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Scientific Articles

Panorama del aprendizaje adaptativo en la educación superior STEM: Análisis tecnopedagógico de experiencias, desafíos y oportunidades de implementación

Overview of adaptive learning in STEM higher education: A techno-pedagogical analysis of experiences, challenges, and opportunities for implementation

Visão geral da aprendizagem adaptativa no ensino superior em STEM: análise tecnopedagógica de experiências, desafios e oportunidades de implementação

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Resumen

A raíz de la pandemia, se registró un incremento importante en el uso de plataformas educativas digitales de aprendizaje adaptativo, principalmente en la educación superior. En el ámbito STEM (Ciencia, Tecnología, Ingeniería y Matemáticas), la adopción de sistemas de aprendizaje adaptativo ha mostrado mejoras significativas en la comprensión conceptual y la autonomía del estudiante, aunque su integración enfrenta retos pedagógicos y tecnológicos. El objetivo de la presente investigación es analizar de manera sistemática las experiencias documentadas sobre la implementación del aprendizaje adaptativo en la educación superior en áreas STEM, identificando los principales desafíos técnicos y pedagógicos, así como las oportunidades de mejora que permitan proponer un Modelo de Madurez Tecnopedagógico para una adecuada integración.

La investigación fue realizada utilizando una metodología de revisión sistemática de literatura basada en la guía PRISMA. Los resultados muestran que el aprendizaje adaptativo contribuye en gran medida al fortalecimiento del desempeño académico y al compromiso de los estudiantes, reduciendo la deserción y fomentando la participación activa, con mayor incidencia en áreas como matemáticas, programación y química. Igualmente, se identificaron diversos desafíos técnicos y pedagógicos relacionados principalmente con el diseño curricular, la autorregulación y la motivación estudiantil. En conclusión, la implementación del aprendizaje adaptativo en STEM evidencia proyección futura favorable, aunque el impacto de estas innovaciones solo se consolida cuando existe una planeación institucional que coordine los aspectos técnicos, formativos y de gestión educativa. Adicionalmente, se identificaron algunas limitaciones como: resistencia al cambio, estrés derivado del uso intensivo de plataformas, y la brecha de infraestructura, lo que condiciona la generalización de los resultados.

Palabras clave: aprendizaje adaptativo, educación superior, innovación educativa, STEM, tecnopedagógico.

Abstract

Following the pandemic, there has been a marked increase in the use of digital adaptive learning platforms, particularly in higher education. Within the STEM (Science, Technology, Engineering and Mathematics) disciplines, the adoption of adaptive learning systems has demonstrated notable improvements in conceptual understanding and student autonomy, although their integration encounters both pedagogical and technological challenges. This study aims to systematically analyze documented experiences of implementing adaptive learning in STEM higher education, identifying the primary technical and pedagogical obstacles as well as opportunities for improvement, thereby enabling the proposal of a techno-pedagogical maturity model.

The research was conducted using a systematic review methodology guided by the PRISMA model. Results indicate that adaptive learning significantly enhances academic performance and student engagement, reduces dropout rates, and promotes active participation, with the most pronounced effects observed in fields such as mathematics, programming, and chemistry. Furthermore, several technical and pedagogical challenges were identified, primarily related to curriculum design, self-regulation, and student motivation. In conclusion, the implementation of adaptive learning in STEM demonstrates strong potential; however, the impact of these innovations is fully realized only when institutional planning coordinates technical, training, and educational management aspects. Additional limitations were noted, including resistance to change, stress associated with intensive platform use, and infrastructure gaps, which constrain the generalizability of the findings.

Keywords: Adaptive learning, Higher education, Educational innovation, STEM, Techno-pedagogical.

Resumo

Como resultado da pandemia, houve um aumento significativo no uso de plataformas digitais de ensino para aprendizagem adaptativa, principalmente no ensino superior. Nas áreas STEM (Ciência, Tecnologia, Engenharia e Matemática), a adoção de sistemas de aprendizagem adaptativa demonstrou melhorias significativas na compreensão conceitual e na autonomia dos alunos, embora sua integração enfrente desafios pedagógicos e tecnológicos. O objetivo desta pesquisa é analisar sistematicamente as experiências documentadas sobre a implementação da aprendizagem adaptativa no ensino superior em áreas STEM, identificando os principais desafios técnicos e pedagógicos, bem como oportunidades de melhoria que permitam a proposição de um Modelo de Maturidade Tecnopedagógica para sua adequada integração.

A pesquisa foi conduzida utilizando uma metodologia de revisão sistemática da literatura baseada nas diretrizes PRISMA. Os resultados mostram que a aprendizagem adaptativa contribui significativamente para o fortalecimento do desempenho acadêmico e do engajamento dos alunos, reduzindo as taxas de evasão e fomentando a participação ativa, com maior impacto em áreas como matemática, programação e química. Da mesma forma, diversos desafios técnicos e pedagógicos foram identificados, principalmente relacionados ao planejamento curricular, à autorregulação e à motivação dos alunos. Em conclusão, a implementação da aprendizagem adaptativa em STEM demonstra perspectivas futuras promissoras, embora o impacto dessas inovações só se consolide quando houver um planejamento institucional que coordene os aspectos técnicos, de formação e de gestão educacional. Além disso, algumas limitações foram identificadas, como a resistência à

mudança, o estresse resultante do uso intensivo de plataformas e a lacuna de infraestrutura, o que dificulta a generalização dos resultados.

Palavras-chave: aprendizagem adaptativa, ensino superior, inovação educacional, STEM, tecnopedagogia.

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Introduction

In recent years, university education, mainly in Latin America, has faced significant challenges that have led to a transformation of teaching practices, especially in STEM areas characterized by their high cognitive demands and high dropout rates.

Universities with a technological focus, faced with the need to modernize their educational processes, have promoted the exploration of adaptive learning environments. These systems adjust the sequence and complexity of the content based on individual performance, prioritizing curricular flexibility and feedback.

Recent research has demonstrated the benefits of adaptive learning in both school and corporate settings. However, its implementation in STEM fields remains limited, particularly in higher education, where there is little systematic research on its success factors, practical limitations, and levels of impact.

