Scientific Whispers: Mapping Innovative Pedagogies in STEAM and Programming Education

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Abstract

Traditional education, especially in STEAM and programming, faces several challenges in capturing the attention and stimulating the new student generation. These challenges are exacerbated by rigid teaching methods and reflect a global difficulty in the educational sector, primarily stemming from the disconnect between traditional teaching and the contemporary needs of the modern world. This article presents a systematic literature review with a mapping study to explore innovative approaches currently employed in teaching, specifically focusing on STEAM and programming education. The conclusions reached make a significant contribution to the field of education, and the mapping conducted has identified the teaching methodologies most researched and investigated by the scientific community. This research also presents a classifying proposal for those methodologies, considering their characteristics and weighing up three dimensions: resources, implementation and receptiveness. As a final reflection, some emerging methodologies were identified that are believed to have great potential to be used for STEAM and programming education.

2012 ACM Subject Classification Applied computing → Education; Software and its engineering → General programming languages

Keywords and phrases Education, STEAM Education, Programming Education, Teaching Methodologies, Innovative Approaches, Mapping, Systematic Literature Review

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1 Introduction

Traditional education has experienced several challenges over the years. With the massification of new technologies and the transition to the digital age, there have been many challenges for the education sector to capture the attention and motivate new generations, who are increasingly in need of digital contact and simplification of long and time-consuming procedures. The majority of today's university students belong to generation Z [3, 16], a group strongly characterized by the presence of the internet and who have a greater command of technology than previous generations, with whom they are closely linked [14]. They are fans of practicality, independent and self-taught, digital natives [14], always connected, a hyper-cognitive generation with the ability to experience several realities at the same time, although their attention span is very short as they are used to get quick answers. In the academic environment, these students are looking for an experience as similar as their

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personal environment, with high interactivity and fluidity of processes, combined with new technologies. They prefer to learn in a more autonomous and flexible way, where they are allowed to experiment without there always being an associated punitive nature [19, 13].

The overall difficulty experienced in teaching is mostly related to the disconnection between traditional teaching and the needs of the modern world. In recent decades, there have been few real changes in teaching methodologies and approaches, which remain deeply rooted in the educational system, which has not been able to evolve at the same vertiginous speed as today's world and, with it, students. Consequently, the stagnation of teaching methodologies has caused strong demotivation and hindered the full learning of 21st century students. Often based on unidirectional methods and the memorization of information [4], traditional teaching thus faces the challenge of combining with new technologies to compete for the attention of the younger generations, by seeking to simplify procedures and create more dynamic contexts adapted to the needs of students in the modern world [7].

The new technologies have proved to be the greatest allies in the renewal of teaching, particularly in the STEAM fields (acronym for Science, Technology, Engineering, Arts and Mathematics), by enabling the creation of differentiated and innovative teaching strategies. They provide greater personalization, flexibility and adaptation to the individual needs of students. With digital platforms and educational applications, teaching can be more flexible and will allow students to progress at their own pace and have access to additional resources to help them deepen their knowledge [9].

Programming teaching is considered by Caspersen and Bennedsen [2] to be one of the seven great challenges of computer education. There are various theories around the factors considered essential in effective education, such as providing feedback, organizing tasks by level of complexity, creating personalized content [5] or offering real-time student support [20]. Over time, there has been a perception among students that the methodologies used in traditional teaching were useless and boring, and teachers have tried to introduce new pedagogical approaches to reverse this impression. Despite these initiatives, students maintain a general feeling of demotivation [5].

In view of the challenges faced by traditional programming teaching, the main aim of this work is to carry out a Systematic Literature Review (SLR), mapping recent studies, to identify innovative methodologies and pedagogical approaches that have been recommended, analyzed and developed to improve programming teaching and that allow students to be truly involved in learning and overcome the real teaching difficulties.

This article is organized into four sections. The first section introduces the topic and defines the study's objectives. The second section outlines the research methodology, including the formulation of the research question, the chosen research strategy, and the results of the literature review, which maps both quantitative studies and catalogued data to provide an overview of the current state of the art and scientific contributions related to innovative educational methodologies or approaches. The third section analyzes the results and includes a proposal for classifying the most researched methodologies based on their characteristics. Finally, the fourth section presents the study's conclusions and discusses future work, including recommendations for further research.

