

Integrated PjBL-STEAM Learning with ESD to Improve Students' Critical Reasoning in Renewable Energy: Bibliometric Analysis

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ABSTRACT

This study aims to map and analyze the development of research on the development of integrated digital teaching materials, PjBL-STEAM, with an ESD framework to improve students' critical reasoning skills on renewable energy materials through bibliometric analysis. Data were obtained from the Scopus database and selected using certain criteria, resulting in 329 articles published from 2012 to 2025. The analysis was conducted using Bibliometrix software to examine publication trends, the most productive journals, the most contributing authors and countries, and thematic evolution. The synthesis results show that the STEAM approach has proven effective in developing students' critical thinking, creativity, and collaboration skills. However, an explicit ESD integration framework in open-ended high school physics materials is still limited. Furthermore, research that simultaneously integrates PjBL, STEAM, and Education for Sustainable Development on renewable energy materials is still rare. These findings indicate a research opportunity to develop integrated digital teaching materials, PjBL-STEAM, with an ESD framework specifically designed to improve students' critical reasoning skills.

Keywords: Bibliometric Analysis, Critical Reasoning, ESD, PjBL, STEAM

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INTRODUCTION

The transition toward sustainable energy systems has become a global priority in response to environmental degradation, climate change, and the increasing demand for energy (Budhiman et al., 2021). Renewable energy is widely recognized as a key solution to these challenges, as it provides environmentally friendly and sustainable alternatives to fossil fuels (Dincer, 2000). However, achieving sustainable energy development requires not only technological innovation but also a transformation in education that equips students with the competencies needed to address complex real-world problems. Education systems are therefore expected to foster critical reasoning, interdisciplinary thinking, and problem-solving skills among students (Ajiga et al., 2025).

In this context, the integration of innovative pedagogical approaches such as Project-Based Learning (PjBL) and the STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach has gained significant attention in educational research. PjBL encourages students to actively construct knowledge through authentic projects, while STEAM promotes interdisciplinary learning and creativity in solving complex problems (Shenbagavalli, 2025; Zhao & Abdullah, 2025). When combined, PjBL-STEAM learning can provide meaningful learning experiences that engage students in real-life issues, including those related to renewable energy and sustainability (Papilaya & Salhuteru, 2024).

Furthermore, the concept of Education for Sustainable Development (ESD) has emerged as an important framework for integrating sustainability principles into educational practices (Kopnina



& Meijers, 2014; Sinakou et al., 2019). ESD aims to empower learners with the knowledge, skills, values, and attitudes needed to contribute to sustainable development. By embedding ESD principles within PjBL-STEAM learning materials, students can develop not only conceptual understanding of renewable energy but also critical reasoning skills to evaluate environmental, social, and economic aspects of sustainability issues (Fitrianto, 2024; Navarro et al., 2023).

Despite the growing interest in PjBL, STEAM education, and ESD, studies that integrate these approaches into learning materials specifically designed to enhance students' critical reasoning skills in the context of renewable energy remain limited. In addition, the development of research in this interdisciplinary area has not been comprehensively mapped (Porter & Rafols, 2009; Marrone & Linnenluecke, 2020). Understanding the trends, research patterns, and emerging themes within this field is important for identifying research gaps and guiding future educational innovations.

Therefore, this study aims to analyze the development of research related to integrated PjBL-STEAM learning materials within an ESD framework to improve students' critical reasoning skills on renewable energy through a bibliometric analysis. By examining publication trends, influential authors, research collaborations, and thematic developments, this study seeks to provide a comprehensive overview of the research landscape and identify potential directions for future studies in sustainable and interdisciplinary science education.

Although numerous studies have explored PjBL, STEAM approaches, and ESD separately or in limited combinations, significant research gaps remain. To date, few studies have systematically integrated an ESD-based PjBL-STEAM framework into the development of learning materials specifically designed to enhance students' critical reasoning skills in the context of renewable energy. Furthermore, bibliometric studies mapping research trends, scientific collaborations, and thematic developments in this interdisciplinary field are still rare. This gap highlights the need for comprehensive research to identify the direction of scientific development and provide an empirical basis for educational innovations relevant to the global challenges of the 21st century. Therefore, the novelty of this research lies in the conceptual integration of PjBL-STEAM within an ESD framework, analyzed through a bibliometric approach to systematically map the research landscape and provide strategic recommendations for the development of sustainable energy education.