In addition to the above, it is necessary to evaluate how these technologies can be properly integrated into university pedagogical models, considering the principles of equity, inclusion, and educational quality.

The objective of this research is to systematically analyze the documented experiences on the implementation of adaptive learning in higher education in STEM areas to identify the main technical and pedagogical challenges, as well as the opportunities for improvement that allow proposing a techno-pedagogical maturity model.

In this context, the purpose of this research is to conduct a systematic literature review based on the PRISMA model to improve the quality and transparency of the review.

The hypothesis was that the implementation of adaptive learning in higher education in STEM areas, when mediated by a coherent techno-pedagogical design, contributes positively to academic performance and student motivation.

Adaptive learning is an educational strategy focused on analyzing data generated during the learning process. This information allows teachers to adjust and personalize teaching content, adequately addressing individual learning characteristics and needs (Parra Rojas, 2023). Although adaptive learning is not a new concept, it has recently gained relevance thanks to technological development and the increasing use of digital educational platforms (Ramírez & León, 2023).

Also, the use of intelligent algorithms allows continuous examination of the information generated by students, detecting trends in their progress and diversity of study strategies, thanks to the emergence and development of Artificial Intelligence (AI) systems (Aparicio-Gómez and Aparicio-Gómez, 2024).

The term STEM (Science, Technology, Engineering, and Mathematics) encompasses diverse areas and is also highly relevant today. The acronym refers to various scientific and technological disciplines, integrating knowledge, skills, and practices related to these fields (Simó et al., 2020). This training, known as STEM literacy, is built progressively throughout one's schooling (Simó et al., 2020).

Materials and methods

The methodology chosen for this research work has a qualitative, documentary approach. The research was carried out through a systematic literature review, which consists of a structured and objective summary integrated through a series of processes, by which the findings of quality research related to the proposed research topic are identified, selected, evaluated, and synthesized (Chan Arceo and Canto Herrera, 2022; Sánchez-Serrano et al., 2022).

Although there are various models for preparing study reviews, in order to ensure scientific rigor in this work it was decided to use the PRISMA guide (Preferred Reporting Items for Systematic Reviews and Meta- Analyses) (Sánchez-Serrano et al., 2022), in addition to integrating a theoretical triangulation and traceability of the process.

Sources of information

Data collection was carried out using a structured systematic review protocol, which included the identification, selection, evaluation, and synthesis of studies. This protocol was the primary instrument for collecting documentary data, as it allowed for the rigorous organization and analysis of published empirical evidence on adaptive learning in higher education in STEM fields.

Furthermore, to obtain a reliable, up-to-date, and high-quality sample, the study followed a systematic literature review approach with a descriptive-comparative emphasis, considering articles published in Scopus and Web of Science, which are considered among the leading international bibliographic databases.

Priority was given to empirical research on adaptive learning applied to university engineering and science programs, following the PRISMA guidelines. A concatenation was used employing the Boolean operator OR and the keywords: adaptive learning, STEM, and higher education, considering that these could be found in the text of the documents, this in order to collect the largest number of works that could enrich the review.

In order to consider only works published in academically relevant journals, the inclusion and exclusion criteria shown in Table 1 were chosen when searching for information in the databases.

Table 1. Inclusion and exclusion criteria used to obtain the sample

Inclusion	Exclusion
Magazine articles.	Articles from congresses and conferences.
Open access publications.	Books and book chapters.
Research related to adaptive learning in STEM.	Restricted access.
Empirical studies.	Duplicate items.
Research conducted at a higher level.	Theoretical studies or reviews.
Works from the last 5 years.	

Source: Own elaboration

Subsequently, the search for articles continued using the search string “adaptive learning OR STEM OR higher education". A total of 44 documents were found in Scopus and 127 in WoS that included the specified keywords and were also published between 2020 and 2025. Once the aforementioned criteria were applied, only 14 articles from the Scopus database and 62 from the WoS database were filtered out and reviewed in greater detail.

Data collection

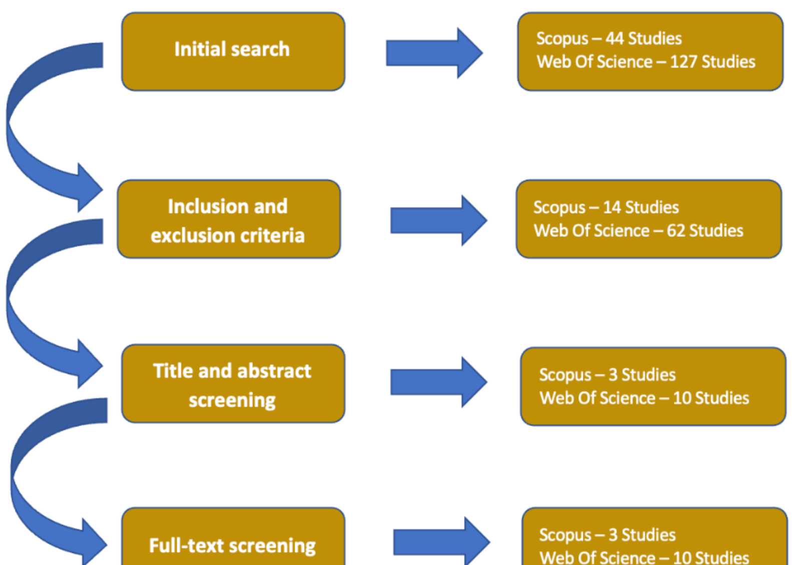
Once the works potentially related to the research topic were identified in the first phase, the relevant information from each of them was downloaded. It is important to note that both the Scopus and WoS databases have functions that allow for the bulk export of information from the works resulting from the search process.

Once the information from the papers was collected, the screening process began, which was carried out by two reviewers. In this process, the papers that had relevant information for the research were selected rigorously and transparently, and those that did not provide adequate information or that were not related to the research topic were discarded.

Abstracts of the studies were strictly reviewed, and it was found that, although many of them included the keywords, they were not works focused on studying the use of adaptive learning in STEM, so they were discarded.