2 Methodology

In line with the general objective described and the motivations associated with the development of this research, a Systematic Literature Review (SLR) was conducted to identify and evaluate scientific production relevant to the topic under analysis and to synthesize existing

research, providing essential information for further studies. This work follows the guidelines of Kitchenham [10], which emphasize the importance and advantages of SLRs and establish a clear, easily reproducible, and highly efficient procedure for conducting them [11, 21].

Research question

It is essential to understand the distinction and interconnection between different levels of pedagogical instruments: educational approaches, teaching methodologies, techniques and tools, and technological applications [6]. Grasping these interconnected concepts is crucial for developing pedagogical practices that are both theoretically sound and practically effective. However, for this research, given the common use of the term "methodology" in educational contexts (where it encompasses any instrument related to pedagogical practices), the terms "methodologies" and "approaches" are employed broadly, without differentiation between the various pedagogical instruments.

The following research question (RQ) was formulated for this research:

RQ: What innovative methodologies and pedagogical approaches have been identified, tested and developed to improve programming education?

Search strategy

Considering the scale of the subject under analysis, a different approach to defining the search string was considered. A strategy of identifying relevant or related keywords was chosen through a bibliometric analysis in VOSviewer. This analysis facilitated the study of the word network associated with the main terms and allowed for the refinement of search filters in a more rigorous way. Therefore, a broader search was conducted in the Scopus database, with the following string:

TITLE-ABS-KEY ((programming OR stem OR steam) AND (education OR teach* OR learn* OR classroom OR school) AND (methodology))*

The file containing the 10744 results was exported, including information on the abstracts and keywords. Words with at least 35 occurrences were considered in VOSviewer. Upon analyzing the word network obtained, it became evident that additional relevant or related words needed to be included, while certain terms like "covid" and "data mining" needed to be excluded, since they largely hidden the real results that were intended to be achieved.

The base search string was readjusted as follows:

TITLE-ABS-KEY ((new OR novel OR innovat*) PRE/0 (method* OR approach*) AND (programming OR stem OR steam) AND (education* OR teach* OR learn* OR classroom OR school OR pedagog*)*

This search string includes terms such as "method", "methodology", or "approach" because these words are commonly used to refer to methodologies. Similarly, terms like "education", "teaching", "learning", "classroom", "school", or "pedagogy" were included, as any of these can denote learning environments. The search targeted programming or STEAM disciplines. Most terms in the search string carry the wildcard operator to encompass diverse variations of each term (e.g., "education" or "educational" for the term "education*"). Regarding the word "classroom", it was decided to use the complete word instead of the broader term ("class*"), as the latter returned too many articles related to programming classes. The proximity operator 'PRE/0' was employed between the terms associated with "innovative" and those associated with "methodology" to ensure these words appeared sequentially and in this exact order.

The research exclusion criteria were directly applied to the terms intended for exclusion, and the following condition was added to the base string:

AND NOT ("covid-19" OR "data-mining" OR "neural network" OR "machine-learning" OR "deep-learning" OR reinforce* OR algorithm* OR genetic OR clustering OR classification OR optimization* OR graph* OR cybersecurity))*

The research inclusion criteria were also incorporated: documents published in the last 5 years, restricted to articles and conference papers in the fields of Computer Science and Engineering, written in English or Portuguese. These criteria were applied after the exclusion criteria:

AND PUBYEAR > 2018 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "ENGI")) AND (LIMIT-TO (LANGUAGE, "English") OR LIMIT-TO (LANGUAGE, "Portuguese"))

Results

The search string was used to query Scopus database in its "advanced search" mode, resulting in 390 documents. A new analysis of the word network visualized in VOSviewer confirmed the accuracy of our search targeting. Upon analyzing the documents retrieved from the Scopus search, it was observed that 2023 had the highest scientific production on this topic, with 88 papers published, compared to 64 publications in 2021, indicating a noticeable upward trend in the exploration of innovative teaching methodologies (Figure 1).

