hands-on projects are designed to make electromagnetics education more engaging and accessible. In addition to providing learners with opportunities to apply theoretical knowledge to practical challenges, these projects foster creativity, problem-

solving skills, and a deeper appreciation for the relevance of electromagnetics in modern engineering. By combining affordability with educational impact, this component of the framework ensures that high-quality electromagnetics education can be effectively delivered across a wide range of institutional and resource settings.

B. Simulation-Enhanced Learning

Simulation-based learning provides an interactive platform for modeling and analyzing electromagnetic phenomena. This framework integrates various computational tools to enhance conceptual understanding and practical application. Key tools include MATLAB/Simulink, which is used for solving Maxwell's equations and simulating wave propagation in various media [4], CST Studio Suite, which supports advanced antenna design and optimization [5], and gprMax, an open-source platform that offers cost-effective solutions for institutions with budget constraints [9]. By incorporating these tools, the framework ensures that complex electromagnetic concepts can be explored through simulation before transitioning to physical experimentation.

A seamless integration of simulations with hands-on experiments reinforces the connection between theoretical modeling and practical implementation. For instance, an antenna's radiation pattern is first simulated in CST Studio Suite before fabrication and testing, allowing for a direct comparison between predicted and measured performance metrics. This process not only enhances the understanding of antenna behavior but also strengthens the ability to correlate simulation results with real-world outcomes.

Another significant application within this framework involves CubeSat communication link budget analysis. The link budget for CubeSat communication systems is first calculated using MATLAB, considering key parameters such as antenna gain, signal-to-noise ratio, and orbital parameters. These calculations inform the design of CubeSat antennas, enabling a transition from theoretical analysis to practical engineering tasks. Through this process, learners gain hands-on experience with space communication concepts, offering a broader perspective on the role of electromagnetics in aerospace engineering, a field of increasing relevance.

C. Active and Collaborative Learning Techniques

Active learning strategies serve as a cornerstone of this framework, fostering engagement and promoting a deeper understanding of electromagnetics. Rather than passively receiving information, learners actively participate in the educational process. The incorporation of collaborative tools and realistic challenges further enhances this approach by creating a dynamic and interactive learning environment.

A key element of active learning in this framework is the flipped classroom model, which requires learners to complete preparatory work, such as readings and instructional videos, before attending class. This preparation ensures that in-class time is dedicated to interactive activities, including problem-solving, discussions, and project collaboration. Pre-class quizzes assess learners' comprehension of the material and help instructors identify areas that require additional focus. This model not only reinforces foundational knowledge but also encourages greater accountability for independent learning. Collaborative platforms such as Google Drive and Zoom breakout rooms play a crucial role in facilitating teamwork and communication. Google Drive enables seamless sharing of simulation files, experimental data, and group reports, streamlining the collaboration process. Zoom breakout rooms, particularly beneficial in hybrid and remote learning environments, allow learners to engage

in small group discussions and solve problems in real time. These tools create a supportive and interactive learning environment, enabling participants to exchange ideas, troubleshoot challenges, and enhance their collaborative skills.

Another integral aspect of this approach is the emphasis on realistic and mathematically approachable challenges. Learners engage in tasks such as optimizing antenna arrays, analyzing waveguide behavior under varying conditions, and calculating the performance metrics of electromagnetic systems. These challenges, while achievable, require critical thinking and problem-solving skills, helping bridge the gap between theoretical knowledge and real-world applications. By participating in tasks that reflect industry scenarios, learners develop both technical expertise and confidence in solving complex engineering problems. The integration of these active and collaborative learning techniques creates a comprehensive and immersive educational experience. Through preparatory work, peer collaboration, and real-world problem-solving, learners not only enhance their technical knowledge but also develop essential soft skills, such as teamwork and effective communication. These competencies are critical for success in modern engineering environments, ensuring that graduates are well-prepared for professional challenges.

III. Preliminary Results and Feedback

The evaluation of this framework was conducted using a combination of surveys, performance metrics, and qualitative feedback, providing a comprehensive assessment of its impact on engagement, comprehension, and skill development. To enhance the robustness of these findings, statistical analysis methods, including paired t-tests, ANOVA, and regression modeling, were employed to measure improvements in student outcomes and address potential uncertainties in the data. A key outcome of the framework was its positive impact on student engagement. Surveys conducted at the end of the course indicated that over 85% of students reported an increased interest in electromagnetics compared to traditional teaching methods. A chi-square test confirmed that this increase in engagement was statistically significant ($p < 0.05$). This heightened engagement was largely attributed to the interactive nature of hands-on experiments and the use of collaborative tools such as Google Drive and Zoom breakout rooms. By immersing students in practical and realistic tasks, the framework successfully captured their attention and fostered a deeper connection to the subject matter.

