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Effectivity of STEAM Education in Physics Learning and Impact to Support SDGs

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ABSTRACT

Objective: *This study aims to identify trends, visualize trend mapping, document sources, types, and determine which countries contribute the most, identify top authors, and explore opportunities for STEAM-based physics learning publications in improving SDG 4 in educational research.* ***Method:*** *This research was conducted using bibliometric analysis and systematic review methods, employing the PRISMA framework to gather relevant data for the discussion. The Scopus database was used, providing data in the form of a CSV file. The analyses were visualized using the VOSViewer application.* ***Results:*** *The data mapping reveals several impactful studies, including: 1) the role of STEAM learning in achieving the 4th sustainable development goal; 2) cell engineering as a contributor to the 13th sustainable development goal; 3) renewable energy sources such as biomass, geothermal energy, steam turbines, and solar energy to support the achievement of SDG 7, as well as the importance of energy efficiency in reducing carbon emissions to contribute to SDG 13. The most common source type identified is journals, with 83 publications, while articles represent the predominant documented type with 67 publications. The United States stands out as the leading country, contributing 42 publications. Additionally, the top authors identified in this study are Hsiao, P.W. and Su, C.H., with a total of 39 citations.* ***Novelty:*** *This research is novel because it specifically evaluates the STEAM learning model's effectiveness in enhancing SDG 4 within the context of physics education.*

INTRODUCTION

The development of technology has ushered in the era of globalization, causing significant changes across various domains, particularly in education (Sjöström et al., 2023; Baatouche et al., 2022). Many learning models are now being developed to meet contemporary needs, including those that integrate Internet of Things (IoT) technology and emphasize the importance of adequate infrastructure (Miranda et al., 2021). Key fields closely associated with these technological advancements include science and engineering (Hubers et al., 2022; Haleem et al., 2022). In particular, science education, and physics, in school settings are interconnected with technology, engineering, and mathematics, making the STEM (Science, Technology, Engineering, and Mathematics) learning model a suitable approach (Aulyana & Fauzi, 2023; Sulaiman et al., 2022). Implementing STEM learning in educational practices is crucial, as it has been shown to enhance motivation, improve communication skills, and boost self-confidence among students (Murphy & Kelp, 2023).

The limitations of STEM learning have highlighted the need to evolve this model into STEAM (Science, Technology, Engineering, Arts, and Mathematics) learning (Razi & Zhou, 2022; Yang, 2023; Gavari-Starkie et al., 2022). Notably, STEM education may not cater to all students effectively and often lacks elements of creativity, innovation, curiosity, and self-motivation (Razi & Zhou, 2022). The inclusion of 'art' in the STEAM framework can evoke emotional responses that are crucial for fostering creativity, expression, empathy, and social awareness (Razi & Zhou, 2022; Belbase et al., 2022; Morari, 2023). Furthermore, STEAM learning is frequently integrated with Project-Based Learning (PjBL), which has proven successful in enhancing critical thinking, problem-solving skills, and student creativity (Miranda et al., 2021; Puspaningtyas et al., 2023; Lu et al., 2023). By improving these competencies, STEAM education plays a vital role in contributing to the achievement of the Sustainable Development Goals (Gavari-Starkie et al., 2022).

The Sustainable Development Goals (SDGs) represent a series of initiatives established by the United Nations (UN) aimed at improving the quality of life globally by 2030 (Saini et al., 2023; Jayasooria & Yi, 2023). Quality education is defined as a system that ensures equal access for all individuals—regardless of gender or age—to comprehensive educational opportunities, including literacy and numeracy, in a supportive and safe learning environment (Chan et al., 2023). Integrating STEAM learning into educational practices is an effective strategy to achieve SDG 4, emphasizing the importance of accessible and inclusive education (Gavari-Starkie et al., 2022; Hsiao et al., 2022). However, recent research by Menasy and Zakharia (2023) indicates that progress towards SDG 4 has stagnated, as highlighted by the lack of improvement in enrollment rates, which continues to be closely monitored by the UN Secretary-General.

To identify the distribution map of research related to STEAM-based physics learning in improving SDG 4 within educational articles, a bibliometric analysis will be conducted. This approach enables the discovery of relevant and contemporary findings as well as research dynamics that could provide insights for future studies (Pham et al., 2023; Zhang et al., 2022; Bircan & Salah, 2021). Additionally, bibliometric analysis allows for data visualization, which helps clarify the distribution of data (Prahani et al., 2023). The objectives of this study include reviewing the literature and mapping keywords on the topic of STEAM-based physics learning aimed at improving SDG 4. Specifically, this study seeks to analyze trends in STEAM-based physics learning research and its contribution to SDG 4 in educational articles over the past decade. It will visualize these trends, analyze document sources and types, and identify which countries have made the most contributions to this research area in the same timeframe. Furthermore, the study will highlight the top authors in the field of STEAM-based physics learning who have contributed to advancing SDG 4 in education research over the past ten years, as well as opportunities for publishing future research in this area. This research is vital for aiding both physics researchers and educators in understanding the impact of the SDGs on educational awareness and practices.