Subsequently, the full text of the remaining studies was reviewed, allowing for the identification of works related to the research topic. The number of works included in this systematic literature review after the screening process is 13 documents: 3 from the Scopus search and 10 from Web of Science. Figure 1 illustrates the document selection process.

Figure 1. Document selection process



Source: Own elaboration

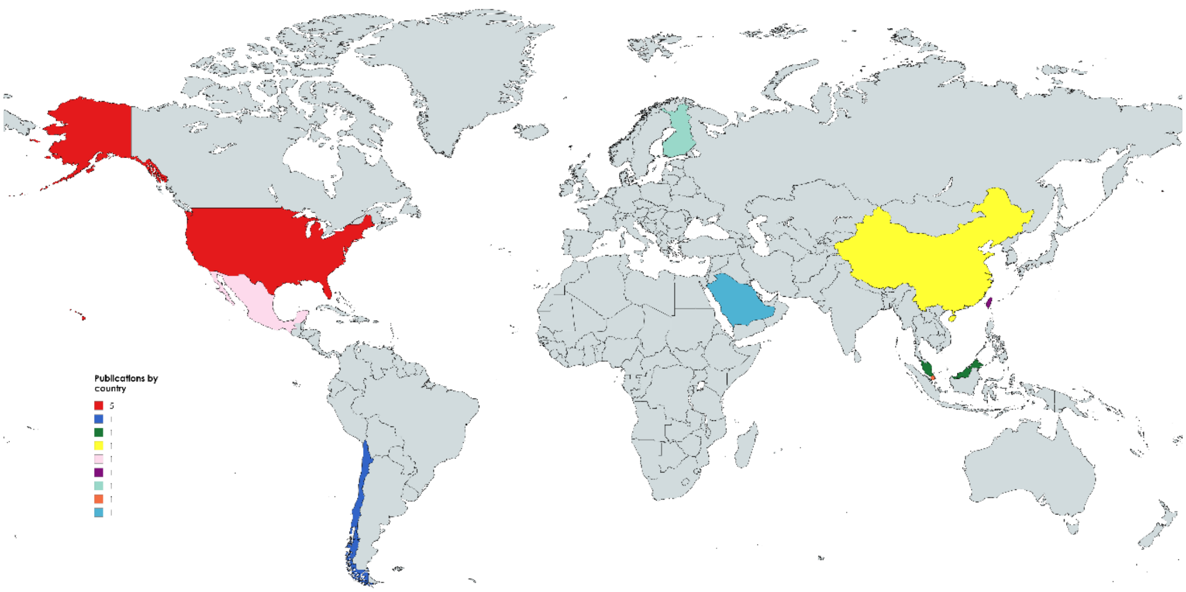
Results

The analysis of the information from the included studies allowed us to identify, in addition to the main results mentioned by the authors, important aspects such as the concentration of studies by geographic location and by area of knowledge. Furthermore, the main technical and pedagogical challenges identified in the implementation of adaptive learning in higher education in STEM fields are highlighted. Finally, a techno-pedagogical maturity model was proposed.

Results by country

Figure 2 shows the distribution of publications by country that met the inclusion criteria (n=13), where n corresponds to the number of works included.

Figure 2. Distribution of included studies by country



Source: Own elaboration

The data shows that North America accounts for 6/13 of the studies, primarily driven by the United States with 5/13, indicating a consolidated research and funding ecosystem in adaptive learning applied to STEM. This could be associated with greater availability of commercial learning analytics platforms. Mexico's presence with 1/13 indicates that the region maintains active adoption efforts, although with a lower density of studies, which could reflect differences in infrastructure, teacher training, and institutional resources.

Asia accounts for 5/13, with countries like China, Taiwan, Singapore, Malaysia, and Saudi Arabia each representing 1/13. A broad and polycentric distribution is observed: these cases point to national agendas that promote university digitization and learning measurement, with a strong focus on engineering. Europe is represented by Finland with 1/13, consistent with its tradition of pedagogical innovation and formative assessment, although the sample indicates specific rather than mass production.

Overall, the geographic map reveals three patterns: (1) university systems with established capacity and technological maturity, such as those in the United States and Singapore, which tend to publish more; (2) countries with educational modernization policies (several Asian countries and Saudi Arabia) that are emerging with specific studies indicating expanding adoption; and (3) Latin America (Chile and Mexico), which is progressing but faces gaps in interoperability, teacher training, and institutional sustainability, which could explain its relatively lower volume. These differences are important because they influence the degree of actual adaptation, immediate feedback, and techno-pedagogical alignment factors associated with improvements in performance and retention.

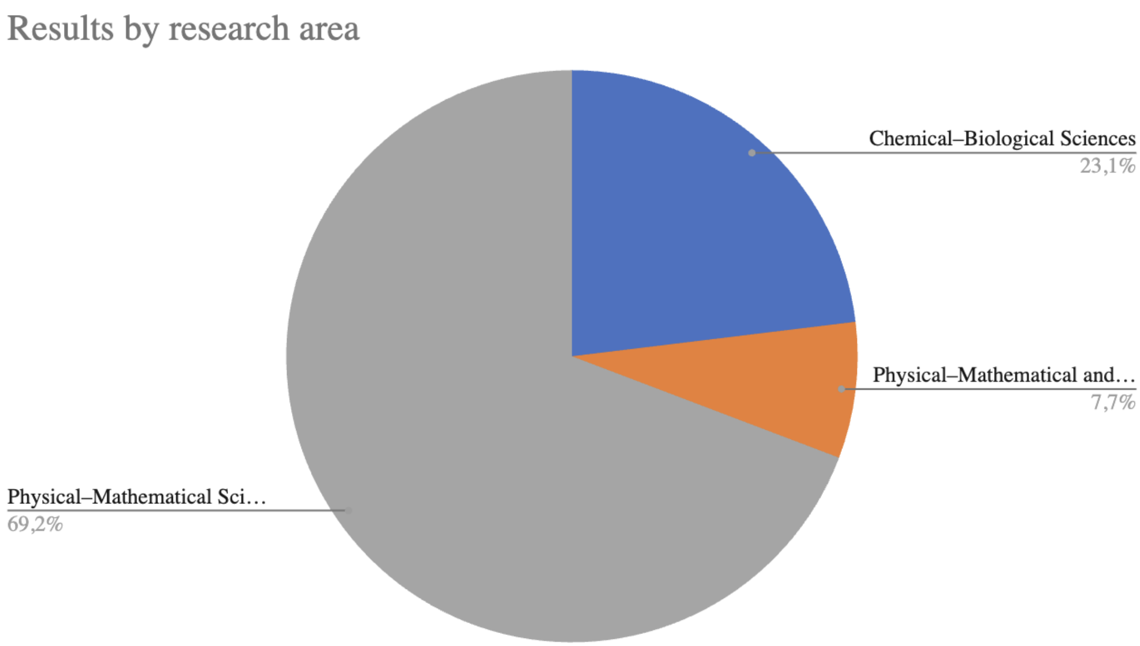
However, it should be considered that the interpretation of the sample size (13 studies) and the search being limited to Scopus / WoS and open access may underrepresent countries with publications in other repositories, and the languages used in the search (English/Spanish) could bias the data in favor of certain contexts. Even so, the data show that the window of opportunity to reduce STEM gaps through adaptive learning is global, but its impact depends on local capacities: digital infrastructure, teacher professional development, data governance (metadata standards that facilitate data organization), and assessment policies that integrate learning analytics.

