International Journal of Evaluation and Research in Education (IJERE)
Vol. 14, No. 2, April 2025, pp. 1253~1263
ISSN: 2252-8822, DOI: 10.11591/ijere.v14i2.31873

Integrating energy literacy into science education: a comprehensive systematic review

Nik Aida Mastura Nik Abdul Majid[1], Kamisah Osman[2], Tan Siok Yee[3]
[1]Faculty of Education, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[2]STEM Enculturation Research Centre, Faculty of Education, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[3]Faculty of Information Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia

Article Info

Article history:

Received Jun 27, 2024
Revised Sep 4, 2024
Accepted Sep 17, 2024

Keywords:

Clean energy
Educational technologies
Energy education
Pedagogical approaches
Renewable energy
STEM
Teaching strategies

ABSTRACT

Energy literacy is vital for preparing future generations to tackle global energy issues and advance sustainable development. However, integrating energy literacy into science education faces challenges due to diverse pedagogical approaches and educational contexts. This systematic literature review synthesizes current research to identify effective strategies for embedding energy literacy in science education. By employing advanced search techniques and preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines, a thorough search across Scopus, Web of Science, and ERIC databases yielded 30 relevant studies meeting inclusion criteria. Findings indicate that interdisciplinary approaches, hands-on experiments, and innovative teaching tools like virtual and augmented reality (VR-AR) effectively enhance students' understanding and attitudes toward energy, particularly renewable energy. Notably, project-based learning and science, technology, engineering, and mathematics (STEM) integration significantly improve problem-solving skills and creativity. Despite these positive outcomes, challenges such as high cognitive load in interdisciplinary courses and the need for ongoing teacher training persist. The review concludes that standardized curricula and professional development programs are necessary to further support teachers. Future research should focus on longitudinal studies to assess the long-term impact of these educational interventions and explore scalable models for diverse educational settings. This review provides valuable insights for educators, policymakers, and researchers aiming to enhance energy literacy through science education.

Corresponding Author:

Kamisah Osman
STEM Enculturation Research Centre, Faculty of Education, Universiti Kebangsaan Malaysia
43600 Bangi, Selangor, Malaysia
Email: kamisah@ukm.edu.my

1. INTRODUCTION

In response to escalating environmental challenges and the urgent need for sustainable development, the role of education in fostering energy literacy is increasingly vital. Energy literacy, which involves understanding the nature and role of energy and applying this knowledge to problem-solving and decision-making, is essential for responsible citizenship [1], [2]. As the global community confronts climate change, resource depletion, and energy security issues, integrating energy literacy into science education becomes a key strategy for equipping future generations with the necessary knowledge and skills [3], [4]. Science education, with its emphasis on inquiry, critical thinking, and problem-solving, provides an ideal platform for embedding energy literacy. By incorporating energy concepts into the curriculum, educators can deepen students' scientific understanding and connect learning to real-world challenges. This integration involves a multidisciplinary approach, drawing from physics, chemistry, biology, and environmental science to offer a comprehensive view of energy production, consumption, and its environmental impacts. A primary goal is to develop students' understanding of key energy concepts, including energy forms, transformations, and the difference between renewable and non-renewable sources. This knowledge is vital for understanding how energy systems function and their broader implications [5], [6]. Beyond conceptual knowledge, energy literacy also aims to shape attitudes and behaviors towards energy use [7]. By linking classroom learning with real-life applications, students are encouraged to reflect on energy consumption, promote efficiency, and advocate for sustainable practices, making their education more relevant and impactful [8].

A key component of energy literacy is the development of skills to critically analyze energy-related information and make informed decisions. In an era of information overload and misinformation, the skill to evaluate source credibility, understand scientific data, and differentiate between evidence-based conclusions and opinions is paramount. Integrating energy literacy into science education equips students with these analytical abilities, enabling them to engage effectively in energy debates and policy discussions [9]. Energy literacy also fosters innovation and creativity in addressing energy challenges. Through hands-on, project-based learning, students can experiment and develop solutions to real-world energy problems. This approach not only deepens their understanding of energy concepts but also cultivates teamwork, problem-solving, and critical thinking skills. Projects such as designing energy-efficient buildings, developing renewable technologies, or analyzing energy consumption patterns make learning both dynamic and impactful. Moreover, energy literacy education plays a significant role in preparing students for careers in the burgeoning green economy. As the demand for renewable energy and sustainable practices rises, so does the need for a workforce skilled in energy-related fields. By embedding energy literacy into science education, schools help close the skills gap, ensuring students are knowledgeable and employable in this rapidly changing job market [10]. In conclusion, integrating energy literacy into science education is a vital undertaking that has far-reaching implications for individuals, communities, and the global society. It empowers students with the knowledge, attitudes, and skills necessary to make informed decisions about energy use and to contribute to a sustainable future. As educators and policymakers recognize the importance of energy literacy, it is essential to continue developing and implementing educational strategies that address this critical aspect of science education. Through such efforts, we can cultivate a generation of energy-literate citizens capable of driving positive change and ensuring a sustainable and prosperous future for all.