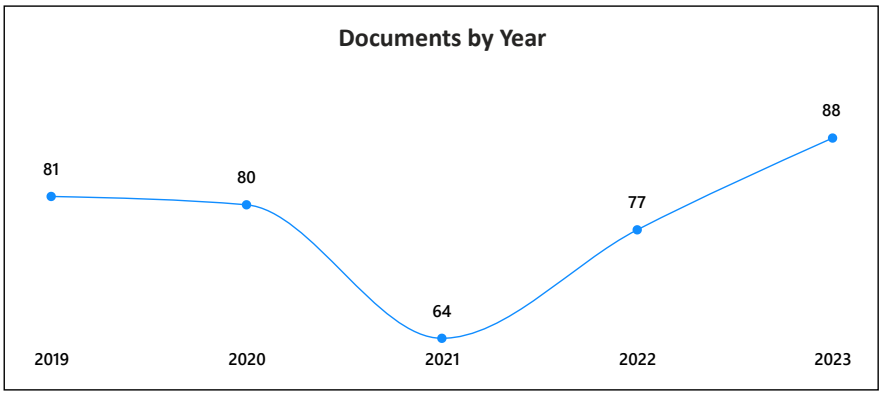

Figure 1 Documents by year.

The three areas in which this research was most concentrated were Computer Science, Engineering and Social Sciences. Leading contributors to scientific production in this field included the United States, China, and Germany, with Portugal ranking eleventh based on 13 articles published in the last five years out of a total of 390 documents. Of these, 119 were scientific articles, and the remaining 271 were conference papers.

In the first analysis of the 390 documents, 9 duplicate articles were identified and excluded. The analysis of the remaining 381 documents was based on the title, author keywords and abstract fields, resulting in the exclusion of 124 documents deemed outside the scope of the research. These documents covered topics such as oil well exploration, medicine, sustainability, labor studies, and more specific topics like artificial intelligence and learning models, industrial

robotics, application programming interfaces (APIs), optimization and aerospace programs, which were not considered teaching methodologies. This selection process yielded a first final set of 257 papers.

The documents selected for a more in-depth analysis were categorized based on the following criteria: type of research (literature review or case study), geographical scope (country and continent; where not specified, author affiliation was used to determine geographical context), educational setting (educational level where the study was conducted), curricular area associated with each study, primary and additional subjects, and whether these subjects could be considered as approaches or methodologies for teaching programming. The results of this categorization are presented in Figures 2, 3, and 4.

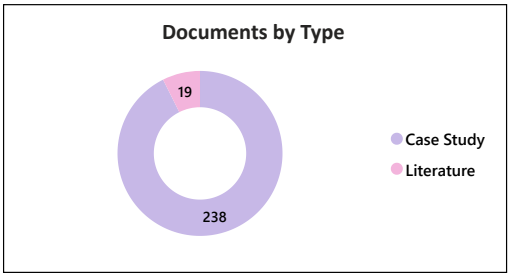

Figure 2 Documents by type.

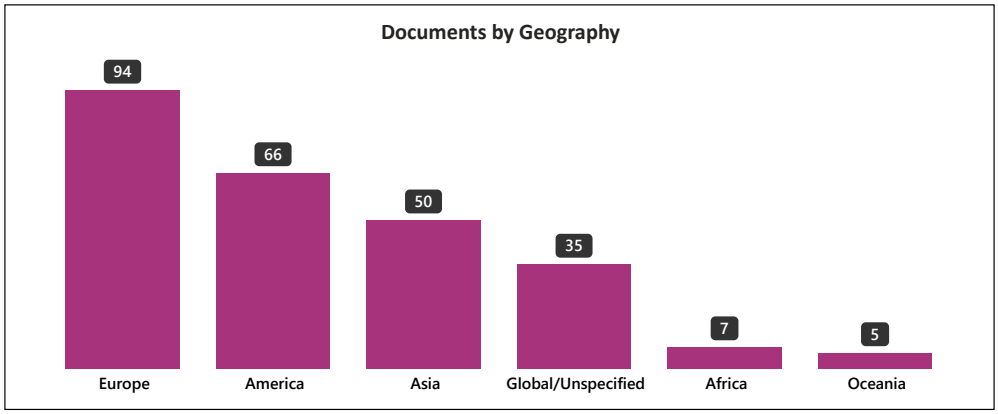

Figure 3 Documents by geography.

It should be noted that the three countries with the highest number of studies were the United States with 54, Spain with 14, and Germany with 10. Portugal conducted 5 studies in this research.