Results by area of knowledge

Analysis of the results based on the area of knowledge where the studies were applied showed that the field of Physics and Mathematics has the highest concentration of studies on the use of adaptive learning in STEM areas, with 69.2% (9/13) of the works focused on this area. It was found that some of the studies were applied in engineering fields and others in technology-related fields. In Mexico, educational systems classify these fields within the area of Physics and Mathematics.

Another STEM area where a significant percentage of studies were conducted is Chemical and Biological Sciences. It was identified that 23.1% of the work was carried out in this area, specifically in chemistry courses. Additionally, one study, representing 7.7% of the total work included in this review, was applied in courses belonging to both areas of knowledge: Physical-Mathematical and Chemical-Biological Sciences. Figure 3 shows the percentages of work associated with each area of knowledge.

Figure 3. Distribution of included studies by area of knowledge



Source: Own elaboration

This analysis showed that the use and study of adaptive learning in STEM higher education is concentrated in very few areas of knowledge, specifically in disciplines such as Mathematics and Chemistry and in some careers related to Technological and Engineering areas.

Technical challenges

Among the relevant information identified through the review and analysis of the selected works, the technical challenges in the implementation of adaptive learning in different STEM contexts stand out, which go beyond merely instrumental or infrastructure aspects.

Beyond the limitations associated with technological aspects, these challenges reveal techno-pedagogical tensions related to the integration of adaptive learning platforms into institutional ecosystems, interoperability between systems, data governance, and the translation or interpretation of learning analytics data into meaningful pedagogical decisions. Based on the above, it was possible to classify the identified technical challenges into four interrelated areas: digital infrastructure, learning analytics and assessment, institutional management, and the pedagogical integration of technology.

Regarding the digital infrastructure axis, one of the challenges identified is the great potential of adaptive platforms and assessments to improve the prediction of student performance; however, it is observed that it is necessary to constantly make adjustments and maintenance, as well as integrate various metrics that help to guarantee their effectiveness (Díaz y Aizman, 2024; Vyas et al., 2021).

For STEM practice, this means that the use of adaptive platforms and assessments should not be limited to their technical implementation, as it requires ongoing management and updates to accurately reflect student progress. Additionally, integrating other metrics such as lab participation, problem-solving, and critical thinking is essential for a more comprehensive view of learning.

Another challenge within this same area is related to the technological limitations and integration problems with institutional LMSs that adaptive learning platforms present, hindering their implementation and effective use (Díaz y Aizman, 2024; Sockalingam et al., 2025). Consequently, it is necessary to strengthen interoperability between adaptive platforms and institutional LMSs, promoting the use of integrated environments that facilitate the adaptation of STEM content according to the specific competencies of each discipline.

Even with current technological advancements and development, identifying suitable tools for adaptive learning remains a challenge, especially given the lack of tools that allow for accurate assessment of student engagement and participation (Sockalingam et al., 2025; Wu et al., 2023).

This situation demands the development and selection of tools that can be adapted to different disciplinary contexts and generate reliable metrics on the level of student engagement, promoting data-driven pedagogical decision-making and more effective personalization of learning.

In the area of analytics and evaluation, one of the main challenges identified is the lack of solid evaluation frameworks that allow for adequate measurement of skills transfer and that can be scaled to track learning and its application beyond the completion of the course (Fischer et al., 2022; Tang y Odeleye, 2023).

This implies, for STEM contexts, the need to move towards assessment models that value the student's immediate performance and the application and sustainability of the skills acquired in real-world scenarios and in the long term, promoting a more comprehensive view of the impact of adaptive learning on scientific and technological training.

Furthermore, the analysis of information generated during the learning process remains complex, especially when trying to establish feasible and reliable predictions between STEM concepts and learning behaviors in massive open online courses (MOOCs), "so the development of hybrid user models requires real-time data processing that increases the accuracy and relevance of the adaptation” (Xia y Qi, 2024; Zairon et al., 2025).

It is recommended to strengthen analytical and real-time data processing capabilities so that adaptive platforms can provide more accurate and contextualized feedback. It is also suggested to integrate interdisciplinary approaches to educational analytics and data science to better understand learning trajectories and optimize personalization in large-scale educational environments.

In the area of institutional management, it was identified that the development and implementation of adaptive assessments and digital educational resources continues to represent major challenges for teachers, mainly due to the time and resources required (Díaz y Aizman, 2024; Sockalingam et al., 2025; Tang y Odeleye, 2023).

Based on this identified challenge, it is suggested to promote institutional strategies that optimize the distribution of available resources, encourage collaborative work between teachers and developers, and integrate innovative tools that help reduce the time and costs of producing adaptive and immersive content, without compromising its pedagogical quality.

