

A Data-Driven Analysis of Electromagnetism Simulation Platforms: Thematic Coverage, Accessibility, and Structural Patterns

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ABSTRACT

Digital simulations have become a central resource in electromagnetics education due to their capacity to support the visualization and exploration of abstract phenomena. Despite their widespread use, systematic analyses examining their thematic coverage, technical characteristics, and accessibility remain limited. This study aims to provide a comprehensive overview of the current landscape of electromagnetism simulation platforms, identifying patterns in content coverage, technological design, and accessibility features. A mixed-methods, data-driven approach was applied to a dataset of 43 simulation platforms. The analysis combined educational data mining, natural language processing (NLP), correlation analysis, and clustering techniques to evaluate variables related to animation type, programming environments, language availability, licensing models, accessibility support, and emerging technological features. NLP-based thematic analysis was used to compare simulation content with standard electromagnetism curricula. The results reveal a strong emphasis on phenomenological and application-oriented topics, with limited representation of core theoretical constructs. Correlation analysis identified associations between language availability, licensing models, and technical complexity, while clustering techniques revealed distinct thematic groupings and patterns of content concentration across platforms. The findings highlight both the pedagogical potential and the structural gaps present in current electromagnetism simulation resources. This study contributes a replicable analytical framework for evaluating digital educational content and offers evidence to support more informed selection and development of simulation tools in physics education.

Keywords: Electromagnetism education, Digital simulations, Educational data mining, Natural language processing, Accessibility, Physics education technology.

INTRODUCTION

Physics education has long been regarded as a cornerstone across various educational levels [1,2] and holds particular relevance within science and engineering degree programs [3,4]. Its importance lies not only in the conceptual framework it provides for understanding natural phenomena, but also in its strong experimental tradition, which fosters scientific reasoning by enabling students to contrast theoretical models with empirical observations. Within this disciplinary field, electromagnetism occupies a central yet particularly challenging position. Due to its high level of abstraction and strong reliance on mathematical formalism, it requires students to integrate conceptual understanding, multiple representations, and problem-solving skills [5]. These challenges often lead to persistent learning difficulties, especially in foundational courses, and demand didactic strategies capable of bridging the gap between formal theory and intuitive understanding. As a result, electromagnetism remains a critical focus in the ongoing improvement of physics education [6].

In recent decades, technological advances have played an increasingly important role in physics education [7–10], extending learning opportunities beyond traditional classroom and laboratory settings. Among these advances, digital simulations have proven particularly effective by enabling dynamic visualization of abstract phenomena and supporting interactive learning experiences [11]. Their value is especially evident in electromagnetism, where the invisibility and complexity of field interactions often hinder intuitive comprehension. Prior studies have demonstrated the effectiveness of platforms such as PhET Interactive Simulations [12], Labster [13], and Gizmos [14] in promoting conceptual understanding and inquiry-based engagement with topics in electricity and magnetism. These tools allow learners to manipulate variables, observe outcomes in real time, and explore scenarios that are impractical in conventional laboratories due to constraints related to cost, time, or safety. When integrated appropriately, simulations can complement lectures, textbooks, and experimental activities, contributing positively to learning outcomes.

Despite the growing availability of simulation platforms in electromagnetism education [15,16], existing research has largely focused on individual tools or specific instructional settings [17]. While such studies offer valuable insights, they rarely adopt a comparative or integrative perspective. Consequently, a significant gap remains in the literature regarding systematic analyses of the broader ecosystem of available simulations, particularly with respect to thematic coverage, technological design, pedagogical affordances, and alignment with standard physics curricula. This gap is increasingly relevant given the rapid diversification of platforms and the expansion of open educational resources, which vary widely in quality, usability, and conceptual depth. At the same time, recent advances in artificial intelligence—especially in natural language processing (NLP)—have created new opportunities for large-scale analysis of educational content and metadata [18]. However, these methods remain largely underutilized in physics education research, and even more so in studies focused on electromagnetism simulations.

This study addresses these gaps through a comprehensive, data-driven analysis of 43 simulation platforms dedicated to electromagnetism education. The analysis begins with a systematic characterization of each platform across three core dimensions: technical features (including programming languages, deployment environments, and interaction models), pedagogical aspects (such as instructional design, curricular alignment, and user engagement), and emerging trends related to innovation. Particular attention is given to the early incorporation of advanced elements, including algorithmic personalization, adaptive feedback mechanisms, and artificial intelligence-based functionalities. Building on this characterization, the study applies techniques from educational data mining, natural language processing, correlation analysis, and clustering to identify patterns of co-occurrence among platform features and to assess how effectively simulation content reflects standard electromagnetism curricula. The findings aim to inform instructional practice and support the strategic development of more coherent, inclusive, and pedagogically grounded digital learning tools in physics education.