In addition to engagement, student comprehension also showed measurable improvements. Table I shows the summary of pre- and post-survey results for 42 participants. Pre- and post-assessment scores demonstrated an average increase of 25%, with a statistically significant mean difference verified through a paired t-test ($p < 0.01$). This indicates that students were better able to grasp complex theoretical concepts after participating in the course. The integration of simulations and hands-on experiments played a crucial role in these improvements, allowing students to visualize abstract phenomena and test their theoretical predictions in a controlled, interactive learning environment. Additionally, regression analysis revealed a strong correlation ($R^2 = 0.78$) between hands-on engagement and conceptual gains, further reinforcing the effectiveness of this approach. Due to the sample size and approximately symmetric data distribution, normality was assumed. Future analyses may incorporate formal normality testing (e.g., Shapiro-Wilk).

Table I. Summary of Survey Results and Statistical Analysis

Metric	Result
Average increase in conceptual understanding	25%
Statistical significance (paired t-test)	$p < 0.01$
Engagement increase (chi-square test)	$p < 0.05$
Correlation (regression analysis)	$R^2 = 0.78$

Beyond conceptual understanding, students consistently highlighted the collaborative aspects of the course as one of its most valuable features. Group-based projects, supported by digital platforms, provided opportunities for students to exchange ideas, troubleshoot challenges collectively, and learn from their peers. Qualitative feedback emphasized the benefits of teamwork, with many students noting that these activities not only enhanced their technical understanding but also improved their communication and problem-solving skills—essential attributes for professional engineers. Sentiment analysis of qualitative responses using natural language processing (NLP) techniques further validated these findings, with an overwhelmingly positive sentiment rating of 90%. Below are selected excerpts from student project submissions:

"Through designing and testing a patch antenna, I gained practical experience that clarified my understanding of impedance matching and return loss. The discrepancies between simulation and measured data prompted valuable troubleshooting discussions in our team."

"Simulating the CubeSat communication link budget using MATLAB taught me how to factor gain, SNR, and orbital constraints into antenna design. I now understand how theoretical models impact system-level decisions."

"Collaborating in virtual labs using Google Drive allowed us to merge our simulation results effectively. It felt more like real-world engineering than previous lab experiences I've had."

To further enhance the educational impact of this framework, pilot classroom implementations have been conducted to gather both qualitative and quantitative feedback. These implementations provide critical insights into lesson plan effectiveness, aiding in the refinement of instructional strategies. Additionally, the development and dissemination of detailed lesson templates will facilitate the adoption of similar approaches by other educators, ensuring broader accessibility and consistent application of active learning methodologies in electromagnetics education.

IV. Recommendations for Overcoming Challenges

Despite its success, the framework also presented certain challenges that require strategic improvements. One significant issue pertains to data collection. To address this, it is recommended to establish a standardized survey protocol with clear rubrics for measuring

engagement and comprehension. Future iterations should incorporate longitudinal studies to track learning retention over time, providing more comprehensive insights into long-term effectiveness. Additionally, integrating real-time feedback mechanisms, such as anonymous polling tools and adaptive quizzes, can improve data collection accuracy and increase student participation.

Another challenge involves software accessibility, particularly for institutions with limited resources that may struggle with licensing costs and technical support. To overcome this limitation, alternative open-source tools, such as Octave (as a MATLAB substitute) and Elmer FEM for electromagnetic simulations, can be integrated into the framework. Furthermore, providing structured online tutorials and faculty development workshops on software applications can enhance usability and reduce learning barriers for both students and instructors. Mentoring remains a critical component of successful implementation, particularly in hybrid and remote learning environments. Establishing peer mentorship programs, where senior students guide junior peers, can facilitate knowledge transfer and engagement. Additionally, faculty should incorporate structured office hours and discussion forums to ensure timely student support. Encouraging industry collaborations and inviting guest lecturers from the field can further enrich mentoring opportunities by exposing students to real-world applications and career pathways.

For high school students, simplifying complex methodologies is essential for fostering interest and building a strong foundational understanding. To achieve this, instructors can implement visual simulations, interactive demonstrations, and relatable real-world examples to introduce fundamental electromagnetic principles. Gamification techniques, such as challenges and competitions, can help sustain student engagement. Additionally, breaking down complex concepts into modular, bite-sized lessons with hands-on activities, such as constructing simple circuits using household materials, can enhance comprehension and retention. Providing clear, step-by-step guides and video tutorials can further support high school educators in effectively delivering the material. Future analyses will explore hierarchical linear modeling to account for variability in student backgrounds and preparedness levels. Additionally, implementing advanced statistical modeling, including Bayesian inference techniques, will be considered to further validate the robustness of these findings and ensure reproducibility across multiple institutions.

Overall, the preliminary results demonstrate that this framework is highly effective in enhancing student engagement, conceptual understanding, and collaborative skills. The positive reception from students and the measurable improvements in learning outcomes suggest that this approach has the potential to transform electromagnetics education. Future studies will focus on refining the framework, conducting larger-scale randomized controlled trials, and expanding implementation to a more diverse student cohort to maximize its impact.