It was identified that the management and use of data in adaptive educational platforms represent considerable challenges, especially due to the difficulties involved in combining indicators of various kinds and due to concerns regarding privacy, governance and the availability of information (Pilotti et al., 2022; Sockalingam et al., 2025; Vyas et al., 2021).

Furthermore, it is proposed to establish clear policies for the management and protection of data associated with the various STEM activities, in addition to developing the infrastructure to integrate various sources of information in a secure and ethical manner.

It is worth mentioning that adaptive platforms face difficulties in adjusting to the various course structures and present usability problems related to navigation and visual design, which limits their pedagogical use and the learning experience of both students and teachers (Fischer et al., 2022; Zairon et al., 2025).

On the other hand, it is recommended to work on developing flexible, adaptive platforms that integrate intuitive interfaces and accessible visual designs, and that can be adapted to the complexity and diversity of courses taught in science, technology, engineering, and mathematics. Therefore, a user-centered design approach and ongoing interdisciplinary collaboration are required.

Regarding the challenges identified in the axis of pedagogical integration of technology, it was found that the integration of AI tools in educational environments faces scalability problems and difficulties in effectively incorporating student input into AI decision-making processes, which limits its capacity for personalized and contextual adaptation (Sung et al., 2025; Yan et al., 2024).

Therefore, it is suggested that work be done on developing more transparent and scalable AI tools capable of integrating student responses and experiences as an essential element influencing the adaptation process. This would lead to more dynamic and equitable personalization, especially in STEM contexts where interaction with technology and problem-solving are fundamental to learning.

On the other hand, intelligent tutoring systems and adaptive educational platforms face the risk that the AI-generated automatic feedback they provide to students may be perceived as inauthentic or insufficient, mainly due to the lack of personalized guidance and the reliance on automated control, which greatly reduces interaction between students and the system (Clark et al., 2022; Contrino et al., 2024; Sung et al., 2025; Yan et al., 2024).

Therefore, we propose working on the development of more humanized and well-contextualized feedback mechanisms that provide pedagogically sound feedback and achieve a balance between automation and teacher intervention. This approach fosters learning experiences where AI complements, rather than replaces, teacher support, aiming to increase motivation, confidence, and satisfaction when using adaptive platforms.

Platforms are subject to the limitations of the language models they employ and have difficulty capturing students' affective states in real time, which implies the need to continuously retrain the model (Sung et al., 2025; Wu et al., 2023; Yan et al., 2024).

This highlights the need to move towards AI models that are more sensitive to the emotional and cognitive aspects of students, capable of integrating multimodal and up-to-date information to facilitate effective monitoring of their learning. Additionally, it is necessary to strengthen the continuous training processes of these models to improve the detection and analysis of interactions with objects and situations specific to scientific and technological disciplines, thereby ensuring more precise and meaningful adaptation.

This analysis made it possible to identify that, within the technical challenges related to the four indicated axes, the one most cited by the authors is that which refers to the various problems related to the automatic feedback generated by AI that is presented to students within adaptive platforms.

Pedagogical challenges

The analysis of the selected works also allowed for the identification of challenges within the pedagogical field of studies. These challenges primarily highlight the need to balance the automation of learning processes with human intervention, to integrate transversal skills, and to improve attention to the cognitive and motivational diversity of students (OECD, 2019). Based on the systematic review, five main areas were identified: learning diversity, self-regulated learning, teaching practice and institutional support, curriculum design and competencies, and motivation and feedback.

Within the learning diversity axis, it was identified that providing support to at-risk students with diverse needs continues to represent a challenge in STEM environments, due to the need to implement multidimensional approaches that consider cognitive, affective and demographic factors, and that respond adaptively to the individual differences that influence student performance and participation (Pilotti et al., 2022; Vyas et al., 2021).

This challenge highlights the importance of designing inclusive and personalized learning strategies that consider the diverse characteristics and needs of students. Furthermore, it requires integrating adaptive learning models that take into account individual and contextual differences, and that promote educational equity and reduce achievement gaps, especially in subjects associated with high dropout or failure rates.

Identifying the factors that influence academic performance is complex due to the diversity present in students who learn in a language other than their mother tongue, which requires designing and implementing parameters and indicators that help guide learning behavior in different STEM courses and accurately show their individual and contextual differences (Pilotti et al., 2022; Xia y Qi, 2024).

It is necessary to develop adaptive platforms that are sensitive to cultural and linguistic aspects, with the capacity to dynamically adjust learning parameters according to students' profiles. This would allow teachers to design more inclusive and effective experiences for students learning in a second language, improving both their conceptual understanding and their participation in diverse scientific and technological areas.

The validity and effectiveness of prediction functions in adaptive platforms depend largely on the ability to make periodic updates and adaptations based on changes in behavioral characteristics and forms of interaction, as well as overcoming the complexity of designing and implementing individual learning paths that accurately reflect learning in STEM contexts (Pilotti et al., 2022; Xia y Qi, 2024).

This challenge highlights the need to strengthen the mechanisms for analyzing and continuously validating predictive models, ensuring they reflect the evolution of learning behaviors and the interactions between concepts. This requires the use of individual learning paths that integrate dynamic knowledge graphs or nodes, and analytical tools capable of capturing the complexity and constant changes of learning in scientific and technological disciplines.

In the area of self-regulation of learning, considerable limitations were identified, mainly caused by factors such as the lack of support from teachers, the use of single evaluation approaches that do not consider individual differences, and the need to develop personalized digital educational resources in advance that promote autonomy and self-evaluation of students (Clark et al., 2022; Yan et al., 2024).

This challenge indicates that institutional teacher training programs must include strategies to support self-regulated learning, as well as implement and promote the use of flexible assessment systems that adapt to each student's pace and learning style. It also requires adequate teacher planning of time and resources needed for the design and development of personalized digital educational resources that support autonomous planning, monitoring, and reflection on learning progress, thereby contributing to the development of scientific and technological competencies.

The deficiency in the development of self-regulated learning skills is mainly caused by the inaccuracy in self-monitoring of learning and by the difficulty students face in distinguishing actual knowledge from assumptions in binary assessments, which makes it difficult to provide accurate feedback for continuous performance improvement (Yan et al., 2024).