OBJECTIVES

The objective of this study is to conduct a systematic and comparative analysis of digital simulation platforms used for electromagnetism education. The work aims to characterize these platforms across technical, pedagogical, and innovation-related dimensions, with particular attention to accessibility, instructional design, and thematic scope. In addition, the study seeks to evaluate the extent to which existing simulations align with the conceptual structure of standard electromagnetism curricula. By identifying recurring design patterns, areas of content concentration, and underrepresented topics, the research aims to provide evidence-based insights that can inform both instructional practice and the future development of digital educational resources in physics.

METHODS

This study adopts a mixed-methods, data-driven approach grounded in computational analysis to examine the current landscape of electromagnetism simulation platforms. An initial systematic search of academic literature, institutional repositories, and open educational resources resulted in the identification of 75 platforms. Based on relevance to electromagnetism, availability of interactive simulations, and accessibility of descriptive metadata, a curated sample of 43 platforms was selected for analysis. Each platform was characterized across multiple dimensions, including technical features, pedagogical accessibility, thematic focus, and emerging innovation trends.

To analyze thematic coverage and structural relationships, the study integrates natural language processing, statistical correlation, and clustering techniques. Textual metadata associated with the simulations were processed to assess alignment with core electromagnetism topics defined by standard physics curricula. In parallel, categorical platform features were examined through correlation and clustering analyses to identify patterns of co-occurrence and structural associations. All analyses were implemented using custom Python scripts, enabling both descriptive and comparative evaluation of the simulation ecosystem.

RESULTS

The analysis of the 43 simulation platforms focused on electromagnetism education was conducted through a multilevel approach that combined quantitative and qualitative techniques. Data mining, content analysis, and advanced visualization techniques were applied to identify relevant patterns and associations across core thematic domains.

The analytical framework was structured into five complementary dimensions: (i) technical characterization, (ii) pedagogical accessibility, (iii) innovation and emerging trends, (iv) thematic coverage, and (v) cross-variable correlational patterns. The results are presented following this structure, integrating descriptive statistics, graphical representations, and analytical interpretations to provide a comprehensive mapping of both prevailing technological trends and pedagogical gaps within the current landscape of digital simulation resources.

Although the full dataset comprises 43 platforms, the sample size may vary slightly across specific variables due to occasional gaps or non-verifiable information.

Technical Characterization of the Simulation Platforms

The technical characterization constitutes a central dimension of the analysis, as it allows for the identification of the technological foundations underpinning the design, operation, and scalability of the simulation platforms. This section examines four essential aspects: the programming languages employed, the development technologies adopted, the installation requirements, and the modalities of user interaction offered by the platforms.

To provide an integrated visual synthesis and facilitate comparative interpretation across technical dimensions, the corresponding graphical representations for each subcomponent are presented jointly as a multipanel figure (Figure 1), rather than as isolated charts for each variable. This arrangement enables a consolidated view of the technological heterogeneity and dominant patterns observed across the platforms.

Programming Languages Employed

The analysis of programming languages implemented in the identified simulation platforms reveals a predominant use of web-oriented technologies, with JavaScript being the most frequently employed (Figure 1.a). It is present in 23 platforms, which can be attributed to its compatibility with modern browsers, elimination of installation requirements, and capacity to support highly interactive and visually dynamic content—characteristics that align well with the demands of online learning environments.

Java, C++, and Python each appear in six platforms. Java remains a widely adopted option due to its cross-platform capabilities and long-standing use in educational software. C++ is commonly selected for simulations that require significant computational efficiency, particularly in models involving complex physical systems. Python's presence reflects its growing importance in scientific education, driven by its accessible syntax and the availability of comprehensive libraries for data analysis and visualization.

Languages with limited representation include Matlab (three platforms), along with isolated instances of Actionscript, Lua, and Octave. These tend to be associated with specialized applications or legacy systems—Actionscript, for example, is linked to Flash-based technologies that are no longer in active use.

It is important to note that several platforms incorporate more than one programming language in their architecture. This hybrid approach enables the integration of user-friendly web interfaces with robust back-end processes, allowing for greater flexibility in both performance and pedagogical design.

While JavaScript has emerged as the dominant standard for simulation development, the presence of other languages reflects the diversity of technical requirements and instructional goals that shape the design of digital educational tools in electromagnetism.

Development Technologies Used

The review of development technologies reveals a clear alignment with current web standards in the design of simulation platforms (Figure 1b). HTML5 stands out as the most widely implemented technology, appearing in 17 cases. Its widespread adoption is likely due to its strong support for multimedia integration, native cross-platform functionality, scalable vector graphics, and the elimination of the need for additional installations or plugins. These features make it especially well-suited for creating responsive and accessible digital educational tools.