RESEARCH METHOD

This research employs bibliometric analysis alongside systematic review methods to facilitate a comprehensive analysis using both qualitative and quantitative data (Pham et al., 2023; Zhang et al., 2022; Lyu et al., 2024). The bibliometric analysis was conducted utilizing the Scopus database, allowing for the evaluation of knowledge development through statistical data amassed from this resource (Lyu et al., 2024). The data from the Scopus database was accessed online on March 28, 2024, using the keyword "STEAM Education SDGs," with no restrictions on the year of publication. The stages of this study are illustrated in Figure 1 (Prahani et al., 2023; Carvalho et al., 2024; Amorós et al., 2023).

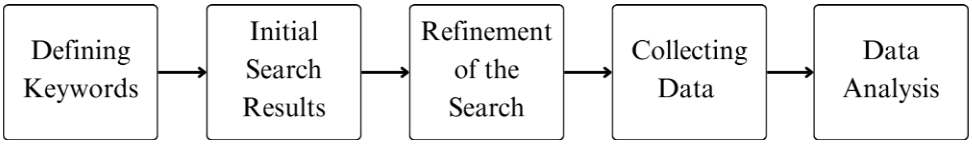


Figure 1. Bibliometric analysis process

In the bibliometric analysis, the Preferred Reporting Items for Review and Meta-Analyses (PRISMA) framework is employed to guide the evaluation of systematic reviews and meta-analyses (Lyu et al., 2024; Khanra et al., 2022). Additionally, the VOSViewer application is used to visualize the data collected from the analysis. The PRISMA framework consists of three phases—Identification, Screening, and Eligibility—and provides items for comprehensive reporting of scientific knowledge and research gaps (Karuppiah et al., 2023; Dewi & Rahayu, 2023). The keywords utilized in the Scopus database search are as follows: "TITLE-ABS-KEY (steam AND sdgs OR sdg OR (sustainable AND development AND goal))"

The search yielded a total of 233 articles. Subsequently, the focus was narrowed to publications from the years 2014 to 2024 (the last ten years), which reduced the number to 179 articles. Further screening was conducted using abstracts, resulting in a final count of 119 articles. The steps of article selection following the PRISMA approach are visualized in Figure 2.

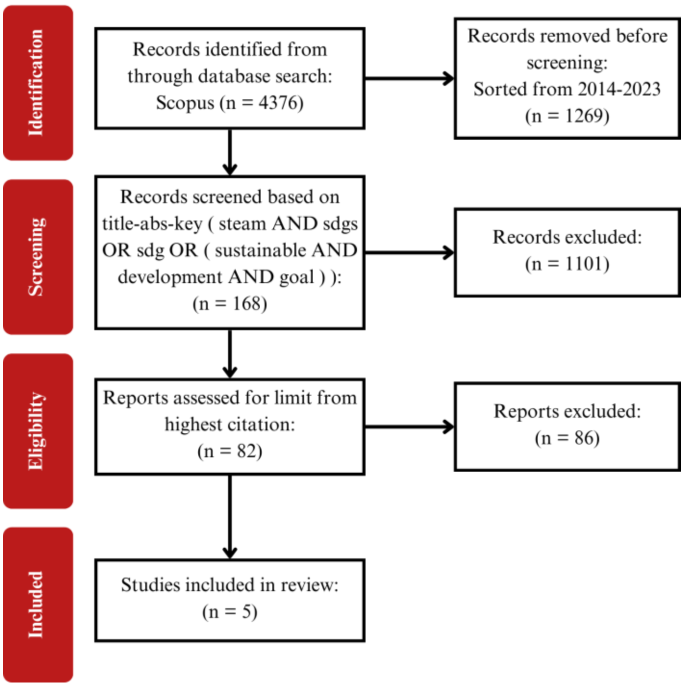


Figure 2. Flow chart of article selection with prisma framework

The 119 documents obtained are then mapped using the VOSViewer application to examine the distribution map, visualization, and interconnections between keywords. This analysis will include an exploration of document sources, the most common affiliations, research citations, contributing countries, subject areas, top sources, authorship, and keywords derived from the data. Following this, a detailed review of the ten articles with the highest citations will be conducted based on the collected database.

RESULTS AND DISCUSSION

Results

The trend of document publications from year to year is illustrated in Figure 3, covering the period from 2014 to 2023. As shown in the figure, there is a noticeable upward trend in the number of documents published in the STEAM (Science, Technology, Engineering, Arts, and Mathematics) category during this timeframe. Although there are fluctuations in publication numbers each year, the overall trend indicates significant growth. From 2014 to 2019, the increase in publications remained relatively stable; however, a marked rise in the number of publications is evident from 2020 to 2023.