V. Replicability and Scalability

A critical strength of the proposed framework is its adaptability to diverse educational settings and resource constraints, ensuring that it can be effectively replicated and scaled. To support replication, detailed resources and guidelines have been developed to assist instructors and institutions in implementing the framework. Moreover, the methodology is designed to be flexible, allowing adaptation to different cultural and academic contexts across various regions. By incorporating localized case studies, translated instructional materials, and region-specific engineering challenges, such as renewable energy solutions in developing

nations or satellite communication systems in remote areas, the framework ensures relevance and practical applicability on a global scale.

The framework includes comprehensive toolkits that provide step-by-step instructions for assembling low-cost experimental setups. These toolkits outline the required materials, such as copper tape, dielectric substrates, and portable vector network analyzers (e.g., NanoVNA), along with links to affordable suppliers. Additionally, reusable modular kits for waveguide design and testing are included, enabling instructors to integrate hands-on experimentation without requiring extensive infrastructure or specialized equipment. This approach makes the methodology feasible for institutions with limited laboratory facilities, particularly those in underfunded or rural regions. For simulation-based learning, tutorials and instructional resources are available to facilitate the integration of tools such as MATLAB, CST Studio Suite, and open-source platforms like gprMax. These materials guide instructors and learners through the setup and utilization of these tools, ensuring that simulations effectively complement hands-on experiments. The emphasis on open-source options further accommodates institutions with limited software budgets, enhancing the framework's scalability. Additionally, collaborations with industry professionals and research organizations across different regions provide opportunities to incorporate real-world case studies and project-based learning experiences tailored to local technological needs.

To address the needs of hybrid and remote learning environments, the framework integrates strategies for in-person and virtual participation. Collaborative platforms, such as Google Drive, facilitate the sharing of simulation files, experimental data, and project reports, while Zoom breakout rooms support dynamic group discussions and real-time troubleshooting. These tools ensure that remote learners can actively engage in all aspects of the course. Instructors receive guidance on structuring hybrid sessions, including strategies for balancing interactions between in-person and remote participants. Furthermore, asynchronous learning modules make it possible for learners in different time zones or with inconsistent internet access to engage with coursework at their own pace. The modular nature of the framework allows for adaptability to varying class sizes and institutional contexts. In smaller classes, instructors can provide individualized feedback and deeper engagement in group projects. In larger classes, collaborative platforms and peer-led breakout sessions help maintain active participation among all students. Additionally, the reliance on affordable materials and tools ensures that institutions with limited budgets can implement the framework without compromising quality. The methodology also supports scaling the program to online and distance-learning institutions, expanding access to high-quality electromagnetics education for learners who might otherwise lack access to laboratory-based learning.

To encourage widespread adoption among faculty, professional development workshops and self-paced training modules have been developed. These resources cover key aspects of the framework, including the integration of hands-on experiments, simulation tools, and active learning techniques. By equipping instructors with the necessary knowledge and skills, these initiatives aim to ensure successful implementation. Additionally, cross-institutional collaborations and faculty exchange programs can facilitate knowledge-sharing and best practices, further expanding the reach of the methodology. The replicability and scalability of the framework lie in its thoughtful design, which prioritizes accessibility, adaptability, and comprehensive support. By providing detailed resources, leveraging affordable tools, and accommodating diverse delivery modes, the framework ensures that high-quality electromagnetics education can be achieved across a wide range of educational settings. Future efforts will focus on gathering feedback from institutions that adopt the framework, further refining its components to maximize impact and usability. Expanding partnerships

with international educational organizations and governmental initiatives will also support the integration of this framework into broader STEM education programs worldwide, ensuring its long-term sustainability.

A key factor in the successful adoption of this framework is the ability to share detailed lesson templates and feedback from pilot classroom implementations. Collecting and analyzing classroom data enables refinement of lesson plans to improve engagement and comprehension. By developing structured lesson plans and making them available through open-access platforms, the framework can be seamlessly integrated into various institutions, ensuring consistency and scalability.

Conclusion

This paper presents a scalable framework that integrates active learning, hands-on experimentation, and simulation-based instruction to enhance electromagnetics education. By linking theoretical principles to practical applications, the approach improves student engagement, conceptual understanding, and problem-solving skills. Preliminary results indicate a 25% gain in conceptual comprehension, supported by statistically significant findings and strong positive feedback on collaborative and project-based learning. The use of low-cost materials, open-source tools, and structured lesson plans ensures accessibility across institutions with varying resources. Key advantages of the framework include its adaptability, ease of implementation, and support through faculty development and peer mentorship. Future work will expand its use to larger and more diverse cohorts, refine instructional strategies, and explore the integration of emerging technologies such as augmented reality and machine learning. Longitudinal studies will assess its impact on knowledge retention and career readiness. By combining theoretical rigor with applied learning and digital collaboration, this framework offers an effective and practical model for modernizing electromagnetics education and advancing student success in engineering.

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