There is also a need to incorporate metacognitive strategies and adaptive tools that foster the development of self-regulated learning and facilitate more precise monitoring of individual progress. This integration would allow for the design and implementation of more comprehensive assessment instruments that overcome the limitations of the traditional format. This could improve the understanding of scientific and technological concepts specific to STEM fields, further promoting evidence-based learning, critical reflection, and continuous improvement.

Regarding the teaching practice and institutional support axis, the active participation of both teachers and students continues to represent one of the main challenges, particularly when interaction occurs through virtual environments. Likewise, teachers' ability to provide timely and personalized attention to these students is often hampered by technological and communication barriers, leading to equity issues in interaction and pedagogical support (Sockalingam et al., 2025).

This challenge demonstrates the need to design hybrid strategies that promote the equitable participation of all students, regardless of their location. It also highlights the need to implement actions aimed at strengthening teachers' skills in digital mediation and remote support, thereby fostering the integration of collaborative learning experiences and effective communication in distributed learning environments.

Identifying innovative and effective pedagogical and andragogical approaches presents an ongoing challenge for teachers and instructional designers, driven primarily by the rapid and constant evolution of adaptive learning technologies and research processes. These processes foster the emergence of innovative tools that facilitate the implementation of models such as cyberphysical learning, adding to this challenge the need to develop integrated technical and pedagogical understanding skills (Contrino et al., 2024; Sockalingam et al., 2025).

These challenges necessitate the adoption of flexible pedagogical methodologies to integrate principles of active and adaptive learning, as well as andragogical strategies to foster autonomous and experiential learning. They also require the implementation of ongoing professional development processes to enhance teachers' digital skills, enabling them to implement innovative pedagogical models and utilize the necessary technological tools.

Another challenge identified in this area stems from factors such as students' lack of engagement when activities are not part of the assessment or are not perceived as mandatory, the high value students and teachers place on face-to-face interaction, and resistance to change within the education system, all of which hinder the adaptation of practical and collaborative learning to online environments. Limitations in the adoption of innovative methodologies and the full utilization of adaptive technologies make it difficult to move towards hybrid or fully digital models (Contrino et al., 2024; Sockalingam et al., 2025).

It is recommended to design practical and collaborative learning experiences using simulators, virtual labs, and immersive learning environments that foster active participation and collaboration in knowledge construction. Furthermore, it is necessary to promote an institutional culture of openness to change, accompanied by change management strategies and professional development for faculty, to effectively integrate adaptive learning in hybrid and digital contexts.

Situations such as the assumption of a similar level of prior knowledge among students, time and focus constraints in studies, the institutional context and the particular profile of the students; generate significant limitations when designing adaptive courses, hinder the transfer of findings and adaptive technologies, and affect the observation of long-term progress and the generalization of results (Contrino et al., 2024; Sockalingam et al., 2025).

These challenges highlight the importance of designing adaptive platforms that consider the diversity of prior knowledge levels, institutional conditions, and the specific characteristics of students. It is also suggested that research be encouraged to further improve and optimize personalization models and adaptive learning solutions.

In the area of curriculum design and competencies, it was found that factors such as the lack of alignment between course objectives, skills transferable to work, and the difficulty in integrating transversal competencies such as communication, teamwork, and systemic thinking, make it necessary to link STEM training with real professional situations through more comprehensive curricular and evaluative strategies (Fischer et al., 2022; Tang y Odeleye, 2023).

These challenges involve evaluating and redesigning curricula and learning activities to foster the development of transferable skills alongside technical knowledge. It is also necessary to strengthen assessment strategies so that they evaluate not only theoretical knowledge but also the development of fundamental STEM skills, such as collaboration, communication, and complex problem-solving abilities.

The lack of teacher training to implement competency-based learning strategies, coupled with student resistance to working on the development of non-technical skills, hinders the implementation of educational strategies that respond to the complexity, abstraction, and multidimensionality that characterize STEM activities, also limiting the connection between theoretical and conceptual knowledge with the development of transferable skills necessary for professional practice (Fischer et al., 2022; Tang y Odeleye, 2023; Wu et al., 2023).

This shows the need for the implementation of teacher training programs regarding competency-based instructional design, and to foster among students a learning culture that values both technical and transversal skills, implementing integrative learning experiences of STEM problems.

Obstacles were also identified in linking learning activities with real professional environments, mainly due to the inherent difficulty of STEM activities and the dynamic and complex nature of the learning process, which makes it necessary to implement comprehensive assessment instruments that consider both theoretical elements and procedures and attitudes in student performance (Tang y Odeleye, 2023; Wu et al., 2023).

This implies the need to develop innovative teaching strategies and holistic assessments that integrate real problems from the professional environment, to foster a more applied, reflective and coherent learning with the complexity of scientific and technological work.

Regarding the motivation and feedback axis, one of the main challenges identified is the difficulty in maintaining student motivation and self-efficacy in challenging technical environments. This is primarily caused by the stress of excessive workload and the time required to adequately complete activities on adaptive platforms, as well as the risk of distraction and demotivation when performing repetitive or meaningless tasks. These conditions can negatively impact students' persistence and commitment to working in highly demanding STEM contexts (Clark et al., 2022; Díaz y Aizman, 2024; Sung et al., 2025).

Therefore, it is recommended to design and implement adaptive learning courses that balance the level of cognitive demand with emotional well-being, incorporating mechanisms that provide relevant feedback, and considering reasonable practice times and activities that maintain the relevance and interest of students in the learning process.

It is suggested that a balance be struck between empathy and the tone of feedback given to students to improve their motivation, especially when combined with a lack of teacher support, which can affect students' autonomy and confidence in working on their own learning process. Providing inadequate or insufficient feedback negatively impacts both motivation and the development of metacognitive strategies in STEM education (Sung et al., 2025; Yan et al., 2024).

Furthermore, it is necessary to implement actions that promote the development of teaching skills regarding the integration of affective feedback processes and the support of self-regulated learning, thus seeking greater empathy and personalization in interactions and fostering the development of student autonomy.