In contrast, the use of Flash is limited to only four platforms, consistent with its obsolescence following official deprecation. Other technologies appear sporadically, including WebGL (2 cases), which is used to enable hardware-accelerated 3D graphics within browsers, and CSS (1 case), which functions as a complementary tool for user interface design and customization.

A few platforms employ more specialized or legacy technologies, each represented in a single case. These include EJSS (Easy Java Simulations), Java Applets, and Rapture. Their presence reflects either continued use of domain-specific academic tools or transitional systems that have not yet migrated to more modern development environments.

The overall distribution illustrates the transition from older, plugin-dependent frameworks toward more robust, sustainable, and browser-native technologies. While HTML5 has become the standard foundation for current simulation development, the coexistence of legacy and niche technologies highlights the diverse technical backgrounds and evolution paths of educational software projects.

Installation Requirements

The installation modality of a simulation platform plays a central role in its usability, particularly in institutional settings with varied technological infrastructures (Figure 1c). The majority of platforms (26 cases) offer full online access, eliminating the need for local installation. This approach facilitates seamless use across different devices and operating systems, and

supports broader accessibility—especially in educational contexts with limited technical support. The prevalence of this model reflects a broader shift toward web-based solutions and simplified deployment processes in digital education.

Conversely, 14 platforms require complete local installation. These are typically associated with more complex simulators, standalone applications, or development environments that demand higher computational resources or greater system-level control. Such requirements may limit their scalability or integration in low-resource settings, although they can offer enhanced performance or functionality in specialized contexts.

A few platforms (2 cases) present variable or unspecified installation requirements, indicating a degree of ambiguity in the documentation or flexibility in deployment. One platform was identified with a hybrid model, where basic functionalities are accessible online, but certain features depend on local components.

This distribution underscores a growing preference for lightweight, browser-based platforms, while still acknowledging the continued relevance of locally installed tools for advanced or specialized applications.

Usage Modalities: Ready-to-Use vs. Programming Environments

An additional component of the technical characterization involves the mode of interaction offered by the platforms, distinguishing between fully pre-configured simulations and those that incorporate programming or customization features (Figure 1d).

Most platforms (31 cases) are designed as ready-to-use tools, requiring no programming knowledge from the user. This design lowers the barrier to adoption and enables rapid integration into teaching practices, particularly in

introductory courses where ease of use is a priority. These simulations support content delivery without demanding technical expertise, making them suitable for a wide range of classroom settings.

In contrast, 7 platforms provide programmable environments that allow users to create, modify, or extend simulations. This functionality is especially valuable in advanced physics and engineering programs, or in teacher training contexts, where computational modeling is part of the educational objectives. By engaging users in the simulation development process, these platforms foster deeper conceptual understanding and transferable technical skills.

A third group (5 platforms) adopts a hybrid model, combining pre-configured simulations with the option to engage in programming. This dual approach enhances pedagogical flexibility, allowing the same platform to be used across different levels of instruction from introductory demonstrations to advanced exploratory tasks, depending on the user’s needs and expertise.

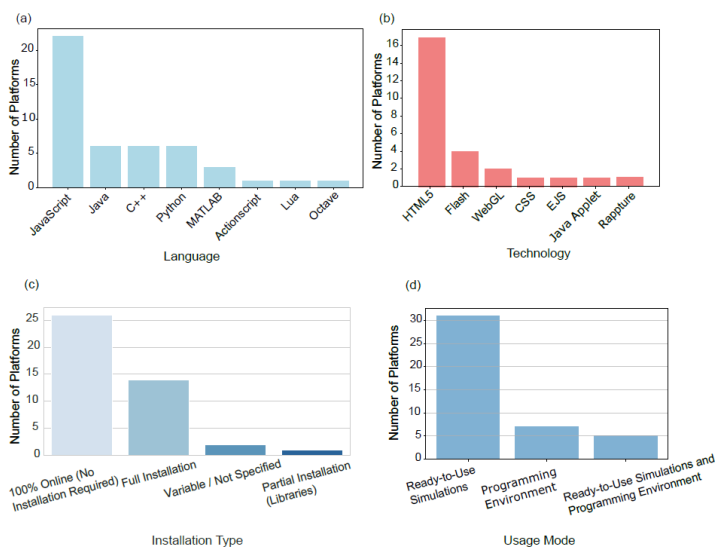


Figure 1. Technical characterization of the 43 simulation platforms: (a) Programming languages, (b) Development technologies, (c) Installation requirements, (d) Usage modalities.