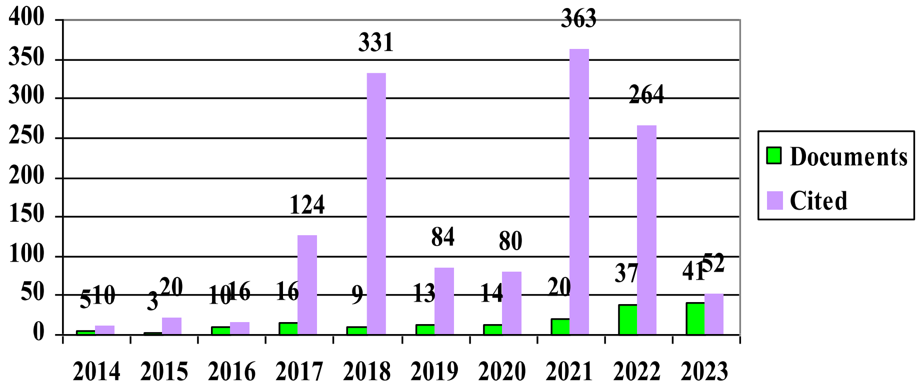


Figure 3. Number of publications from 2014-2024

This publication trend reflects a growing interest in STEAM research related to the Sustainable Development Goals (SDGs). This increase can likely be attributed to heightened awareness of the critical role STEAM plays in achieving sustainable development objectives. The rise in publications concerning SDGs and STEAM implies several positive developments, including increased awareness and engagement in pursuing the SDGs, fostering innovation and the development of technologies that support sustainable development, enhancing collaboration and partnerships across disciplines and institutions, influencing public policy, and building capacity and knowledge regarding the interconnections between STEAM and the SDGs (Sjöström et al., 2023). Consequently, STEAM research focused on the SDGs holds significant potential to impact the educational landscape (Baatouche et al., 2022). The findings and recommendations derived from such research can be instrumental in designing more effective learning experiences aimed at achieving sustainable development goals.

The number of citations for STEAM publications related to the SDGs has increased from 2014 to 2023. Despite fluctuations in the number of documents published each year, there is an overall significant upward trend in citations. A particularly notable spike occurred in 2021 and 2022, indicating heightened interest during those years. Although 2023 experienced a decrease in the number of documents published compared to the previous two years, the total remained higher than in earlier years.

This trend further underscores the growing interest in STEAM research focused on the Sustainable Development Goals (SDGs) (Miranda et al., 2021; Hubers et al., 2022).

Based on the research results illustrated in Figure 4(a), the types of publications utilized in STEAM research aimed at improving the SDGs are identified. Between 2014 and 2023, a total of 168 documents addressing STEAM and the SDGs were published. Specifically, the breakdown includes one book, one erratum, three conference reviews, 15 reviews, 17 book chapters, 64 conference papers, and 67 articles. This data indicates that conference papers and articles comprise the most common types of published documents, while books and errata represent the least. Overall, the findings reveal a diverse range of research types related to STEAM learning that contribute to the advancement of the Sustainable Development Goals.

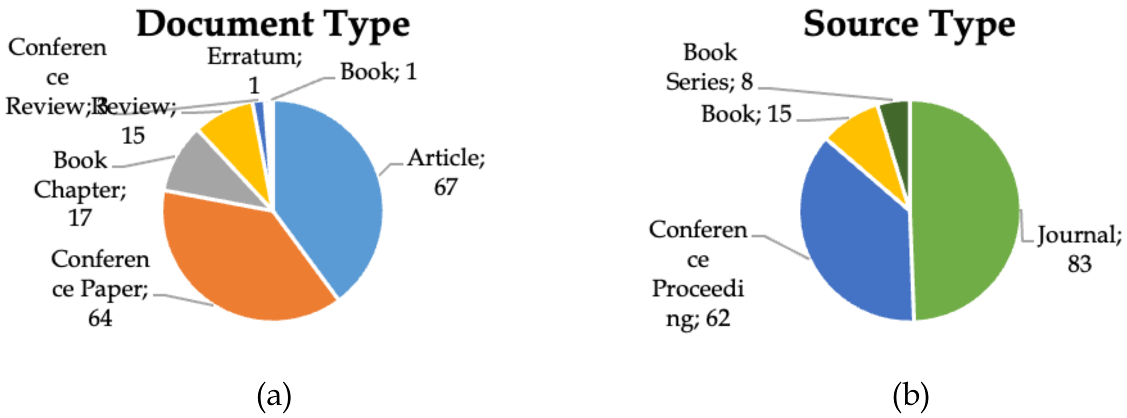
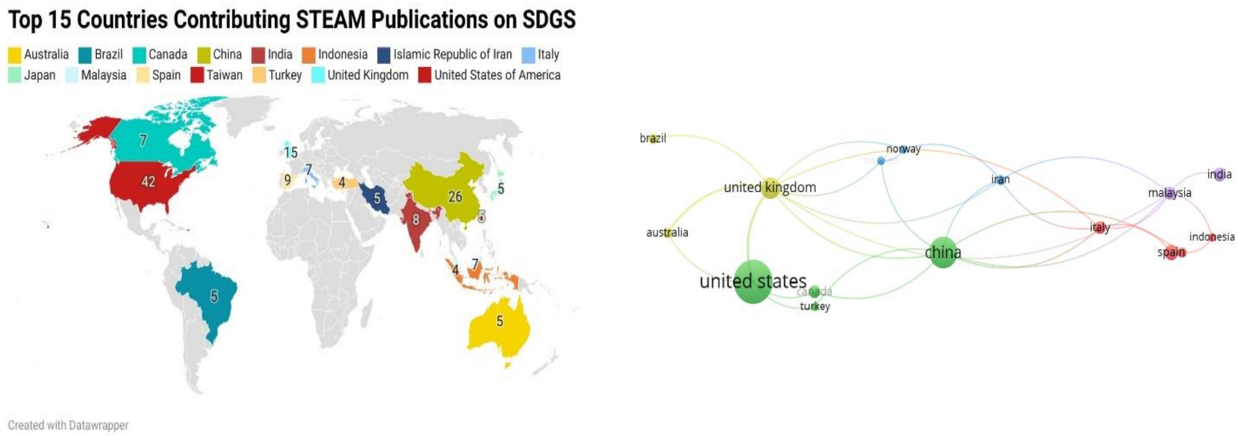