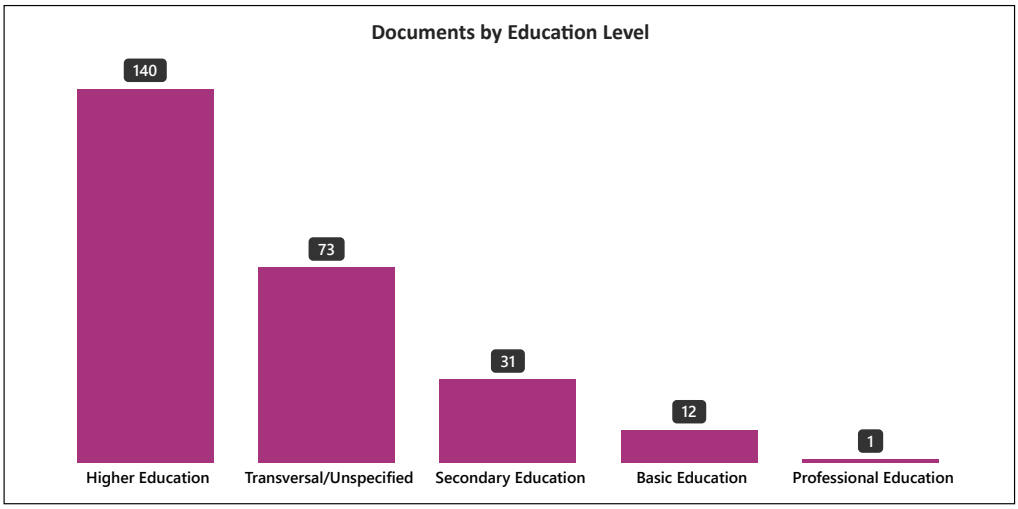

Figure 4 Documents by educational level.

The information regarding the school subjects is presented in Figure 5.

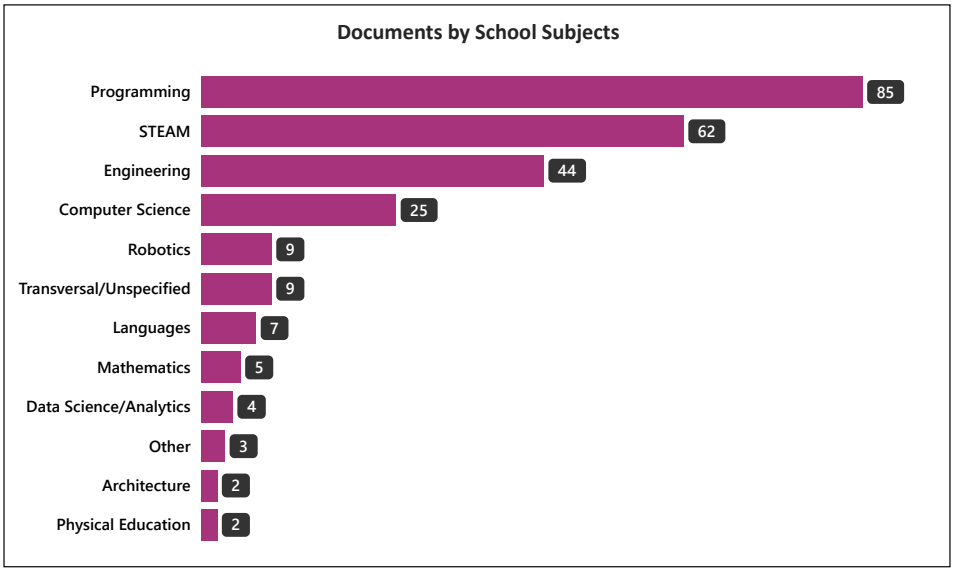

Figure 5 Documents by school subjects.

Considering the main themes of the analyzed studies, while all may be relevant for implementing significant improvements in the education system, it is significant to determine whether each identified theme can attend as an approach or methodology in programming teaching. Among the subjects identified in the 257 publications analyzed, 67 were deemed unsuitable for implementation as innovative approaches to programming education and were excluded. The five core subjects most frequently mentioned in these publications were accessible/inclusive education, learning analytics, teacher development, ethics, and human behavior.