METHODS

This study employed a bibliometric analysis to examine the development of research related to integrated PjBL and STEAM learning materials within the ESD framework to improve students' critical reasoning skills in the context of renewable energy. Bibliometric analysis is a quantitative approach used to evaluate scientific publications and identify research trends, collaboration networks, and emerging themes within a particular field (Pritchard, 1969; Donthu et al., 2021). This method enables researchers to systematically map the intellectual structure, conceptual evolution, and scholarly impact of research topics over time (Zupic & Čater, 2015). Furthermore, bibliometric tools such as co-authorship, co-citation, and keyword co-occurrence analyses provide comprehensive insights into knowledge development and interdisciplinary connections (van Eck & Waltman, 2010). To facilitate robust and reproducible analysis, this study utilized the Bibliometrix package, a widely recognized tool for science mapping and bibliometric studies (Aria & Cuccurullo, 2017).

The bibliographic data used in this study were obtained from the Scopus database, which is widely recognized as one of the largest and most comprehensive databases of peer-reviewed scientific literature. Scopus was selected because it provides high-quality indexing of international journals and allows for advanced bibliometric data extraction.

The search was conducted in the titles, abstracts, and keywords of publications to ensure that the retrieved documents were relevant to the research topic. Only journal articles and conference papers written in English were included to ensure the quality and accessibility of the data.

The data collection process was carried out using specific keywords related to PjBL, STEAM, ESD, critical reasoning skills, and renewable energy. The search query used in the Scopus database was structured as Figure.1.

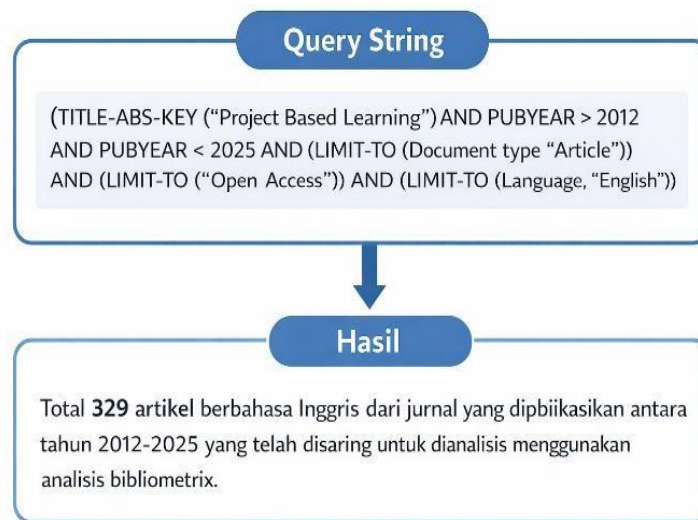


Figure 1 Query String keywords.

The search was conducted in [month year], and publications from [for example: 2014–2024] were included in the analysis. After the initial retrieval process, duplicate and irrelevant documents were removed through a screening process based on titles and abstracts. The final dataset consisted of publications that were directly relevant to the research focus.

The bibliographic information, including authors, titles, publication years, keywords, affiliations, and citations, was then exported in CSV format for further analysis.

The bibliometric analysis in this study consisted of several analytical stages:

- (i). Performance Analysis
- (ii). This analysis examined the productivity and impact of publications, including the number of publications per year, most productive authors, most influential journals, and most cited documents.
- (iii). Science Mapping Analysis
- (iv). Science mapping was conducted to identify the intellectual structure and relationships within the research field. This analysis included:
 - (v). Co-authorship analysis to examine collaboration networks among researchers and institutions.
 - (vi). Co-occurrence analysis of keywords to identify dominant research themes.
 - (vii). Citation analysis to identify influential publications within the field.
- (viii). Trend Analysis.

This analysis aimed to identify the evolution of research topics over time and emerging themes related to integrated PjBL-STEAM learning materials and ESD in renewable energy education.