2. LITERATURE REVIEW

Integrating energy literacy into science education is crucial for fostering an informed citizenry capable of making responsible decisions regarding energy consumption and sustainability. Research highlights the significance of environmental literacy among university students, emphasizing the need for a curriculum that instills both knowledge and motivation to protect environmental systems [11]. Despite high levels of knowledge in areas like energy and pollution, behavioral intentions remained largely unaffected, indicating the need for a national strategy to enhance curricula [12]. Demographic factors, including gender, school location, and parents' education level, significantly influence students' energy literacy, underscoring the importance of tailored educational strategies. In the context of game-based learning, students can manipulate building configurations and energy options, enhancing their understanding of energy costs and emissions. By leveraging game elements and behavioral insights, gamification-based interventions motivate users to adopt energy-saving behaviors [13]. The interactive and practical nature of the game significantly increases students' engagement and energy literacy. Complementing this, findings show that integrating hands-on, scenario-based learning can effectively promote energy literacy and drive the behavioral changes necessary to achieve net-zero energy goals [14].

Moreover, adult education plays a pivotal role in enhancing energy literacy. This is echoed by advocates for redefining science literacy to focus on community literacy, emphasizing the role of core scientific values and social interchange in achieving true scientific literacy [15]. The inclusion of socioscientific issues in the curriculum is another effective strategy for promoting energy literacy. Researchers propose using role play to enhance students' values and decision-making skills regarding nuclear energy, highlighting the importance of ethical reasoning and emotive engagement [16]. This method helps students better understand the complexities of energy issues, fostering critical thinking and informed decision-making. Further studies underscore the importance of addressing complex social and environmental issues in science education to support sustainable development goals [17]. Integrating these topics into science education can enhance students' overall scientific literacy, preparing them for informed participation in energy-related discussions and decision-making.

Additionally, the research highlights the role of science literacy in promoting energy conservation behaviors among youth through enhanced climate change knowledge efficacy [18]. The study emphasizes the need for integrating environmentalism into science education to encourage practical energy-saving actions in daily life. It also underscores the importance of incorporating climate change knowledge into science curricula, suggesting that a strong foundation in scientific concepts can facilitate practical applications in energy conservation. Similarly, findings demonstrate that service-learning programs like Connect Science significantly improve students' energy attitudes and behaviors, showing that hands-on, community-oriented science education can effectively enhance energy literacy [19]. High-fidelity implementation of such programs leads to better science achievement and energy behaviors, providing a practical framework for engaging students in real-world energy issues.

Cultivating energy literacy requires a comprehensive approach that integrates innovative learning media, technological advancements, and social engagement strategies. Digital technologies have become crucial in advancing the United Nations 2030 agenda for quality education, particularly during the COVID-19 pandemic, which accelerated their adoption. The convenience of digital devices and learning media has significantly increased student engagement and interest in research [20], [21]. Efforts to improve energy literacy also extend to using innovative media like reading literacy comics and web-based resources. Recent studies show that comics can effectively facilitate understanding of energy concepts [22], while web projects like the ocean energy web project have successfully increased renewable energy literacy among secondary school students by providing engaging and informative resources [23].

Furthermore, social media in promoting energy citizenship is essential. Utilizing social media for energy-related discussions can enhance citizens' understanding and participation in energy transition initiatives. This highlights the potential of digital and social media tools in creating a more informed and active citizenry regarding energy issues [24]. Together, these insights emphasize the critical role of diverse educational tools and platforms in fostering comprehensive energy literacy. Therefore, a digital approach can be adapted to energy education by incorporating digital tools and platforms that facilitate interactive learning experiences. Through the embedding energy concepts within science curricula and utilizing interactive and community-based learning approaches, educators can equip students with the knowledge, skills, and motivation to engage in sustainable energy practices. In conclusion, integrating energy literacy into science education involves a multifaceted approach that includes creative educational tools, online platforms and strategies for fostering social involvement. By leveraging these tools, educators can enhance students' understanding of energy concepts, promote renewable energy awareness, and foster active energy citizenship.