Figure 4. (a) Type of publication, (b) Source of publication

Moreover, the study's results also reveal the distribution of source types, as visualized in Figure 4(b). The most commonly utilized source types are journals, with a total of 83 publications, followed by conference proceedings with 62 publications. This indicates that researchers focusing on STEAM to improve the SDGs primarily prefer journals and conference proceedings as their preferred publication outlets. Additionally, other source types include books with 15 publications and book series with eight publications. This diversity in source types suggests a broader range of platforms for disseminating research in this field, rather than relying solely on one or two specific sources.

Over the past ten years, the top 15 countries contributing to STEAM-based physics learning research aimed at improving SDG 4 in educational research have been identified, with the data visualized in Figure 5(a). According to the findings, the United States leads with 42 articles, followed by China with 26 articles and the United Kingdom with 15 articles. Other countries with contributions of fewer than ten studies include Spain, Canada, Italy, Australia, India, Taiwan, Japan, Brazil, Turkey, and Indonesia. These results indicate a strong interest in STEAM learning research to improve the SDGs from the United States, with notable engagement from researchers in China and the United Kingdom as well. The diversity of countries involved in this research highlights a growing global awareness of the importance of achieving the SDGs. This analysis underscores the significance of international collaboration in reaching sustainable development goals. Countries with substantial contributions should continue to foster innovation and sustainable research, while those with lower contributions are encouraged to increase their involvement in the STEAM field.

Furthermore, the data presented in Figure 5(b) illustrates the mapping of countries collaborating on STEAM research to enhance the Sustainable Development Goals (SDGs) based on their clusters. This mapping visually represents the partnerships and cooperative networks among countries, showcasing how they work together in the pursuit of research that integrates STEAM learning and contributes to achieving the SDGs. The clusters highlight the interconnectedness of nations in addressing educational and sustainable development challenges, emphasizing the importance of collaboration in fostering effective solutions.



(a) (b)

Figure 5. Top 15 countries contributing to research in the last 10 years

Table 1 displays a selection of keywords that frequently appear in STEAM-based physics learning research aimed at improving SDG 4 in educational research. Among these, the most commonly used keyword in this study is "sustainable development," indicating its central relevance to the discourse surrounding STEAM education and the Sustainable Development Goals. This highlights the importance of sustainability as a core theme in the ongoing research and discussions within the field.

Table 1. Top 10 keywords in STEAM-based physics learning research in improving SDGs 4 2014-2023

STEAM-based Physics Learning in Enhancing SDG 4 in Education Research					
Keywords	**Occurrence**	**Total Link Strength**	**Keywords**	**Occurrence**	**Total Link Strength**
Sustainable development	71	449	Geothermal energy	16	189
Steam	35	124	Renewable energy resources	14	137
Cell engineering	18	308	Steam turbines	14	123
Carbon dioxide	18	131	Energy efficiency	14	95
Biomass	18	88	Solar energy	13	132

The keyword "sustainable development" appears 71 times in the study, with a total link strength of 449, indicating that it is the primary keyword in this research. Other significant keywords include "STEAM," "cell engineering," "carbon dioxide," "biomass," "geothermsal energy," "renewable energy resources," "steam turbines," "energy efficiency," and "solar energy". The mapping results reveal that the trend of STEAM-based physics learning research aimed at enhancing SDG 4 in educational research can be summarized as follows: 1) STEAM learning to achieve the fourth Sustainable Development Goal; 2) cell engineering to fulfill the 12th Sustainable Development Goal; 3) the use of biomass, geothermal energy, steam turbines, and solar energy as renewable energy sources contributing to the achievement of SDG 7; and 4) utilizing renewable energy resources while prioritizing energy efficiency to reduce carbon dioxide emissions, thereby supporting SDG 13. This aligns with the findings from researchers such as (Ramzoo et al. 2021), who emphasize the critical role of renewable energy sources—including solar energy (Hoang et al., 2022), wind energy (Chen et al., 2023), and hydroelectricity (Remiro-Cinca et al., 2023) in enhancing energy efficiency as a strategy to mitigate carbon dioxide (CO_2) emissions and lessen adverse environmental impacts.