The bibliometric data were analyzed and visualized using VOSviewer and Microsoft Excel. Microsoft Excel was used for descriptive statistical analysis, such as publication trends and frequency counts. Meanwhile, VOSviewer was used to generate network visualizations, including keyword co-occurrence maps, co-authorship networks, and citation relationships.

VOSviewer enables the visualization of bibliometric networks in the form of clusters, where each cluster represents a group of related research topics. This visualization helps to identify major research themes and the connections among them within the field of sustainable science education.

This study employed bibliometric analysis and bibliometric visualization. Bibliometric analysis provides an approach to understanding the volume of research and uncovering emerging trends within a topic. This study employed the bibliometric analysis steps outlined by Donthu et al. (2021), including determining the purpose and scope of the bibliometric study, selecting bibliometric analysis techniques, collecting data for the bibliometric analysis, conducting the bibliometric analysis, and presenting the results. In this study, bibliometric analysis was used to manage, analyze, and visualize research developments related to digital simulation-based interactive learning media to enhance students' conceptual understanding of renewable energy. Data analysis was performed using Bibliometrix software version 4.5.2 and VOSviewer version 1.6.20. Bibliometrix is an R package that provides a comprehensive mapping tool for bibliometric analysis (Saepuloh & Bastian, 2025). Bibliometrix was used to obtain information on the development of related literature, authors, relevant journals, frequently cited references, international collaboration networks, thematic maps, and the evolution of research themes. On the other hand, VOSviewer is a software developed for bibliometric analysis by providing network visualization, overlay, and data density (Ananda et al., 2025; Rohmayanti & Astuti, 2023). This study uses VOSviewer to map collaboration networks among researchers, author citations, and keyword networks.

RESULT AND DISCUSSION

Data analysis was performed using Bibliometrix software version 4.5.2 and VOSviewer version 1.6.20. Bibliometrix is an R package as a comprehensive mapping tool for bibliometric analysis (Saepuloh & Bastian, 2025). Bibliometrix was used to obtain information on the development of related literature, authors, relevant journals, most frequently cited references, collaboration networks between countries, thematic maps, and the evolution of research themes. On the other hand, VOSviewer is software developed for bibliometric analysis by providing network visualization, overlay, and data density (Ananda et al., 2025; Rohmayanti & Astuti, 2023). Table 1 show information publication that research in this paper.

Table 1 Main Information of The Collected Data

Description	Results
Year	2012-2025
Source	187
Documents	329
Annual growth rate	25.03%
Average age of documents	2.71
Average citations per documents	18.69
Keywords	1252
Authors	1362
Single author	30
International author collaboration	25.84%
Number of Co-authors per document	4.34
Country of the corresponding author	28
References	3049

Table 1 presents the main information derived from the bibliometric dataset analyzed in this study. The data encompass publications from 2012 to 2025, obtained from 187 sources and comprising 329 documents, indicating sustained scholarly interest in the integration of Project-Based Learning (PjBL), STEAM education, and Education for Sustainable Development (ESD) within the context of renewable energy and critical reasoning skills. The annual growth rate of 25.03% reflects a rapidly expanding research field, while the average age of documents at 2.71

years highlights its contemporary relevance. The average citation rate of 18.69 per document suggests a notable academic impact. A total of 1,252 keywords reveal diverse and evolving research themes, supported by contributions from 1,362 authors. Of these, only 30 documents were authored individually, indicating a strong preference for collaborative research, as further evidenced by an average of 4.34 co-authors per document. International collaboration accounts for 25.84% of the publications, involving corresponding authors from 28 countries, which underscores the global significance of this research domain. Additionally, the dataset includes 3,049 references, demonstrating a robust theoretical foundation. Overall, these findings indicate that the field is dynamic, interdisciplinary, collaborative, and increasingly influential in advancing sustainable and innovative educational practices.