The lack of specific affective feedback skills typical of novice teachers, coupled with the demand for face-to-face interaction with the teacher by students, makes it necessary to implement actions aimed at strengthening the communication and socio-emotional skills of teachers, through which they will be able to design strategies that allow them to maintain closeness and support with students, improving motivation and meaningful learning in STEM contexts (Contrino et al., 2024; Sung et al., 2025).

This will involve developing teacher training programs focused on affective feedback skills and on the design of hybrid experiences that incorporate the advantages of human support when working in digital environments.

The diverse perceptions surrounding the use of adaptive learning demonstrate that, while it promotes retention, it can generate frustration among students with lower levels of prior knowledge. This situation is exacerbated by factors such as low student engagement when required to complete non-mandatory activities, poor implementation of innovative educational strategies, and the complexity of adapting activities and resources to different learning styles. Furthermore, the lack of self-regulation and self-monitoring techniques negatively impacts student participation and autonomy in adaptive STEM environments (Contrino et al., 2024; Díaz y Aizman, 2024; Yan et al., 2024; Zairon et al., 2025).

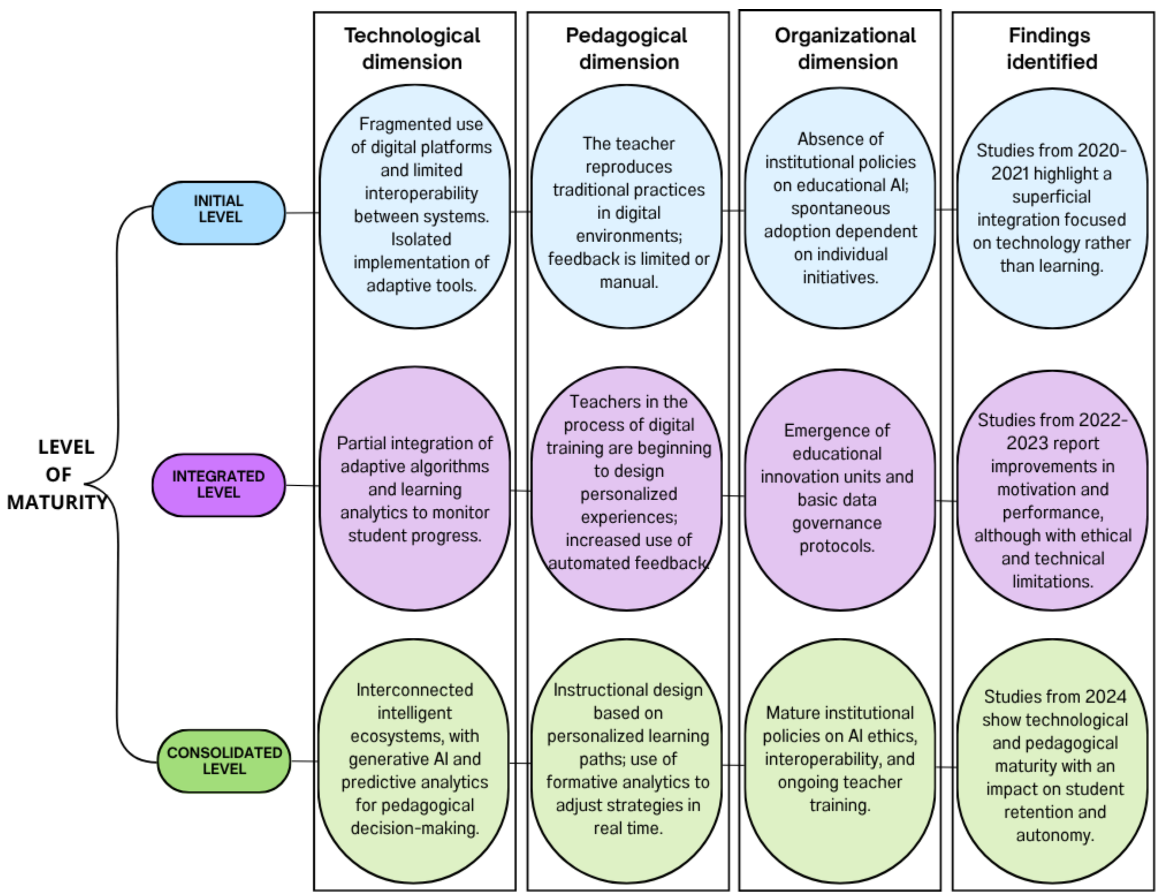
This challenge indicates that it is necessary to design adaptive courses that integrate meaningful teaching strategies, formative monitoring, and support resources that help to achieve adequate development of self-regulation skills, seeking to improve the motivation and active participation of students regardless of their different levels of competence.

Techno-pedagogical maturity model

Techno-pedagogical Maturity Model (TMM) was proposed, consisting of three evolutionary levels, inductively derived from the review, which describe how higher education institutions advance in the integration of AI-based adaptive learning systems.

In the proposed model, the technological, pedagogical, and organizational dimensions are gradually integrated, moving from a limited use of digital tools to an educational culture that adapts learning to the needs of each student; therefore, it is conceived as a progressive model. Figure 4 shows the proposed MMT.

Figure 4. Techno-pedagogical Maturity Model (TMM)



Source: Own elaboration

At the primary level, technology is used in a basic and disconnected way. Teachers commonly replicate traditional methods online, and there is no institutional strategy to guide the process. The focus is more on the tool itself than on improving learning.

At the integrated level, institutions begin to link technology with teaching. Platforms with basic analytics are used, and more personalized learning experiences are promoted. At this level, teams or departments are typically formed to support educational innovation.

Finally, technology, pedagogy, and organization work in a coordinated manner. Intelligent systems and advanced analytics are used to adapt learning to each student, and the institution promotes a sustainable, student-centered digital culture.

Discussion

The analysis of studies in this systematic literature review provided insight into how adaptive learning has been implemented in higher education within the STEM fields internationally. In addition to describing experiences, the comparative analysis of cases reveals significant overlaps and gaps in evidence, reflecting both the potential and limitations of this approach.