The remaining 190 publications addressed core or additional subjects related to potential teaching methodologies, techniques, or approaches. Figure 6 presents the most frequently mentioned topics, based on the total number of occurrences across both core and additional subjects.

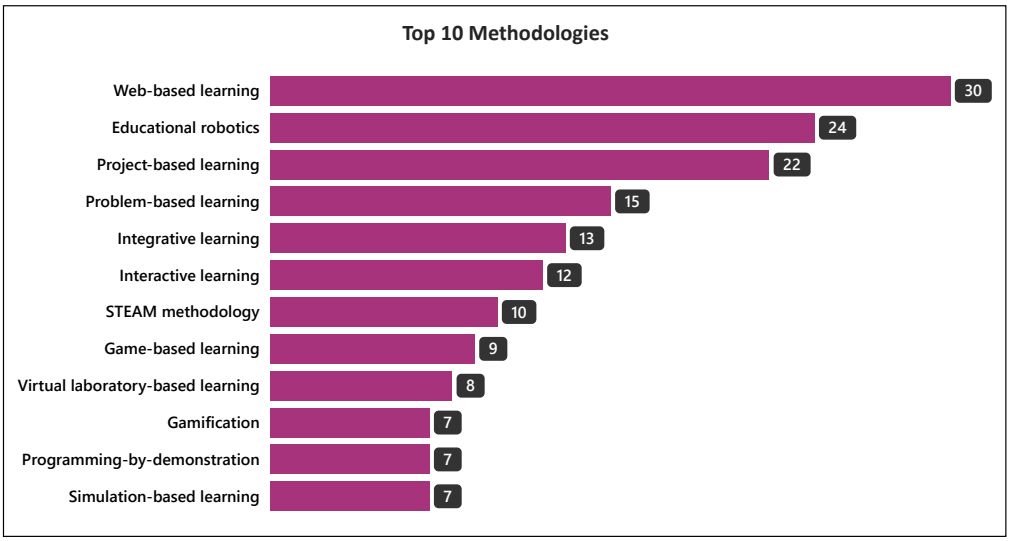

Figure 6 Top 10 methodologies caption*.

* The figure displays twelve results, as the last three entries record the same number of occurrences.

There is a clear trend towards studying "web-based learning" pedagogical approaches, which include the use of web-based platforms as educational resources. Some familiar terms, such as "project-based learning" (which involves the development of projects as the basis of learning), "problem-based learning" (where students learn by solving real-world problems), or even the "STEAM methodology" (an integrated learning approach that requires an intentional linking of rules, assessments, and the design and implementation of lessons between two or more STEAM subjects to be taught, assessed in, and through each other) continue to be investigated as pedagogical approaches that can create significant changes in teaching.

The synergy between curriculum areas is particularly noteworthy, especially with the integration of "educational robotics" to enhance programming education. Equally significant are methodologies related to the use of games in the educational context ("gamification" or "game-based learning"), which are increasingly studied as innovative teaching approaches. Key terms such as "outcome-based learning", "augmented reality", "block-based programming", "educational Internet of Things" (IoT), "intelligent tutoring systems" (ITS), "mobile-based learning", and "virtual reality", along with other less frequently mentioned terms, were also identified.

A special note on the following concepts: "agile teaching", an educational approach that applies agile principles widely used in industry, identified in papers [8, 18, 1]; "educational escape rooms" (EER or DEER) [12, 17], an emerging concept linked with gamified or game-based learning methodologies that introduces a potentially innovative teaching approach known as "out-of-the-box learning"; and "work-integrated learning", which incorporates work-based training as an educational approach [15].

Figure 7 illustrates the flowchart used for selecting the relevant articles for the SLR.