This study uses VOSviewer to map collaborative networks among researchers, author citations, and keyword networks. Figure 2 explores the network map between keywords. VOSviewer's network visualization mode is used to depict the network. Each keyword is represented by a circle with colors ranging from blue to yellow. The color in this keyword visualization indicates the year of publication in which the keyword frequently appears. The results of the bibliometric analysis of Scopus data through mapping using VOSviewer's assistance, as shown in the following figure, show the research gap on the topic studied. This gap lies in STEAM-based Project-Based Learning with the ESD framework to improve students' critical reasoning skills, which is still wide open.

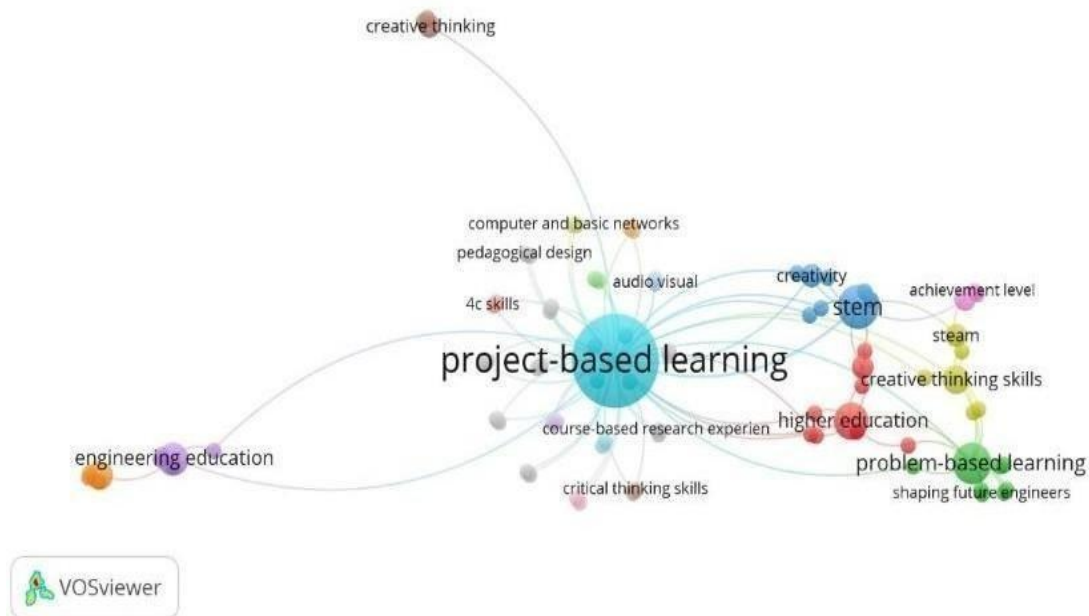


Figure 2 Network Visualization Keywords

Figure 2 shows a relatively high publication output. The lowest number was in 2014, with fewer than 10 publications, but each year there has been a significant increase. This development reflects the growing interest in research on interactive learning media based on digital simulations to improve students' conceptual understanding of renewable energy. The peak publication productivity on this topic will occur in 2025. Based on this trend analysis, the number of annual publications is expected to continue to increase. The number of publications on this topic is shown in Figure 3.