Pedagogical Accessibility

In addition to technical considerations, the pedagogical accessibility of simulation platforms plays a central role in determining their potential for curricular integration, adaptability to diverse instructional contexts, and inclusivity across student populations. This dimension is particularly relevant when evaluating the usability and educational value of digital tools beyond their technological sophistication. The analysis focuses on three critical aspects: licensing models, target educational levels and language availability, which together provide a comprehensive view of the platforms' practical implementation in real-world teaching environments.

Licensing Models

Access modalities, whether free, subscription-based, or commercially licensed, significantly influence the adoption, dissemination, and long-term viability of simulation platforms in educational settings. As shown in Figure 2a, a majority of platforms (72.1%) are freely accessible. This high proportion represents a major strength in promoting equitable access to quality digital resources, especially in institutions with limited financial capacity or technological infrastructure.

In contrast, 16.3% of platforms follow a subscription-based model, and 11.6% require the purchase of commercial licenses. While these models may include added benefits such as dedicated support, advanced features, or integration services, they also introduce economic barriers that can restrict use in underfunded educational systems, particularly in low-income regions.

The predominance of freely available platforms underscores a strong commitment to open and inclusive educational practices within the field. However, the presence of fee-based models highlights the need to consider how cost structures may impact the scalability

and equity of simulation-based teaching tools, especially when deployed across diverse institutional and geographic contexts.

Targeted Educational Levels

The distribution of platforms according to their intended educational level (Figure 2b) reflects a strong alignment with the curricular needs of secondary (40.7%) and undergraduate education (43.2%). These platforms are primarily designed to support conceptual understanding, reinforce theoretical content, and enable virtual experimentation—pedagogical objectives that are central to general physics instruction at these levels.

By contrast, platforms specifically aimed at primary education (8.6%), technical and vocational training (4.9%), and postgraduate or research-oriented contexts (1.4%, 1.2%) are comparatively rare. This imbalance indicates not only an underrepresentation of certain educational segments, but also highlights areas for potential growth. In particular, there is a clear opportunity to expand the development of simulation tools adapted to early learners—where interactive visual aids can foster foundational scientific thinking—as well as to specialized domains that require advanced modeling capabilities.

The current focus on secondary and undergraduate audiences suggests a prioritization of broad applicability and curricular standardization. However, diversifying target levels could enhance the reach and inclusivity of these digital resources, responding more effectively to the heterogeneous demands of the educational landscape.

Language Availability

Language is an important factor in ensuring accessibility, especially in a global educational context where simulation platforms are used by teachers and students in many linguistic regions. As shown in Figure 2c, English appears as the main language in 62.7% of the platforms. This is not surprising given its central role in scientific communication and the fact that many of these tools are created in English-speaking countries or for English-dominant markets.

A smaller but significant group of platforms (23.3%) support more than one language. This multilingual design helps expand their reach and makes them easier to adopt in classrooms around the world, especially where English is not the first language. Spanish is available in 9.3% of platforms, and another 4.7% include content in both Spanish and English. While these percentages are still limited, they show a growing interest in addressing the needs of Spanish-speaking users.

Although English continues to dominate, these results point to a clear opportunity: developing more multilingual platforms would not only improve access but also make these resources more relevant in diverse cultural and educational settings.

Emerging Trends and Innovation Dimensions

Recent developments in educational technology have begun to influence the design and functionality of physics simulation platforms. In this section, three aspects are examined to understand how innovation is shaping the field: the integration of artificial intelligence (AI), the use of animation for representing physical phenomena, and the geographic origin of platform developers. Together, these elements provide insight into both the technological maturity and global distribution of current resources used for teaching electromagnetism.

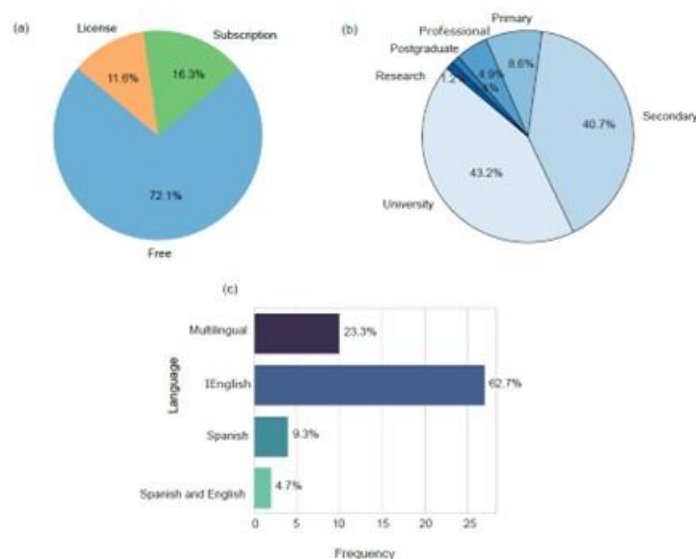


Figure 2. Pedagogical Accessibility Of The 43 Simulation Platforms: (A) Licensing Models, (B) Targeted Educational Levels, (C) Language Availability.