Figure 6. Most relevant keywords in STEAM-based physics learning research in improving SDG 4 in educational research

Furthermore, from the data obtained and then visualized in Figure 7, results from mapping keywords of STEAM learning research to improve SDGs are used to identify the latest trends and research updates. The study has 4 clusters in STEAM learning research to improve SDGs. The first cluster is red, which amounts to 32 items; in this cluster, the most significant occurrences are carbon dioxide, biomass, and energy efficiency. Furthermore, cluster 2 in green has 17 items with the most significant occurrence: temperature, solar energy, and solar power generation. Then, cluster 3, with a blue color and 16 items, has the most significant occurrences of sustainable development, steam, and sustainability. Finally, cluster 4 is yellow with 15 items, with the highest occurrences of cell engineering, geothermal energy, renewable energy sources, steam turbines, and computational fluid dynamics.

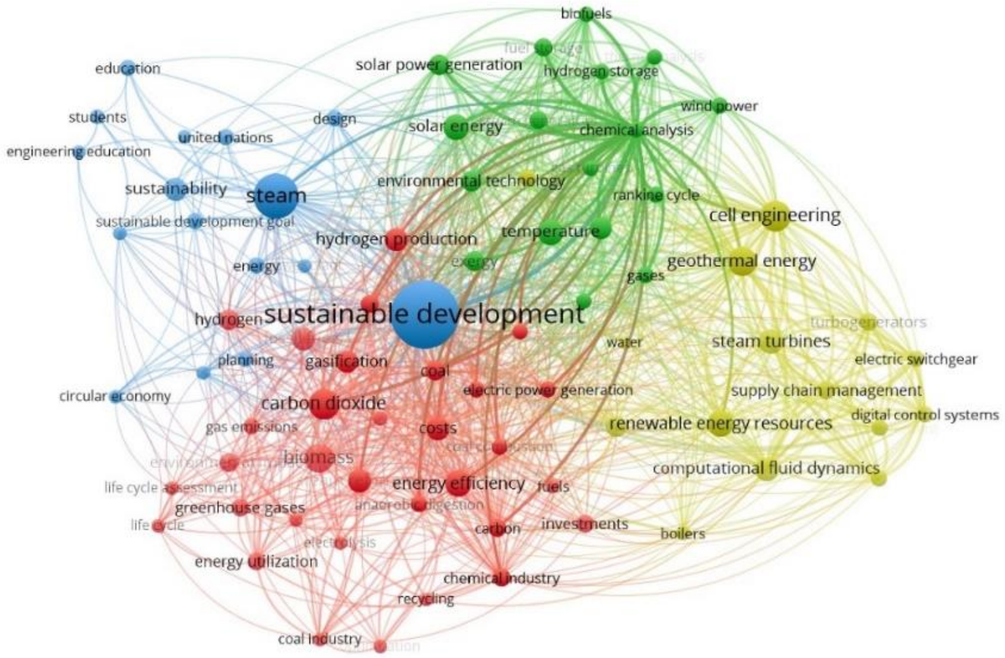
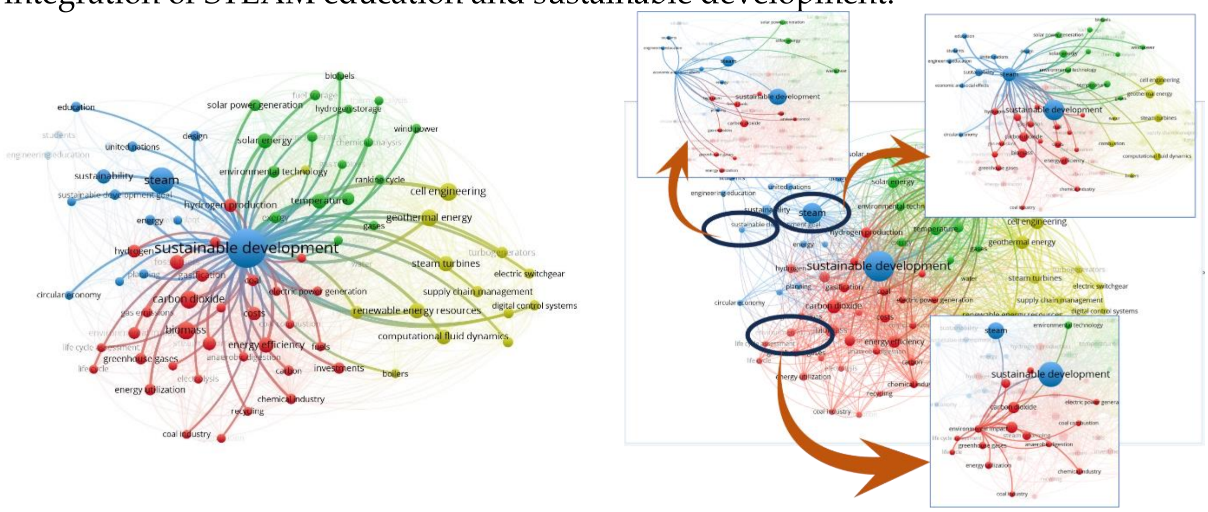