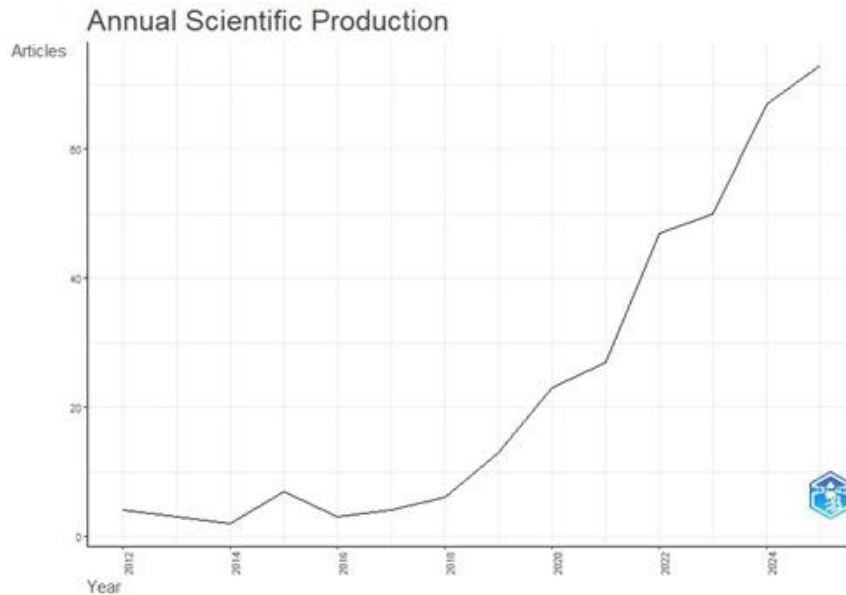


Figure 3 The Number of Publications on the Development of Integrated PjBL-STEAM Teaching Materials Using The ESD Framework to Improve Students' Critical Reasoning Skills in Renewable Energy from 2012 to 2025.

Table 2 shows research publications related to the application of PjBL-STEAM with Education for Sustainable Development to improve students' critical reasoning skills on renewable energy materials, which are spread across various countries, indicating that this topic has global attention. Using bibliometric analysis through Bibliometrix software, the ten most productive countries were identified based on total citations (TC) and average article citations as indicators of productivity and scientific impact of research.

Table 2 Information on the 10 Most Productive Countries

Country	TC
Indonesia	135
China	127
Jerman	83
United Kingdom	63
USA	60
Spain	51
France	26
Netherlands	24
Ireland	22
Australia	20

The world map visualization in Figure 4 shows the international collaboration network between countries in this research. Blue colors with varying degrees of saturation represent the intensity of each country's publication contributions, with darker blue indicating higher productivity. Red lines connecting countries depict patterns of research collaboration, with thicker lines indicating stronger cooperation. From this visualization, it is clear that countries with high productivity, such as Indonesia, China, Germany, the United Kingdom, and Australia, are actively involved in cross-border collaboration. This indicates that the development of integrated PjBL-STEAM teaching materials to improve students' critical reasoning skills on

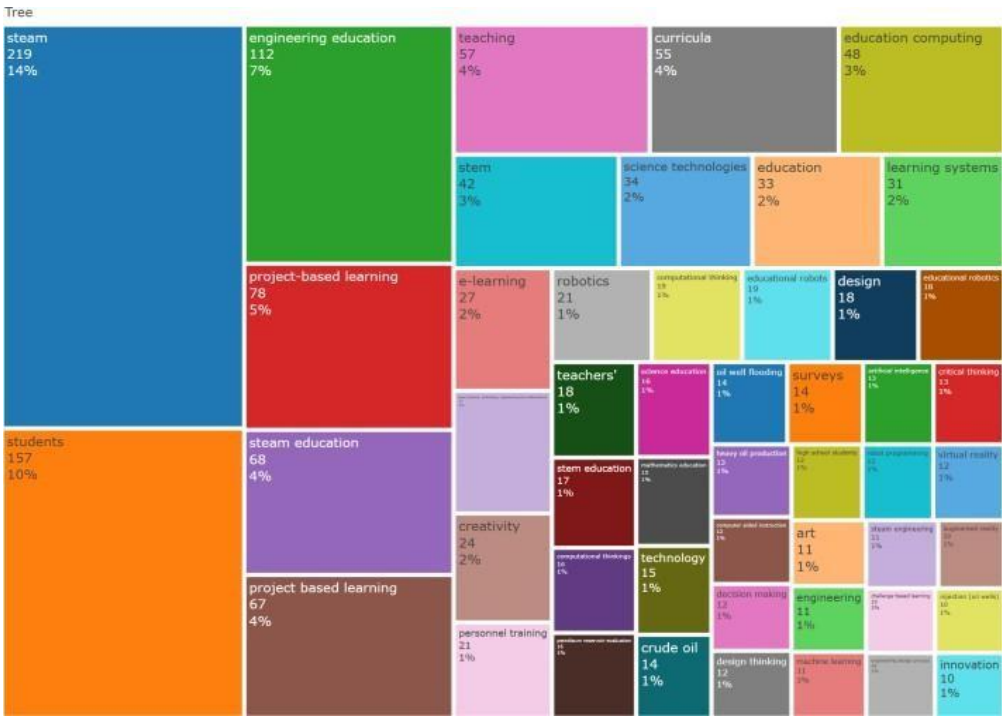


Figure 6 Worldcloud

The thematic mapping obtained from the Bibliometrix analysis is presented in Figures 6 and 7. This thematic evolution analysis aims to categorize the themes used in the literature on education for sustainable development.