Integration of Artificial Intelligence

While artificial intelligence has gained increasing attention in the broader landscape of educational technologies, its use in simulation platforms focused specifically on electromagnetism remains relatively limited. According to the results, only 18.6% of the analyzed platforms incorporate AI-related functionalities, whereas 79.1% do not currently make use of these technologies.

Among the platforms that do include AI, the most frequent applications involve personalized learning pathways, adaptive feedback mechanisms during simulation tasks, and, in a few cases, the automated generation of scenarios that respond to user behavior or performance. Although these features are still emerging, they point to AI’s potential to enrich the learning experience by making instructional content more flexible and responsive to individual needs.

Animation Types Employed

Visual representation is a central component in educational simulations, as it directly affects how students engage with and understand complex physical concepts. The analysis of animation types used across platforms shows a clear predominance of two-dimensional (2D) interactive animations, which appear in 67.4% of the cases.

Three-dimensional (3D) animations are used in 23.3% of the platforms. Although they offer greater spatial realism, their adoption remains limited. Even less common are advanced or specialized formats—such as fully editable animations, models with real-time data integration, or modular systems that rely on non-animated representations—each appearing in only a few isolated cases.

The widespread use of 2D animations is likely tied to several practical advantages: they are easier to develop, more compatible with a wide range of browsers and devices, and require less processing power. These factors make 2D models more accessible in diverse educational environments, especially those with limited technical infrastructure.

Countries of Origin

The geographic distribution of simulation platform development reveals marked disparities in global participation. The United States accounts for nearly half of the platforms analyzed (48.8%), indicating a strong concentration of development activity in a single country. Other contributions come from Western Europe—particularly the United Kingdom, Germany, France, and Sweden—and from India, although in much smaller numbers.

In contrast, regions such as Latin America and Africa are minimally represented. This uneven distribution points to a clear concentration of technological development in established innovation hubs, and highlights the challenges that emerging regions face in producing localized educational technologies.

These imbalances are shaped by multiple factors, including disparities in access to infrastructure, availability of research funding, and levels of collaboration between academic institutions, educational software developers, and national innovation systems. Addressing these gaps requires greater support for regional capacity-building, as well as initiatives aimed at fostering the creation of culturally relevant and context-sensitive simulation tools.

Thematic Coverage of Electromagnetism Simulations

Beyond technical and accessibility considerations, the pedagogical value of simulation platforms depends largely on how well their content aligns with core topics in electromagnetism. Thematic coverage is a fundamental factor in determining their curricular relevance and ability to support learning across different educational levels.

This section presents a structured analysis of the concepts addressed in the reviewed platforms, based on the extraction and classification of thematic tags associated with each simulation. From the original set of 43 platforms, a subset of 23 was selected for detailed thematic analysis. The selection was based on three criteria: (1) availability of clear and descriptive documentation; (2) inclusion of simulations explicitly related to electromagnetism; and (3) consistent use of terminology that enabled reliable tagging and comparison. Platforms that lacked sufficient metadata, focused on other areas of physics, or showed

inconsistencies in their content were excluded to preserve analytical rigor.

The resulting dataset allowed for the quantification of topic frequency and the evaluation of both conceptual breadth and depth. Using a combination of data mining, content analysis, and visualization tools, patterns in topic distribution were identified and explored through heatmaps and clustering techniques. This multi-layered approach made it possible to detect areas of high thematic density, as well as underrepresented topics that point to opportunities for future development.

The findings offer a clearer picture of the current coverage of electromagnetism concepts within simulation tools, and serve as a guide for both the strategic selection of existing resources and the informed design of new educational materials.

Tag Frequency Analysis

The tag frequency analysis (Figure 3a) reveals a strong emphasis on applied and observable phenomena. Tags such as magnetic field, current, electric field, induction, and circuits appear most frequently, suggesting that most simulations are designed to support conceptual understanding through visual and interactive representations.

In contrast, key theoretical elements—such as Ohm's Law, Coulomb's Law, voltage, and Lorentz force—are noticeably underrepresented. Even more striking is the near absence of tags referring to fundamental, integrative constructs like Maxwell's equations, which serve as the conceptual backbone of electromagnetism. This gap indicates a clear opportunity to expand the thematic scope of available simulations to include not only phenomenological content but also the deeper theoretical frameworks that structure the discipline.