The current systematic analysis was developed to answer the main research questions: i) what are the most effective strategies for integrating energy literacy into science education?; and ii) how does the inclusion of energy literacy in the science curriculum influence students’ attitudes and understanding towards energy conservation and sustainability? This investigation focuses on identifying and evaluating the approaches that can effectively embed energy literacy within science education frameworks. In particular, this study emphasizes the importance of educational strategies and their impact on students' awareness and attitudes towards energy issues. Given the growing need for sustainability and the critical role of education in fostering responsible energy behaviors, this analysis pays special attention to innovative pedagogical methods and curriculum reforms. Furthermore, the investigation considers the demographic factors that influence energy literacy, aiming to propose tailored educational strategies. The subsequent section outlines the methodology used to address the research questions, detailing the systematic approach taken to review and synthesize relevant scientific literature. This includes the selection criteria for identifying pertinent studies and the analytical framework used to assess their findings. The third section conducts a comprehensive analysis of the literature, examining various educational interventions and their outcomes on students' energy literacy. Finally, the section discusses the implications of these findings for educators and policymakers, emphasizing the steps needed to enhance energy literacy through science education. This includes recommendations for curriculum development, teacher training, and the integration of interactive and community-based learning approaches. By addressing these issues, the analysis aims to inform future research and educational practices, contributing to a more energy-literate society.

3. METHOD

3.1. Identification

The systematic review process for this study involved several critical steps to identify a substantial body of relevant literature. Initially, keywords were selected, followed by the identification of related terms using dictionaries, thesauri, encyclopedias, and previous research. All pertinent terms were then chosen to formulate search strings for the Scopus, Web of Science, and ERIC databases, as presented in Table 1. In the first stage of the systematic review, 1,177 publications were successfully retrieved from these databases for the current study project.

Table 1. The search string

Database	Search string
Scopus	TITLE-ABS-KEY (("energy literacy" OR "energy education" OR "energy sustainability" OR "renewable energy" OR "green energy" OR "clean energy" OR "energy source*") AND (school* OR universit* OR college* OR institution*) AND (science AND education)) AND (LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2023) OR LIMIT-TO (PUBYEAR, 2024)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (LANGUAGE, "English")) Date of access: May 2024
Web of Science	(("energy literacy" OR "energy education" OR "energy sustainability" OR "renewable energy" OR "green energy" OR "clean energy" OR "energy source*") AND (school* OR universit* OR college* OR institution*) AND (science AND education)) (Topic) and 2024 or 2023 or 2022 or 2021 or 2020 (Publication Years) and Article (Document Types) and English (Languages) Date of access: May 2024
ERIC	("energy literacy" OR "energy education" OR "energy sustainability" OR "renewable energy" OR "green energy" OR "clean energy" OR "energy source*") AND (school* OR universit* OR college* OR institution*) AND "science education" Date of access: May 2024

3.2. Screening

During the screening process, the collection of potentially relevant research items was reviewed to ensure alignment with the predetermined research topic or questions. The selection of research items based on the theme of integrating energy literacy into science education was a key content-related criterion applied during this stage. Duplicate papers identified in this step were eliminated. According to the inclusion and exclusion criteria of this study, 138 papers were reviewed in the second stage of screening after excluding 1,039 publications in the first stage, as shown in Table 2. Given that research articles are the primary source of valuable recommendations, this criterion was prioritized. Excluded from the current study were reviews, meta-syntheses, meta-analyses, books, book series, chapters, and conference proceedings. Furthermore, the review was confined to English-language publications from the years 2020 to 2024. In total, 42 publications were excluded due to duplication.

Table 2. The selection criterion is searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2020–2024	<2020
Literature type	Journal (Article)	Conference, book, review
Publication stage	Final	In press

3.3. Eligibility

In the third phase, known as the eligibility assessment, a compilation of 96 articles was assembled. During this stage, a thorough examination of the titles and core content of all articles was conducted to ensure their alignment with the inclusion criteria and their relevance to the study's research objectives. Consequently, 66 articles were excluded because they did not meet the criteria due to being out of scope, having titles that were not significantly relevant, abstracts not related to the study's objectives, or lacking full-text access based on empirical evidence. As a result, a total of 30 articles remains for the forthcoming review.