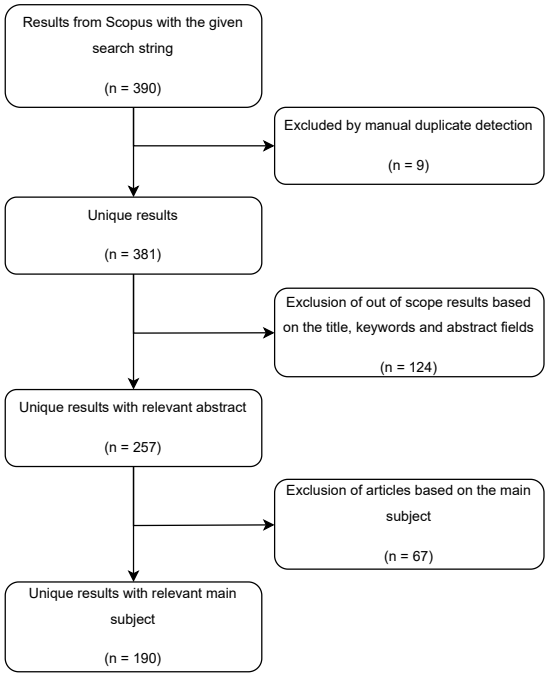

Figure 7 SLR workflow.

3 Discussion

The results obtained from literature mapping have enabled us to draw initial conclusions regarding recent efforts focused on analyzing specific methodologies. Figure 6 illustrates the methodologies or approaches identified most frequently in the studies analyzed.

Each methodology possesses unique characteristics, ranging from its objectives and required resources or knowledge, to the time-frame for effective implementation, the additional efforts educators need to invest for success, and its anticipated impact on students, among other factors. These characteristics yield both advantages and disadvantages that must be carefully assessed, as they significantly influence the choice of methodology to adopt.

A classification proposal of the main methodologies identified in Figure 6 is presented, considering the characteristics that emerged from reading and analyzing the articles referring to them. No additional studies have been conducted on specific approaches to classifying the use of teaching methodologies. For this classification proposal, three dimensions were considered: resources, implementation and receptiveness.

In the resources dimension, situations requiring additional infrastructures (technological or otherwise) not typically found in standard educational settings were considered. This dimension focuses on analyzing the potential impacts of costs (for developing or acquiring these infrastructures) and support (such as the need for a specialized infrastructure support team).

In the implementation dimension, which examines the actual application of the identified methodology in real educational contexts, factors of difficulty and time were considered. Difficulty refers to the level of challenge in implementing the methodology, such as interdis-

ciplinary requirements, collaborative efforts among teachers, or integration difficulties into traditional curricula. Time indicates the expected implementation duration, whether the methodology can be implemented immediately or requires a longer timeframe.

Lastly, the receptiveness dimension assesses the acceptance of the innovative methodology, considering both the educator pillar (which examines additional challenges or those that require greater efforts from teachers) and the student pillar (which reflects the motivation with which students might embrace this methodology, particularly if it is deemed innovative, disruptive, and aligns with their educational expectations).

For each of the six criteria mentioned, a scale of 1 to 5 was utilized, with 1 indicating "very poor" and 5 indicating "excellent". Figure 8 illustrates the ratings assigned to each dimension and provides an overall score for each methodology.

Methodology	Resources		Implementation		Receptiveness		Overall Score
	Cost	Support	Difficulty	Time	Educator	Student	
Web-based learning	3,00	3,00	4,00	4,00	3,00	4,00	3,50
Educational robotics	2,00	2,00	3,00	3,00	3,00	5,00	3,00
Project-based learning	4,00	4,00	3,00	4,00	3,00	4,00	3,67
Problem-based learning	5,00	5,00	3,00	5,00	4,00	3,00	4,17
Integrative learning	3,00	3,00	2,00	3,00	3,00	5,00	3,17
Interactive learning	4,00	5,00	4,00	5,00	3,00	3,00	4,00
STEAM methodology	2,00	2,00	2,00	2,00	3,00	5,00	2,67
Game-based learning	3,00	3,00	3,00	4,00	4,00	5,00	3,67
Virtual-laboratory based learning	1,00	2,00	3,00	3,00	3,00	5,00	2,83
Gamification	3,00	3,00	3,00	4,00	4,00	5,00	3,67
Programming-by-demonstration	4,00	4,00	3,00	4,00	3,00	4,00	3,67
Simulation-based learning	2,00	2,00	3,00	3,00	3,00	5,00	3,00

Figure 8 Top 10 methodologies classification.

Through the analysis of the overall classification, we can observe that "problem-based learning" and "interactive learning" are the two methodologies with the highest scores. It is noteworthy that these methodologies do not require additional resources in such an indispensable manner, and their ratings in this dimension are higher compared to other methodologies, which influenced the final score. They are also methodologies that can be implemented in less time and do not involve excessive implementation difficulties. However, they are the most penalized in terms of receptiveness, considering, notably, their potentially lower attractiveness to students.