Thematic Coverage per Platform

The heatmap shown in Figure 3b provides a detailed view of how conceptual tags are distributed across the different simulation platforms. Each row represents a specific platform or institutional project, while the columns correspond to thematic tags related to key electromagnetism topics. To keep the visualization concise, the tags on the horizontal axis are identified numerically (from 1 to 40, in increments of 5), with their full descriptions listed in the accompanying reference table (e.g., 1 = Kirchhoff, 2 = Electric Field, 3 = Magnetic Field, etc.). Color intensity reflects the frequency of simulations associated with each tag, ranging from light (minimal or no coverage) to dark shades (greater coverage).

The heatmap allows for quick comparisons of thematic scope and specialization across platforms. Some, like PhET, Walter Fendt Simulations, CK-12, UNAM – Ingeniería, and Physics Aviary, stand out for their broad and varied

coverage. These platforms show strong representation across multiple conceptual areas, suggesting careful pedagogical planning and a commitment to addressing a wide spectrum of curricular needs. Walter Fendt, in particular, displays consistent coverage across nearly all thematic categories, reflecting a highly structured and comprehensive approach.

In contrast, platforms such as Labster and COMSOL Multiphysics, present a more focused profile, typically concentrating on a narrower set of advanced or application-oriented topics. This pattern aligns with their frequent use in specialized contexts, such as engineering education or professional training, where depth in specific areas takes precedence over breadth.

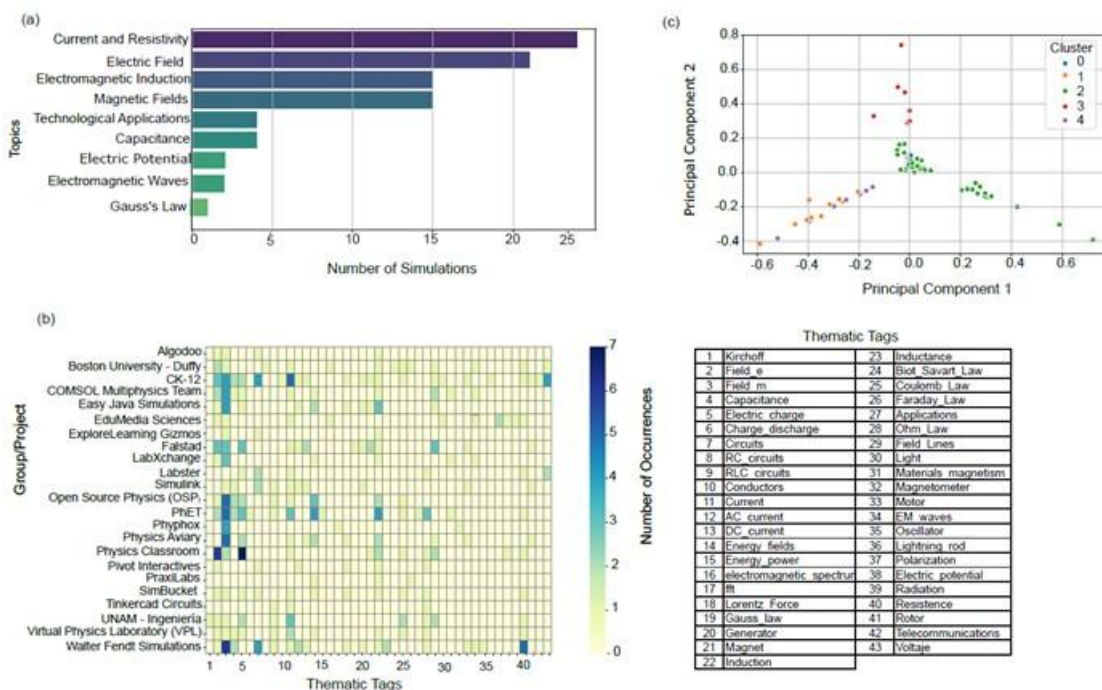


Figure 3. Thematic analysis of digital simulations in electromagnetism. (a) Frequency of core topics across 43 simulations. (b) Heatmap of thematic coverage by platform. (c) Cluster analysis based on semantic embeddings of thematic tags using PCA and K-means.

Thematic Clustering

To explore underlying patterns in the conceptual organization of electromagnetism simulations, an unsupervised analysis was conducted using a combination of Natural Language Processing (NLP), dimensionality reduction, and clustering techniques.

This approach made it possible to move beyond manual categorization and uncover emergent thematic structures based on simulation descriptions and associated conceptual tags.

A semantic feature matrix was built using the standardized labels and descriptive metadata from the 23 selected platforms. Principal Component Analysis (PCA) was then applied to reduce dimensionality, allowing for the preservation of the most relevant variation across thematic features while making the data suitable for two-dimensional visualization. The transformed dataset was subsequently analyzed using the K-means clustering algorithm to identify groups of simulations with shared conceptual profiles.