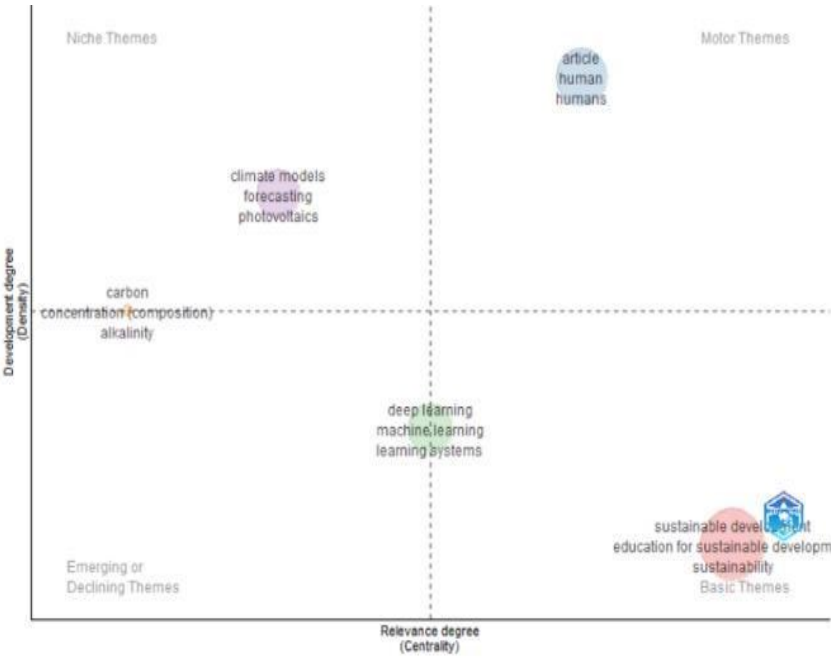


Figure 7 Thematic evolution map

Figure 8 presents the thematic evolution with a strong research focus on sustainability education, within the context of students, curriculum, and higher education from 2012 to 2025.