3.4. Data abstraction and analysis

One of the assessment procedures in this study was an integrative analysis, which examined and synthesized a variety of research designs, focusing on quantitative approaches. The primary objective was to identify relevant topics and subtopics. The initial phase involved data collection, during which the authors meticulously reviewed 30 publications for claims or information pertinent to the study's subjects, as depicted in Figure 1. Subsequently, the authors examined significant recent research on incorporating energy literacy into science education, investigating both the findings and methodologies of the studies. The authors collaborated to develop themes based on the data, recording observations, opinions, puzzles, and other relevant ideas throughout the analysis process. They compared outcomes to ensure consistency in theme development and discussed any differing opinions to reach a consensus. The resulting themes were then refined to ensure coherence. To evaluate the validity of the identified themes, two experts in science education conducted an analytical review. This expert review process ensured the significance, clarity, and applicability of each subtheme, thereby establishing domain validity.

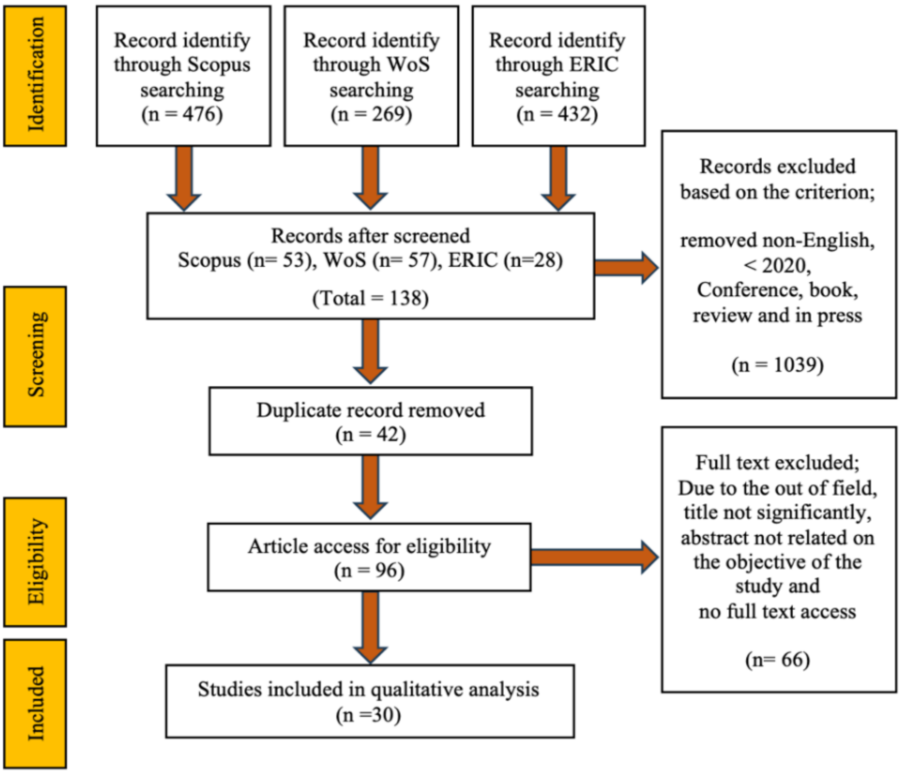

Figure 1. Flow diagram of the proposed searching study [25]

4. RESULTS

Energy literacy is a crucial component of science education, addressing one of the most pressing global challenges: sustainable energy consumption and conservation. As educators and policymakers strive to enhance public understanding of energy systems, integrating energy literacy into science curricula has become increasingly significant. Based on an advanced searching technique using databases such as Scopus, Web of Science, and ERIC, 30 articles were extracted and analyzed to address the research questions. The articles were categorized based on three main themes: effective strategies for integrating energy literacy (9 articles), the impact on students' attitudes and understanding of energy conservation and sustainability (8 articles), and ways to enhance energy education by aligning it with broader educational goals (13 articles). This categorization facilitated a comprehensive analysis of the current state of energy literacy integration and its impact on educational outcomes.