Figure 3c presents the resulting scatter plot, where each point represents an individual simulation associated with one of the selected platforms. Since many platforms include more than one electromagnetism simulation, multiple data points may correspond to the same source. The two axes correspond to the first and second principal components, derived from linear combinations of the original thematic variables. Although these components are not directly interpretable, the spatial distribution of the points reflects their semantic proximity: simulations

positioned closer together tend to share similar conceptual content, while those further apart exhibit thematic differences. The five clusters identified by the algorithm are distinguished by color, making it possible to visualize emergent groupings based on shared content characteristics.

The clusters show clear thematic coherence:

- Cluster 0 (dark blue): A small group focused on electromagnetic waves and time-dependent field phenomena. These simulations cover advanced but less frequently addressed topics such as wave propagation and dynamic field behavior.
- Cluster 1 (orange): Contains simulations centered on static magnetism, often illustrating magnetic fields produced by permanent magnets and their interaction with basic instruments. These are generally aimed at introductory levels.
- Cluster 2 (green): The most populated and varied group, covering electromagnetic induction, alternating current circuits, and energy-related applications. It reflects a strong focus on applied topics commonly found in educational simulations.
- Cluster 3 (red): A more specific cluster emphasizing Faraday's Law and induction processes involving coils and magnets. These simulations regularly feature high visual interactivity and are well-suited for instructional use.
- Cluster 4 (purple): Comprises simulations on electrostatics, including electric fields from point charges, electric potential, and links to basic technological components such as capacitors and motors.

Two main insights emerge from this analysis. First, most simulations fall within clusters that prioritize phenomenological and application-oriented content (Clusters 1–3), suggesting a strong tendency to favor topics that are both visually accessible and experimentally intuitive. Second, more advanced theoretical constructs—such as Gauss's Law, Maxwell's Equations, and wave equations—are either missing or only marginally represented, appearing in smaller and more isolated clusters.

By grouping simulations into thematically cohesive categories, this clustering analysis offers practical guidance for instructors seeking conceptually aligned tools, and points to clear opportunities for developers to address content areas that remain underexplored. More broadly, it illustrates how NLP and machine learning techniques can support curriculum mapping and the evaluation of digital educational resources in physics.

CONCLUSIONS

This study provides a multidimensional overview of the current landscape of digital simulation platforms for electromagnetism education through the integration of computational analysis, natural language processing, and clustering techniques. The findings reveal both encouraging developments and persistent structural limitations that shape the pedagogical potential of these resources.

On the positive side, the prevalence of freely accessible, web-based platforms reflects notable progress in economic and operational accessibility, supporting broader adoption across diverse educational contexts. In addition, the strong alignment of most simulations with secondary and undergraduate curricula indicates responsiveness to core instructional needs in physics education.

At the same time, significant asymmetries remain. Linguistic diversity is limited, with English dominating the ecosystem, and thematic coverage continues to favor phenomenological and application-oriented content, while fundamental theoretical concepts—such as Maxwell's equations, Gauss's law, and electromagnetic wave models—are underrepresented. These limitations constrain the applicability of simulations in more advanced or conceptually rigorous settings. Correlation analyses further suggest a weak integration between pedagogical objectives, technical sophistication, and inclusive access, as features such as multilingual support, advanced visualization, or AI integration tend to appear sporadically and are often associated with commercial platforms.

Geographic concentration also persists, with most platforms originating from a small number of high-capacity regions and limited representation from Latin America, Africa, and other emerging contexts. While the study is restricted to publicly available platforms and relies on heterogeneous metadata quality, it nevertheless offers actionable insights to guide the development and evaluation of more inclusive, curriculum-aligned, and pedagogically

robust simulation tools. Advancing this field will require sustained collaboration among educators, developers, and policymakers to ensure that future simulations address both technological innovation and the diverse educational needs of a global learning community.