Figure 7. Network visualization

The keywords with the most significant and decisive number of occurrences in the circles represent the primary topics that attract researchers in related studies. Conversely, keywords with fewer occurrences suggest that some studies focus on subtopics within the broader theme of "STEAM Learning to Improve SDGs". To explore the novelty of STEAM learning research trends and their impact on improving SDGs more thoroughly, an investigation will be conducted using the occurrence visualization presented in Figure 8. This analysis aims to highlight emerging trends and areas of interest within the field, providing insights into how researchers are approaching the integration of STEAM education and sustainable development.



(a) (b)

Figure 8. Keyword mapping result (a) Sustainable development (b) Sustainable development goal, STEAM, and environmental impact

Figure 8 illustrates more specific keyword mappings related to sustainable development, sustainable development goals, STEAM, and environmental impact. The primary trends discussed in STEAM learning to improve the SDGs are highlighted in Figures 8(a) and 8(b), which are linked to various potential areas for future research. In Figure 8(a), the keyword with the highest occurrences, "sustainable development," connects to numerous other keywords, such as STEAM, education, environmental technology, temperature, and renewable energy sources. This indicates that the topic of sustainable development holds significant potential for further exploration, as it encompasses a wide range of fields. The keywords identified in this figure also reveal connections to other SDGs beyond just quality education, specifically SDG 7 (affordable and clean energy) and SDG 13 (climate action). Within the context of physics learning, topics related to alternative energy align with SDG 7, while subjects on global warming and climate change are associated with SDG 13. Hence, integrating STEAM learning in physics education can effectively contribute to the advancement of multiple SDGs, particularly SDGs 4, 7, and 13.

In Figure 8(b), the branches related to sustainable development encompass several interrelated aspects, including economic and social effects, environmental impact, and STEAM. Sustainable development recognizes the interconnectedness of these dimensions, which together address various challenges (Beck et al., 2023). From an economic and social perspective, sustainable development aims to foster inclusive and sustainable growth, targeting objectives such as poverty reduction, enhanced access to essential services, and the creation of decent jobs (Leal Filho et al., 2019). The environmental impact is also a critical focus, emphasizing the importance of protecting natural resources, preventing environmental degradation, and reducing pollution levels (Kolawole & Iyiola, 2023; Ajibade et al., 2020). STEM and STEAM disciplines are pivotal in addressing these goals by generating innovative solutions to pressing challenges, such as renewable energy development, effective water management, and sustainable agricultural practices (Belbase et al., 2022; Smith & Watson, 2019). The close interconnections among these aspects underscore the necessity of a holistic and integrated approach to achieving sustainable and inclusive development.

The section on economics and social effects is closely linked to keywords such as STEAM, greenhouse gases, solar energy, and solar power generators. This relationship indicates that economic levels and social impacts significantly influence greenhouse gas emissions (Long & Feng, 2024), which in turn contribute to global warming (Letcher, 2021). Through STEAM learning, students can be introduced to solar power generators that harness solar energy, classified as alternative energy or "green energy" (Hariyono et al., 2023). In the context of physics education, this learning can be implemented through project-based approaches, as seen in various research efforts (Rizki et al., 2023), aimed at enhancing students' creative thinking skills (Millen & Supahar, 2023; Anisa et al., 2023). Therefore, STEAM-based physics learning has the potential to effectively contribute to the achievement of SDGs 4, 7, and 13.

The environmental impact segment is connected to keywords such as STEAM, life cycle, environmental technology, electric power generation, greenhouse gases, and energy utilization. This relationship reveals that environmental impacts are influenced by various factors, including environmental treatment techniques, electricity generation, energy utilization, the chemical industry, and greenhouse gas emissions, along with the application of STEAM learning (Molla et al., 2024). STEAM and STEM disciplines are crucial in developing innovative solutions for reducing environmental impacts (Mikhaylovsky et al., 2021; Balsalobre-Lorente, 2024). This encompasses the use of greener environmental technologies designed to monitor and mitigate pollution (Li et al., 2023) and the advancement of renewable energy technologies that can replace fossil fuels, which are significant contributors to greenhouse gas emissions (Mikulčić et al., 2022). The life cycle approach evaluates the environmental impact of a product or process from its inception through to its final stages, including raw material processing, manufacturing, distribution, use, and disposal (Bharbuiya & Das, 2023). STEM disciplines play a pivotal role in assessing and enhancing this life cycle in order to minimize environmental footprints.