4.1. Innovative teaching methods and tools in energy education

The application of innovative teaching methods and tools has significantly enhanced the effectiveness of energy education. These methods include virtual and augmented reality (VR-AR), remote online laboratories, serious games, and gamification, each contributing uniquely to student engagement and comprehension. The implementation of VR-AR systems in coal-based energy education aims to transform negative perceptions of the coal mining industry. Traditional views of coal mining as dirty and dangerous have persisted due to ineffective science communication. A VR-AR system for intelligent coal mining significantly improved public perception, particularly among students, reducing negative impressions by a substantial margin [26]. This underscores the potential of VR-AR in reshaping outdated stereotypes and enhancing public understanding of modern, sustainable coal mining practices.

In addition, remote and virtual laboratories have gained importance in renewable energy education, particularly in engineering and science disciplines. In Jordan, the integration of remote renewable energy laboratories into the educational framework has shown significant benefits. These labs enable students to conduct experiments and engage with complex concepts in a virtual environment, enhancing their learning experience. Evaluations using the technology acceptance model (TAM) and structural equation model (SEM) indicate that remote labs improve students' perceptions and the overall quality of online education [27]. The successful integration of these technologies highlights the critical role of remote labs as essential resources for contemporary engineering education.

Furthermore, the integration of gamification and information and communication technology (ICT) into the teaching of natural science has demonstrated efficacy in enhancing student motivation and well-being, while it may not significantly influence academic performance. A study conducted in primary schools shown that incorporating gamification approaches and ICT resources into the teaching of renewable energies increased student involvement and enjoyment in the learning process [28]. This discovery highlights the importance of using innovative teaching methods to improve the appeal and effectiveness of learning. Serious games provide a unique method for energy education, with the goal of improving energy literacy through interactive and engaging means. The mini-game "Illumi's World" integrates parametric building information modeling (BIM) and energy simulations to instruct users on green building design and energy literacy. Players can customize building configurations, assess energy expenditures, and monitor performance via game dashboards, providing a valuable learning experience [29]. Similarly, a project that encompassed various fields of study transformed a conventional board game into a digital video game with the objective of instructing elementary school students on topics related to energy and sustainability. The collaborative design process, involving students, instructors, and staff from several disciplines, ultimately improved the energy literacy of K-12 pupils [30]. Moreover, employing a model-as-game method to instruct the intricate dynamics of clean energy subsidies has proven advantageous. This method effectively imparts knowledge on policy planning and cost-benefit analysis to non-experts through a cooperative multiplayer game that simulates real-world circumstances. The educational experience is engaging and immersive [31].

The development of educational kits such as "Energy, Environment and Sustainability" (KEAS) in Guinea-Bissau signifies a substantial advancement in ensuring equal opportunities for science education. This effort, which focuses on enhancing scientific knowledge for the purpose of sustainable development, has demonstrated its efficacy in teacher training and the promotion of environmental consciousness [32]. Hybrid courses that integrate fundamental scientific principles with environmentally friendly technologies provide a pragmatic approach to energy education. For instance, the implementation of biofuel research through basic experiments in electrical engineering curricula has demonstrated efficacy. These studies, carried out at a private university in Lima, highlighted the practicality of incorporating green energy subjects into undergraduate courses, thereby motivating students to go deeper into research in this area [33]. Furthermore, the combination of project-based learning and integrated e-learning (INTe-L) methodologies has demonstrated efficacy in instructing the subject of "energy sources" in the field of physics. A study conducted in Slovakia found that students who participated in project-based learning incorporating INTe-L aspects demonstrated superior academic performance and had a more favorable disposition towards the subject of physics [34]. Collectively, innovative teaching methods and tools, such as VR-AR systems, remote online laboratories, gamification, and hybrid courses, play a crucial role in enhancing energy education. These approaches not only improve students' understanding and engagement but also address the evolving needs of modern education. By leveraging these technologies and methodologies, educators can provide more effective and appealing learning experiences, ultimately fostering a more energy-literate society.

4.2. Impact of energy education on students' knowledge and skills

The impact of energy education on students' knowledge and skills has been a focus of various educational interventions, particularly those integrating interdisciplinary approaches and advanced pedagogical strategies. Studies have shown that well-structured energy education programs can significantly enhance students' understanding of energy concepts, foster positive attitudes towards renewable energy, and develop critical skills such as problem-solving, creativity, and system thinking. One notable study investigated the effect of an interdisciplinary course on solar cells for 12th-grade students. This 20-hour course combined sustainability, physics, and electronics to expose students to advanced technological applications of theoretical physics within the context of renewable energy. The findings indicated that students developed positive attitudes toward interdisciplinary learning, perceiving it as a natural reflection of reality that enhances understanding of disciplinary content. The course was considered important and engaging, although it was also noted for its high cognitive load [35].