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REFERENCES

- [1] K. T. Kotsis, "Physics education in EU high schools: Knowledge, curriculum, and student understanding," *Eur. J. Contemp. Educ. E-Learning*, vol. 2, no. 4, pp. 28–38, 2024. <https://ejceel.com/index.php/journal/article/view/105/69>.
- [2] I. Usembayeva, B. Kurbanbekov, S. Ramankulov, A. Batyrbekova, K. Kelesbayev, and A. Akhanova, "3D Modeling and Printing in Physics Education: The Importance of STEM Technology for Interpreting Physics Concepts," *Qubahan Acad. J.*, vol. 4, no. 3, pp. 45–58, 2024. <https://doi.org/10.48161/qaj.v4n3a727>.
- [3] V. T. Ngo, "Applying the engineering design process to teach the physics course for engineering students using the flipped classroom combined with an instructional design model," *J. Res. Innov. Teach. Learn.*, 2024. <https://doi.org/10.1108/JRIT-07-2023-0095>
- [4] N. A. Muxamadaliyevich, "The role of physics courses in the training of future civil engineers," *Am. J. Res. Humanit. Soc. Sci.*, vol. 19, pp. 23–29, 2023.
- [5] M. Michelini, A. Mossenta, I. Testa, R. Viola, and A. Testa, "Teaching Electromagnetism: Issues and changes," in *Proc. GIREP/EPEC Conf. Front. Phys. Educ.*, 2007, pp. 33–37. https://www.researchgate.net/profile/Jenaro-Guisasola/publication/228571202_Teaching_Electromagnetism_Issues_and_changes/links/oc9605215b314eee7f00000/Teaching-Electromagnetism-Issues-and-changes.pdf
- [6] M. Villavicencio, R. Méndez-Fragoso, and J. A. E. Roa-Neri, "La importancia de la interdisciplina en la enseñanza del electromagnetismo en el nivel superior," *Lat. Am. J. Sci. Educ.*, vol. 6, p. 12022, 2019. https://lajse.org/may19/2019_12022.pdf
- [7] R. A. Faresta, T. Z. S. B. Nicholas, Y. Chi, I. A. N. Sinambela, and A. Z. Mopoliu, "Utilization of technology in physics education: A literature review and implications for the future physics learning," *Lensa: J. Kependidikan Fisika*, vol. 12, no. 1, pp. 1–27, 2024. <https://doi.org/10.33394/j-lkf.v12i1.11676>
- [8] A. Yurchenko, V. V. Proshkin, O. Naboka, V. Shamonina, and O. Semenikhina, "The use of digital technologies in education: the case of physics learning," *Int. J. Res. E-learning*, vol. 9, no. 2, pp. 1–25, 2023.
- [9] M. Shafiq, M. A. Sami, N. Bano, R. Bano, and M. Rashid, "Artificial intelligence in physics education: Transforming learning from primary to university level," *Indus J. Soc. Sci.*, vol. 3, no. 1, pp. 717–733, 2025. <https://doi.org/10.59075/ijss.v3i1.807>
- [10] Yurchenko, Artem, et al. "The use of digital technologies in education: the case of physics learning." *International Journal of Research in E-learning* 9 (2) (2023): 1-25. <https://www.ceeol.com/search/article-detail?id=1241976>
- [11] E. Klemencic, M. Mencinger, and R. Repnik, "Enhancing digital competences through the integration of simulations in physics," in *EDULEARN24 Proc.*, IATED, 2024, pp. 2898–2905. doi: [10.21125/edulearn.2024.0782](https://doi.org/10.21125/edulearn.2024.0782)
- [12] M. J. P. Dantic and A. Fluraon, "PhET interactive simulation approach in teaching electricity and magnetism among science teacher education students," *J. Sci. Educ. (JSE)*, vol. 2, no. 2, pp. 88–98, 2022. <https://jse.rezkimedia.org/index.php/jse/article/view/101>
- [13] A. B. Cabural, "Enhancing conceptual understanding of electricity and magnetism through VR simulations," *Int. J. Curr. Sci. Res. Rev.*, vol. 7, no. 10, pp. 7909–7917, 2024. DOI: [10.47191/ijcsrr/V7-i10-50](https://doi.org/10.47191/ijcsrr/V7-i10-50)
- [14] R. E. Vorsah and T. A. Tamakloe, "Exploring science & mathematics models through AI technology to advance high school education right." *International Journal of Research Publication and Reviews*, vol. 02, no. 04, pp. 185–206.

- [15] C. M. Furse and E. T. Iskander, "Electromagnetics education: Past, present, and future directions," in *The Advancing World of Applied Electromagnetics*, Cham: Springer, 2024, pp. 227–249. https://link.springer.com/chapter/10.1007/978-3-031-39824-7_9
- [16] Z. Malikova and G. Ormanova, "Methods of teaching the chapter 'Electromagnetism' in physics using digital educational resources," *Avrasya Sosyal ve Ekonomi Arařt. Derg.*, vol. 10, no. Prof. Dr. Raskul Ibragimov Özel Sayısı, pp. 101–115, 2023. <https://dergipark.org.tr/tr/pub/asead/article/1287476>
- [17] J. D. González et al., "Impact of the use of virtual laboratories of electromagnetism in the development of competences in engineering students," *J. Phys.: Conf. Ser.*, vol. 1247, no. 1, p. 012018, 2019. DOI 10.1088/1742-6596/1247/1/012018
- [18] J. Tussupov et al., "Analysis of short texts using intelligent clustering methods," *Algorithms*, vol. 18, no. 5, p. 289, 2025. <https://doi.org/10.3390/a18050289>