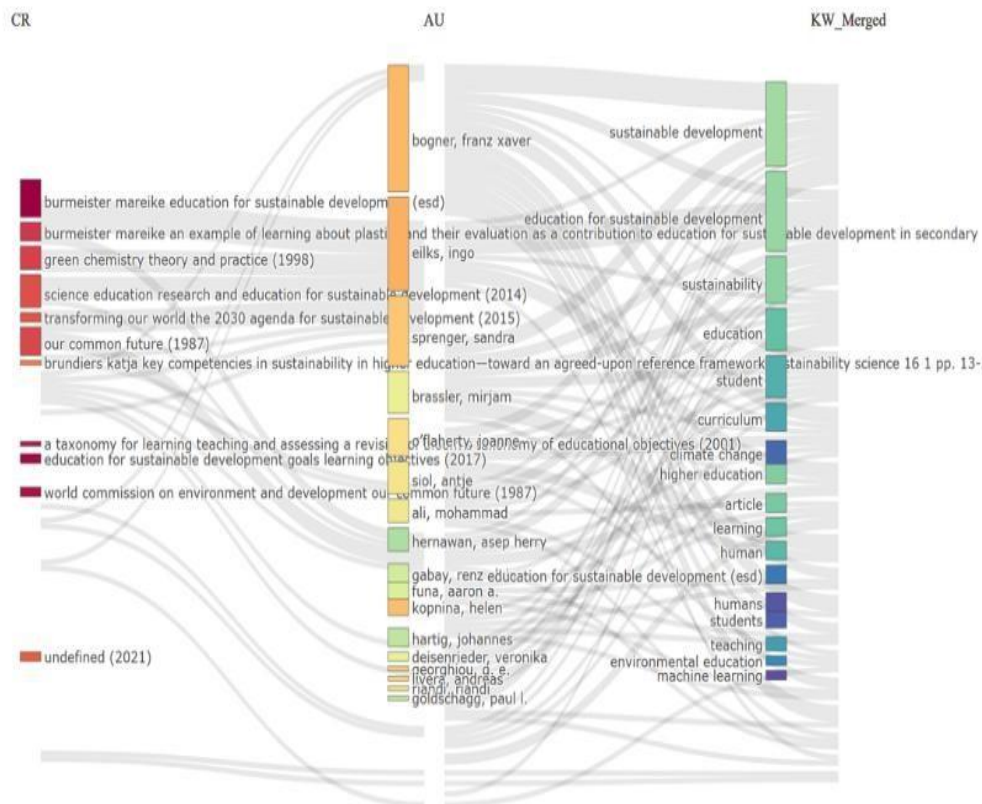


Figure 8 Thematic development 2012-2025

This evolution is the relationship between cited references (CR), authors (AU), and integrated keywords (KW). This visualization illustrates how frequently used reference sources are related to specific authors, which are then connected back to research themes through keywords (Bratt, 2018). The flow in the graph is visualized using gray lines that display the relationships between elements, making it easier to see the overall pattern of research connections (Guo, 2009). The emerging keywords indicate the development of increasingly diverse themes (Weismayer & Pezenka, 2017). The emergence of themes such as curriculum, higher education, human students, and education indicates that research is starting to emphasize empirical validation as well as the context of education and learners.

CONCLUSION

Analysis of the thesis proposal using the SLR method indicates that the research has a strong and up-to-date theoretical foundation, clearly identified and relevant research gaps, and the integration of PjBL–STEAM–ESD in renewable energy topics represents a scientific novelty. Furthermore, the SLR reinforces the urgency and significance of the research. The proposed development plays a crucial role as an academic justification and guides the thesis research design. Based on the results of a Systematic Literature Review (SLR) based on bibliometric analysis of 329 Scopus-indexed articles from 2012–2025, it can be concluded that research on the development of digital teaching materials integrated with PjBL and the STEAM approach shows a significant upward trend and is receiving global attention. This is demonstrated by the

growing number of publications, high levels of international collaboration, and the dominance of reputable journals publishing on related topics.

The literature synthesis reveals that PjBL-based digital teaching materials are effective in enhancing students' active engagement, conceptual understanding, and contextual learning experiences. The STEAM approach has been shown to contribute positively to developing 21st-century skills, particularly critical reasoning, creativity, collaboration, and problem-solving. However, the explicit integration of ESD into physics teaching materials, particularly renewable energy topics at the high school level, remains relatively limited.

Furthermore, the results of keyword mapping and thematic evolution indicate that research simultaneously integrating PjBL, STEAM, and the ESD framework in the development of digital teaching materials is still rare. Therefore, it can be concluded that the development of digital teaching materials integrated with PjBL-STEAM with the ESD framework has great potential and represents a relevant research opportunity to improve students' critical reasoning skills while supporting sustainable development goals in the context of science education.

In conclusion, the findings of this SLR affirm that the development of digital teaching materials integrating PjBL, the STEAM approach, and the ESD framework represents a relevant, innovative, and scientifically grounded contribution to science education, particularly in renewable energy topics at the high school level. The synthesis highlights a significant global research trend, confirms the effectiveness of PjBL and STEAM in enhancing students' engagement, conceptual understanding, and 21st-century competencies, and identifies a clear research gap in the explicit integration of ESD into physics teaching materials. However, this study is subject to several limitations, including its reliance on 329 Scopus-indexed publications from 2012 to 2025, the exclusion of other scholarly databases, and the inherent constraints of bibliometric analysis, which emphasize quantitative trends over qualitative pedagogical insights. Despite these limitations, the study offers important implications: theoretically, it strengthens the conceptual foundation for integrated and sustainability-oriented learning; practically, it provides academic justification and guidance for designing innovative digital teaching materials that enhance students' critical reasoning skills; and strategically, it supports the advancement of Sustainable Development Goals (SDGs) and contemporary educational reforms. Therefore, this research presents a meaningful and promising direction for future studies and educational innovation in science education.

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