Furthermore, electricity generation is a critical aspect of environmental impact due to the substantial energy consumption and resultant emissions. The development of new technologies in renewable energy—such as solar, wind, and hydroelectric energy—demonstrates how STEM contributes to lessening the environmental impact of electricity generation. Additionally, greenhouse gases are one of the primary drivers of climate change, making their reduction a central focus in efforts to diminish environmental impacts. STEM technologies are employed to create solutions for reducing greenhouse gas emissions, whether through emission reduction technologies or by developing clean energy alternatives (Li et al., 2023). Consequently, energy utilization is also closely tied to environmental impacts, as excessive energy consumption can lead to pollution and increased greenhouse gas emissions (Long & Feng, 2023). Thus, STEM and STEAM play a vital role in mitigating environmental impacts by developing technologies, analyzing life cycles, enhancing electricity generation, reducing greenhouse gas emissions, and improving energy efficiency. Table 2 shows overview of the most cited papers in STEAM learning in realizing SDGs.

Table 2. Overview of the most cited papers in STEAM learning in realizing SDGs

Author(s)	Citation; SJR	Research Findings and Recommendations
Hsiao et al. (2021)	39; 0,67 (Q1)	Integrating STEAM education into learning can improve students' motivation, self-efficacy, satisfaction, and learning outcomes. This can contribute to the Sustainable Development Goals (SDGs) planned by the United Nations.
Lu & Huang (2022)	11; 0,67 (Q1)	The PBL-based STEAM curriculum positively impacts the creativity and learning outcomes of students with special education needs. It also increases students' self-confidence and self-efficacy and may benefit their future employability and entrepreneurship. This research supports UN Sustainable Development Goal 4, which emphasizes inclusive and equitable quality education for all students.
Manikutty et al. (2022)	5; 0,26	STEAM training can increase the ability to integrate technology into learners' projects to improve their problem-solving skills.
Hsiao et al. (2022)	2; 0,67 (Q1)	Using CAIM combined with PBL in STEAM education can improve students' creativity. This shows that the linkage between STEAM (Science, Technology, Engineering, Arts, Mathematics) and PBL (Project-Based Learning) can positively improve student creativity in learning.
Amalu et al. (2023)	1; 3,6 (Q1)	This research found that the skills of innovation, problem-solving, leadership, problem analysis, conflict management, and customer service are essential in facing the needs of the Solar Energy Technology Science (SETS) industry. This relates to the Sustainable Development Goals (SDGs), especially in education, where solar energy technology training modules are needed for STEM and

Author(s)	Citation; SJR	Research Findings and Recommendations
		STEAM students in order to meet industry needs and increase employment opportunities in the SETS sector.

Based on the related keywords, steam learning in environmental treatment engineering education and the chemical industry can also help reduce environmental impacts, such as greenhouse gases, residual energy use, and waste from power plants. Then, the STEAM keyword is related to several alternative energies such as wind, biofuel, solar, and steam, and it is also related to energy efficiency, greenhouse gases, temperature, industry, education, design, and students. These keywords have a broader domain than the previous keywords. The related keywords indicate that steam learning in education can utilize alternative energy and maintain energy efficiency to reduce greenhouse gases produced. Steam learning is also related to design and is classified as art to improve students' creative thinking skills (Zayyinah et al., 2022). Research (Zayyinah et al., 2022) also states that project-based learning can improve students' 21st-century skills, such as critical thinking, communication, and creative thinking.

These keywords suggest a broader domain of exploration compared to prior ones, indicating that STEAM learning in education can effectively leverage alternative energy sources while promoting energy efficiency to minimize greenhouse gas production. Furthermore, STEAM learning incorporates elements of design, classified as a component of art, which is vital for enhancing students' creative thinking skills (Zayyinah et al., 2022). Project-based learning can significantly improve students' 21st-century skills, including critical thinking, communication, and creative thinking (Zayyinah et al., 2022). By integrating these aspects into STEAM education, students are better equipped to tackle contemporary challenges related to sustainability and environmental stewardship.

Discussion

With the advancement of technology and the Internet of Things (IoT), the implementation of technology in physics learning has become increasingly necessary. One notable example is Augmented Reality (AR), which integrates virtual objects seamlessly into the real world (Arzak & Prahani, 2023; Novita, 2023). AR can assist students in visualizing concepts and materials that are otherwise unattainable in reality (Rahmat et al., 2023). The impact of AR technology on STEM (Science, Technology, Engineering, Mathematics) learning makes it a vital component of STEAM education. In physics learning, AR has been shown to enhance students' learning outcomes as well as their attitudes toward physics education (Sriadhi et al., 2022). This enhancement occurs through various mechanisms, including increased student motivation due to the accessibility of AR technology outside the classroom, and the integration of AR with Problem-Based Learning (PBL) models, which boosts cognitive engagement. Additionally, the review indicates that merging AR with STEM learning creates a more engaging and holistic educational experience. This integration challenges students to undertake projects that enhance their confidence and skills in AR, ultimately supporting the teaching and learning process. By leveraging AR technology, educators can foster deeper understanding and interest in physics and related fields among students.