This aligns with the research on the water-energy education for the next generation (WE2NG) program, which highlighted the effectiveness of long-duration, inquiry-based professional development for K-12 science, technology, engineering, and mathematics (STEM) educators. The program's success was reflected in increased teacher confidence and growth, which indirectly benefits student learning outcomes [36]. Additionally, a study on the impact of 5E-based STEM education in the context of solar energy on female junior high school students revealed significant improvements in creativity and academic achievement. The STEM-based approach, focusing on energy concepts and energy conversion, resulted in increased originality and elaboration in students' creative outputs. This overlap between high performance in science, math, and creativity underscores the effectiveness of integrating STEM education with energy literacy [37].

Furthermore, research assessing energy literacy among Iranian ninth-grade students found that while knowledge levels were low, students demonstrated good attitudes and values towards energy issues. Factors such as gender, school location, and parents' education level significantly influenced energy literacy, with rural students showing more positive attitudes than their urban counterparts [38]. The use of creative teaching modules in STEM education has also shown promising results. For instance, the creative teaching-STEM (CT-STEM) module for high school students involved activities related to energy literacy and sustainability, utilizing outdoor education and hands-on projects. This approach not only enhanced students' creativity and problem-solving skills but also increased their interest in STEM fields [39]. Similarly, the Schools4Future project in Germany enabled students to engage in climate protection activities, such as drawing up CO_2 balances and identifying renewable energy potentials within school buildings. This hands-on, citizen science approach fostered a deeper understanding of climate change and empowered students to take action [40].

Moreover, integrating engineering design processes (EDP) into STEM makerspace activities has been effective in fostering system thinking skills. A study involving high school students demonstrated that those who participated in STEM-PBL integrated EDP activities performed better in system thinking tasks than those who followed traditional STEM approaches. This method encouraged active engagement in hands-on and mind-on activities, highlighting the importance of practical, technology-based learning in energy education [41]. Additionally, block-based programming introduced alongside traditional education has proven to be a powerful tool for developing environmental awareness and cognitive abilities among students. A study in Shanghai showed that students who participated in both theoretical and practical STEM projects scored higher in environmental literacy tests, indicating the effectiveness of combining traditional learning with innovative STEM projects [42]. Overall, these studies collectively illustrate the transformative potential of innovative educational strategies in enhancing energy literacy among students. By incorporating interdisciplinary learning, hands-on projects, and advanced pedagogical methods, educators can significantly improve students' knowledge, attitudes, and skills related to energy and sustainability.

4.3. Energy education and sustainable development

Energy education plays a pivotal role in advancing sustainable development by enhancing students' knowledge, attitudes, and skills related to energy systems and technologies. The growing emphasis on renewable energy sources, energy efficiency, and environmental sustainability necessitates a comprehensive understanding among future generations, who will be the decision-makers and innovators in addressing global energy challenges. Various educational interventions, ranging from interdisciplinary courses and hands-on experiments to collaborative learning projects and innovative teaching methodologies, have been implemented to foster energy literacy and promote sustainable practices. Table 3 provides a comprehensive analysis of recent studies on energy education and sustainable development, summarizing their objectives, methodologies, findings, and conclusions. The studies span diverse contexts, including high school and university settings, teacher training programs, and public outreach initiatives. By examining the impact of these educational efforts, Table 3 highlights effective strategies and identifies areas for future research, aiming to contribute to the ongoing discourse on integrating energy education into broader sustainability education frameworks.

5. DISCUSSION

The integration of contemporary technologies and interactive tools has significantly advanced energy education. VR-AR, and remote online laboratories have notably enhanced educational outcomes and student satisfaction. These technologies, combined with ICT-driven gamification, make learning more interactive and appealing, fostering a deeper understanding of energy concepts and technical skills. Hybrid courses that incorporate practical power generation projects further reinforce these benefits by allowing students to apply theoretical knowledge in real-world contexts, promoting the adoption of sustainable energy practices.