In STEM fields, learning is built through experimentation, problem-solving, and the manipulation of variables in real or simulated contexts. However, it is important to consider that this type of learning requires hands-on activities, laboratory work, and collaborative projects that cannot always be adequately replicated using the adaptive platforms available at institutions.

Furthermore, educators and researchers currently face the challenge of adapting adaptive learning models to situations that go beyond simply tracking progress or personalizing content. Therefore, a more holistic approach is proposed to incorporate collaborative dynamics, problem-solving, and critical thinking.

As Wu et al. (2023) point out, traditional platforms have limitations in capturing and evaluating complex and evolving learning processes, especially those that depend on peer interaction and the collective construction of knowledge. Therefore, the challenge lies not only in incorporating technology but also in designing learning ecosystems capable of integrating all the characteristics of STEM fields.

The analysis shows that the most recent systematic reviews on adaptive learning in higher education have contributed significantly to the topic. However, in several cases, they omit distinctive elements of the STEM context, where teaching is based on experimentation, problem-solving, and the practical application of knowledge. This is the case in the work of Rodríguez Aroca (2024), which does not address the specific pedagogical and technological characteristics of scientific and engineering disciplines. This limits the understanding of the scope of adaptive learning.

Regarding the use of adaptive platforms, the landscape identified is varied. There is no clear preference for a specific platform, reflecting the diversity of institutional contexts and pedagogical needs.

Although Prada Segura and Beltrán Gómez (2024) mention that Moodle continues to be one of the most widely used platforms in higher education, the review shows a contrast in the STEM field. Of the studies analyzed, only Díaz and Aizman (2024) used Moodle with an adaptive approach, while other researchers opted for other commercial solutions or their own developments.

LMS, a greater application of adaptive learning experiences was identified in areas such as mathematics and chemistry, which historically have high rates of failure and dropout (Tang & Odeleye, 2023). It can be inferred that adaptive learning has been implemented as a strategy to address the challenges of conceptual understanding and student motivation inherent in these disciplines.

The results also showed that students perceive adaptive learning positively, mainly due to the clearer explanations, continuous feedback, and practice opportunities it offers compared to traditional environments (Tang & Odeleye, 2023). This reinforces the idea that the potential of adaptive learning in STEM lies not only in the technology used, but also in its ability to address the specific challenges of these disciplines.

Additionally, the reviewed articles show that adaptive learning has positive effects on higher education in STEM fields, improving performance, motivation, and learning, especially in hybrid courses that combine face-to-face and online learning. However, it is noted that in some areas, such as the sciences (except chemistry), there is limited research evidence analyzing its application, which presents a significant opportunity to expand its study from a techno-pedagogical perspective.

The results also align with previous research highlighting the benefits of adaptive learning for improving performance in disciplines such as mathematics, programming, and engineering (Holmes et al., 2022). However, the analysis suggests that the success of adaptive learning depends less on the level of technology used and more on its pedagogical integration and the support provided by the teacher. In this regard, we agree with Simó et al. (2020), who point out that technology, without a solid curriculum design and a supporting institutional framework, does not guarantee meaningful learning. Therefore, the importance of developing models that integrate technological and pedagogical innovation becomes clear.

It should be noted that significant limitations were also identified, such as resistance to change from both teachers and students, stress associated with the intensive use of platforms, and infrastructure gaps, especially in countries with less educational innovation. These results contrast with publications that present adaptive learning as a “universal” solution, without acknowledging the diversity of contexts (Johnson et al., 2012).

In terms of international comparison, it is observed that countries with educational systems boasting greater digital infrastructure and innovation, such as the United States, Singapore, and Finland, show a higher concentration of studies on the implementation of adaptive learning compared to Latin America and some regions of Asia. This situation aligns with the findings of the United Nations Educational, Scientific and Cultural Organization (UNESCO), which warns of existing gaps in the digitalization of higher education (UNESCO, 2023).

Additionally, the proposal regarding the MMT demonstrated that the success of adaptive learning depends not only on having adequate infrastructure and technological tools, but also on their coherent integration with teaching and institutional organization. When a university makes progress in these three areas, it ceases to use technology merely as a complement or support and begins to transform into an institution that makes educational decisions based on performance data and pedagogical outcomes.

Conclusions

The results obtained with this research allow us to partially confirm the initial hypothesis which indicates that the implementation of adaptive learning in higher education in STEM areas, when mediated by a techno-pedagogical design, contributes positively to academic performance and student motivation, since its effectiveness depends largely on techno-pedagogical, institutional and contextual factors.

First, the analyses showed that adaptive learning generates consistent benefits in disciplines such as mathematics, programming, and chemistry, areas where improvements in performance, continuous assessment, and positive student perception were identified. These results align with the information found in the reviewed articles, which mention the potential of adaptive learning to reduce early dropout rates in STEM programs, especially in the first two years of study, as indicated in the reviewed literature.

Secondly, the results showed that the main technical challenges are concentrated in adaptive learning platforms and the use of AI. The need for integration with institutional Learning Management Systems (LMS), usability issues, and limitations of AI models represent recurring obstacles.

The results indicate that adaptive learning represents an important opportunity for STEM higher education, provided it is implemented sustainably, aligning curriculum design, teacher support, ethical considerations, and pedagogical approach.

It is also important to highlight that this research identified recurring limitations such as resistance to change, stress derived from the intensive use of platforms, and the infrastructure gap in some educational contexts, which limits the generalizability of the results. Furthermore, the search was limited to articles published only in Scopus and Web of Science. Science.

Future lines of research

The importance of conducting further research based on the results of this study is highlighted, particularly research that analyzes how adaptive learning operates in practical situations, such as laboratories or experimental activities in STEM areas identified as underexplored, such as physics or biology. Therefore, it would be useful to compare different types of platforms, both commercial and those developed by the universities themselves, to understand their true impact on learning.

It is also suggested that further research be conducted on how AI and learning analytics can support teachers in their pedagogical decision-making. Finally, it is suggested that models be developed that include not only cognitive aspects but also emotional and social factors, in order to make learning student-centered and personalized. This is proposed with the aim of improving students' perceptions of the automated feedback they receive on adaptive learning platforms.

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