However, it is crucial to emphasize the importance of support for teachers in developing learning materials and scenarios. Teachers require opportunities and training to enhance their skills in integrating Augmented Reality (AR) into their teaching practices. Overall, the application of AR in STEM learning, particularly within the context of physics education, demonstrates significant potential to improve educational quality in alignment with the UN Sustainable Development Goals (SDGs). Integrating AR not only boosts student motivation and learning outcomes but also enriches the educational experience by providing access to immersive content that meets industry demands and future technological advancements (Rizki et al., 2024). Therefore, incorporating AR in STEAM education can serve as an effective strategy to achieve the SDGs, particularly in fostering inclusive, quality, and innovative learning environments.

Figure 3 illustrates the increase in publications focused on STEAM-based physics learning research aimed at improving SDGs 4. Despite this upward trend in the number of publications, progress toward achieving SDGs 4 appears to be stagnant. This stagnation is evidenced by the enrollment rate, which has shown no significant improvement even under close monitoring by the UN Secretary-General (Menasy & Zakharia, 2023). Interestingly, previous studies have not adequately addressed this stagnation in SDGs 4. Moreover, they have not explored the potential of STEAM-integrated Augmented Reality (AR) in physics learning as a means to enhance 21st-century skills and further advance SDGs 4. This gap highlights the need for future research to investigate the integration of AR in STEAM education as a strategy to foster engagement and improve educational outcomes aligned with sustainable development goals.

This study recommends the integration of STEAM learning to enhance SDGs 7, which focuses on affordable and clean energy, and to combine STEAM learning with Augmented Reality (AR) as a means to improve both SDGs 4 and SDGs 7 in future research. A key finding from the discussion is that STEAM plays a vital role in realizing and achieving the Sustainable Development Goals (SDGs), particularly through its integration into physics education.

- Potential to Support SDGs: STEAM learning has substantial potential to aid in the attainment of the SDGs, specifically SDG 4 (Quality Education), SDG 7 (Affordable and Clean Energy), and SDG 13 (Action on Climate Change). By integrating STEAM concepts into physics education, students can better understand the connections between physical phenomena and pressing sustainable development issues, such as renewable energy and climate change.
- Enhancing Engagement and Creativity: STEAM-based physics learning fosters greater student engagement, creativity, and problem-solving skills. This approach allows students to learn and apply physics concepts in real-world contexts, leading to innovative solutions for sustainable development challenges.
- Positive Impact on SDGs: The incorporation of STEAM in physics learning positively influences the achievement of the SDGs, especially in areas related to understanding and developing strategies to address challenges such as clean energy, greenhouse gas reduction, and the effects of climate change.
- Development of 21st-century skills: STEAM learning is instrumental in enhancing essential 21st-century skills, including critical thinking, creativity, and teamwork, which are crucial for tackling the complex challenges related to the SDGs.

In summary, integrating STEAM into physics education not only deepens students' understanding of physics concepts but also equips them with the critical thinking, creativity, and skills necessary to devise innovative solutions that support the achievement of the SDGs. This underscores the potential of STEAM education to cultivate a generation that cares for the environment and can contribute to global sustainable development.

CONCLUSION

Fundamental Finding: Based on the research that has been done, it is known that the trend of STEAM-based physics learning research in improving SDG 4 in educational articles over the past 10 years has continued to increase yearly. Many studies can be made from this topic as obtained from data mapping, among others: 1) STEAM learning to achieve the 4th sustainable development goal; 2) cell engineering to achieve the 12th sustainable development goal; 3) biomass, geothermal energy, STEAM turbines, and solar energy as a form of renewable energy that helps achieve SDG 7; using renewable energy resources by paying attention to energy efficiency to be able to reduce carbon dioxide to achieve SDG 13. This study's most common source type is a journal of 83 publications, and the most documented type is an article of 67 publications. Then, the country with the most publications is the United States, with 42 publications. Furthermore, the top authors in this study are Hsiao, P.W. and Su, C.H., with 39 citations. **Implication:** Integrating augmented reality (AR) into STEAM-based physics learning can significantly advance SDG 4, SDG 7, and SDG 13 by enhancing 21st-century skills and linking physics concepts to real-world sustainability challenges. This approach fosters critical thinking, creativity, and teamwork while enabling students to develop innovative solutions aligned with sustainable development goals. **Limitation:** The integration of AR in STEAM education is hindered by limited teacher training and resources for effective implementation. Additionally, there is a lack of empirical studies directly connecting AR-enhanced learning to measurable progress in achieving SDG 4 and related goals, highlighting the need for further research and support. **Future Research:** Future research should explore the effects of AR-integrated STEAM physics learning on the SDGs and examine the potential of SDG 7 within STEAM-based physics education.

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