Beyond technological integration, interdisciplinary methodologies and advanced teaching approaches have been critical in enhancing students’ understanding, perspectives, and skills in energy education. For instance, a multidisciplinary course on solar cells, integrating principles of sustainability, physics, and electronics, has demonstrated that such approaches significantly contribute to the advancement of sustainable energy education. However, the cognitive demands of these interdisciplinary courses require careful management to avoid overwhelming students. Continued professional development for educators is essential, as supplementary training for K-12 STEM educators has been linked to increased self-assurance and improved student growth. The 5E teaching model, particularly in the context of energy education, has also been effective, enhancing student creativity and academic performance, thus supporting the integration of STEM and energy literacy into curricula.

Table 3. The research article finding based on the proposed searching criterion

No.	Study	Objectives	Methodologies	Findings	Conclusion and future research
1	[43]	To understand Hungarian higher education students' views on renewable and nuclear energy.	Online survey with 328 university students.	Students prefer solar and wind power but distrust nuclear energy.	Targeted education needed to align student views with national strategies. Future research should address nuclear energy misconceptions.
2	[44]	To evaluate the impact of photovoltaic solar systems on sustainable development in Brazilian schools.	Teacher survey at Rio Grande do Norte Federal Institute of Education Science and Technology.	Teachers value renewable energy but struggle to integrate it into lessons.	Continuous renewable energy teacher training is advised. Research should examine how to incorporate renewable energy principles into daily instruction.
3	[45]	To investigate impact of environmental education on renewable energy awareness among Colombian students.	Linear mixed model with student and school-level data.	Environmental education's impact is limited; socio-economic status is more influential.	Suggests more socio-economic integration in education. Future research should identify effective renewable energy education methods.
4	[46]	To examine Malaysian university students' perceptions of renewable energy.	Survey with 2,863 students by educational background and income levels.	Non-science students and lower economic groups need more focus despite a positive view of renewable energy.	Promotes targeted awareness programmed. Future studies should overcome educational gaps and promote renewable energy inclusively.
5	[47]	To teach students about systemic energy changes through an interdisciplinary course.	Interdisciplinary course combining technical knowledge, art, and humanities.	Students gained insights into energy transitions and systemic change.	Promote transdisciplinary education. Future research should explore long-term effects on career choices.
6	[48]	To adapt university chemistry lab research on dye-sensitized solar cells for high school courses.	Action research with iterative course revisions and surveys.	Students and teachers reported improved understanding and multidisciplinary learning.	Shows how hands-on learning improves energy literacy. Future study should scale and integrate such courses into larger curriculums.
7	[49]	To demonstrate catalysis, renewable energy, and chemical safety concepts using a portable apparatus.	Experimental demonstration with platinum-catalyzed hydrogen oxidation.	The apparatus clearly demonstrated scientific concepts to various audiences.	Demonstrates hands-on learning benefits. Future research should focus on scaling and curriculum integration.
8	[50]	To educate students on photocatalytic hydrogen production and hydrogen fuel cell integration.	Experimental demonstration using Pt-loaded titanium dioxide and hydrogen fuel cells.	Students learned about renewable energy technologies and their applications.	Encourages similar experiments in chemistry curriculum to engage students. More research should create comprehensive renewable energy modules.
9	[51]	To connect education and engineering students through a wind energy community project.	Interdisciplinary project with teacher training and classroom activities.	Hands-on experience increased learning and skills, valued by both teachers and students.	Interdisciplinary projects for deeper learning are recommended. Future studies should examine students' job paths over time.
10	[52]	To analyze the benefits of collaborative learning and renewable energy education for teacher training.	Qualitative case study with 32 teachers.	Teachers improved their understanding of environmental issues and renewable energies.	Emphasizes collaborative learning in teacher education. Future study should examine scalable collaborative learning approaches in varied educational settings.
11	[53]	To explore pre-service teachers' knowledge about energy in online discussions.	Qualitative study with video-based discussions.	Students shared life experiences and funds of knowledge, enriching discussions on energy inequities.	Stresses social justice in energy education. Future research should provide FoK frameworks for online and in-person education.
12	[54]	To analyze how science textbooks teach energy awareness (grades 1-12).	Quantitative analysis of 67 Hungarian textbooks.	Renewable energy concepts are common, but fewer tasks require applying environmental awareness knowledge.	Claims textbooks require more attitude-forming and practical assignments. Develop textbooks that better integrate EA into learning activities in future study.
13	[55]	To investigate the link between the energy trilemma index (ETI) and a country's education level, focusing on school life expectancy and STEM predispositions.	Regression analysis on data from 118 countries using OLS and MM-estimator.	Higher school life expectancy correlates with a higher energy transition index, but there's no link between the energy transition index and the percentage of STEM graduates.	Promotes energy sustainability by emphasizing school life expectancy above STEM graduates. Future studies should examine socially varied CE techniques.