On the other hand, upon analyzing from the student's perspective, the methodologies identified with the highest potential receptiveness and overall score were "gamification" and "game-based learning", followed by "integrative learning". The methodologies "educational robotics", "STEAM methodology", "virtual-laboratory based learning", and "simulation-based learning", although they also score highly in student receptiveness, are the ones with more penalizing indicators of additional resources.

From the implementation perspective, considering difficulty and time factors, the methodologies that allow for more immediate implementation are "problem-based learning", "web-based learning", and "interactive learning", contrasting with "integrative learning" and "STEAM methodology", which pose greater implementation challenges.

The methodology identified with the lowest overall score was "STEAM methodology", particularly impacted by its interdisciplinary nature, which involves the integrated teaching of two or more STEAM disciplines. It requires significant additional resources, both in terms of cost and support, and presents increased difficulties in implementing this interdisciplinary approach.

This concludes the main objective of this study with the answer to the RQ: "What innovative methodologies and pedagogical approaches have been identified, tested and developed to improve the teaching of programming?".

While the primary objective of this research has been achieved, it is important to reflect on certain methodologies identified in the study. These methodologies, while not the most frequently mentioned, are considered to have significant potential for future use in programming education as emerging approaches. Figure 9 presents these methodologies, classified with the same parameters as the previous ones.

Methodology	Resources		Implementation		Receptiveness		Overall Score
	Cost	Support	Difficulty	Time	Educator	Student	
Agile teaching	4,00	3,00	3,00	4,00	3,00	4,00	3,50
Digital educational escape rooms	3,00	3,00	3,00	4,00	4,00	5,00	3,67
Work-integrated learning	5,00	4,00	3,00	4,00	4,00	5,00	4,17

Figure 9 Emerging methodologies classification.

4 Conclusion

The problems affecting traditional teaching, especially in STEM (Science, Technology, Engineering and Mathematics), are a worldwide reality. This article conducts a systematic literature review and mapping study focused on innovative methodologies or approaches applied in the field of education, particularly in programming education. It is part of a larger, more comprehensive research project that is currently nearing completion. The primary objective was to identify methodologies that can support future research in this area.

The conclusions derived from this research provide significant contributions to the field of education. The mapping conducted enabled the aggregation of studies into geographic analyses, educational strengths, curricular areas, and themes addressed. In the quantitative analysis, the methodologies with the highest number of occurrences in the articles were mentioned, with particular emphasis on the top three: "web-based learning", "educational robotics", and "project-based learning".

A classification proposal for these methodologies was also presented, considering their characteristics and weighting across the dimensions of resources, implementation, and receptiveness. From the analysis and classification of each methodology, it was concluded that "problem-based learning" and "interactive learning" are the two methodologies with the highest overall rating. They achieved consistent scores across all considered dimensions, highlighting the practicality of their implementation. The methodology with the lowest overall score was the "STEAM methodology", primarily due to the challenges associated with implementing interdisciplinary learning across various STEAM disciplines.

This research also enabled a final reflection on emerging methodologies that, while not the most referenced, are believed to hold significant potential for future use in programming education. These include pedagogical approaches such as "agile teaching", "educational

escape rooms" (EER) or "digital educational escape rooms" (DEER) and "work-integrated learning". These methodologies should be considered for inclusion in new research efforts that incorporate practical applications.

Considering the more extensive research that is still ongoing, the aggregate analysis of this study has enabled the compilation of a comprehensive list of all teaching methodologies mentioned in the publications obtained through our search strategy. Each methodology will be accompanied by a brief description, chronological origin, and its main advantages and disadvantages. This list will be made available in due course and upon completion, both as a shared dataset and in a new publication.

The SLR presented in this article will also continue with a thorough reading of relevant articles to identify additional findings.

As a suggestion for future work, new dimensions could be investigated for the classification framework proposed, such as sustainability of the analyzed methodology or other relevant considerations. Further research could explore existing classification methodologies that might replace the proposed framework or potentially test the accuracy and effectiveness of the proposed classification in real-world environments.

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