This research also highlights disparities in students' knowledge of energy issues, influenced by factors such as gender, school location, and parental education levels, despite generally positive attitudes towards energy. These gaps suggest the need for targeted educational interventions to promote a more inclusive approach to energy education. Experiential learning, including outdoor education and hands-on projects, has been shown to significantly enhance the creativity, problem-solving skills, and enthusiasm of STEM students. For instance, involving students in climate preservation initiatives not only deepens their understanding of climate change but also empowers them to take actionable steps in addressing these challenges. Additionally, incorporating EDP into STEM education enhances students' systems thinking skills, which are essential for tackling complex energy challenges, while also boosting their environmental consciousness and overall academic performance, outperforming traditional methods. Overall, this study indicates that innovative teaching approaches-when combined with interdisciplinary learning, hands-on projects, and advanced pedagogical methods-can significantly improve students' knowledge, attitudes, and skills in energy and sustainability. These approaches are essential in preparing the next generation to effectively address global energy challenges.

6. CONCLUSION

Energy education is crucial for equipping students with the knowledge and skills needed to address global energy challenges and foster sustainable development. By deepening understanding of renewable energy sources, energy efficiency, and environmental sustainability, it lays the groundwork for innovative solutions and effective action. Transdisciplinary approaches, practical experiments, collaborative learning, and advanced teaching techniques are vital in advancing energy literacy and promoting sustainability across various educational levels, from K-12 to higher education and public outreach. While students generally favor renewable energy, they exhibit skepticism towards nuclear options, underscoring the need for focused educational interventions. Experiential learning and hands-on projects are particularly effective in conveying fundamental concepts, while interdisciplinary courses that merge technical knowledge with the arts and humanities improve comprehension of complex energy systems and foster systemic thinking. Furthermore, incorporating social justice into energy education is also critical, as socio-economic factors and student background significantly influence awareness and attitudes towards renewable energy. To address these disparities, consistent curricula, ongoing teacher development, and inclusive educational practices are imperative. These insights underline the importance of a comprehensive and adaptive approach to energy education, ensuring students are well-prepared to confront and solve future energy-related challenges.

ACKNOWLEDGEMENTS

The authors sincerely acknowledge the financial support provided by Universiti Kebangsaan Malaysia (UKM) through the research grant, code GG-2023-007. This support was essential in facilitating the successful completion of this research and the preparation of this article.

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BIOGRAPHIES OF AUTHORS

Nik Aida Mastura Nik Abdul Majid is a Ph.D. candidate in science education currently in her second year at the Universiti Kebangsaan Malaysia. She is dedicated to enhancing the quality of teaching and learning in science education. Her research interests focus on the development of educational modules and the integration of technology in learning. She can be contacted at email: nikaidamajid@gmail.com; p120955@siswa.ukm.edu.my.

Kamisah Osman is a distinguished academic in science education, renowned for her expertise in teaching methodologies, measurement and evaluation, and STEM education. She holds a Ph.D. (1999) and a Master's degree (1995) from the University of Manchester, along with a Bachelor's degree from Universiti Kebangsaan Malaysia. Throughout her career, she has significantly contributed to research and leadership in higher education. She currently serves as the Director of the Quality Assurance Centre at Universiti Kebangsaan Malaysia. Concurrently, she excels as the Head of Module for Science Education at the STEM Enculturation Research Centre, where she demonstrated exceptional leadership in curriculum development and pedagogical innovation. Her scholarly contributions include numerous high-impact articles in indexed journals, underscoring her commitment to advancing knowledge in science education. She can be contacted at email: kamisah@ukm.edu.my.

Tan Siok Yee is a renowned expert in information science, specializing in augmented reality, image processing, and mobile computing. She received her Ph.D. in Industrial Computing (2017) and her B.Sc. in Information Technology with Honors (Multimedia Studies) (2013) from Universiti Kebangsaan Malaysia. In 2014, she was a visiting researcher at the HIT Lab, University of Canterbury, New Zealand. Currently, Dr. Tan is a senior lecturer at the Faculty of Information Science and Technology, Universiti Kebangsaan Malaysia. She has published many high-impact articles in respected journals, showcasing her commitment to advancing her field. She can be contacted at email: esther@ukm.edu.my.