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Enhancing Students' Scientific Skills Through a Low-Carbon Education-Based Youth Research Training Program

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Abstract

The increasing consequences of global climate change underscore the necessity for the integration of low-carbon education and renewable energy frameworks within the educational paradigm for learners. This study develops a training curriculum for Youth Scientific Paper/ Karya Ilmiah Remaja (KIR) that incorporates these principles to enhance students' scientific proficiency. Utilizing a Systematic Literature Review (SLR) approach, thirty indexed scholarly articles from the last decade were rigorously analyzed. The results reveal that the inclusion of low-carbon education and renewable energy within KIR training programs significantly improves students' abilities in critical thinking, problem-solving, and data analysis while concurrently fostering environmental awareness. Effective implementation strategies include project-based learning, hands-on renewable energy experiments (such as solar panels and wind turbines), and collaborations with environmental organizations. However, challenges such as limited resources, insufficient mentor training, and inadequate policy support hinder successful implementation. Despite these obstacles, the integration of low-carbon education and renewable energy within KIR initiatives holds substantial promise for cultivating environmentally responsible scientific skills among students. This initiative aligns with the Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action), thus contributing to a more sustainable future.

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INTRODUCTION

The imperative to confront climate change has escalated, highlighting the critical need for educational frameworks rooted in environmental doctrines, particularly focusing on Low-Carbon Education (LCE). The phenomenon of climate change, primarily instigated by an overabundance of greenhouse gas emissions, necessitates a profound reconfiguration of energy production and consumption methodologies. Education serves an indispensable function in cultivating environmental consciousness and advocating for sustainable practices vital for achieving a sustainable future (Agbakwuru et al., 2024). Low-carbon education is posited as a pivotal strategy, amalgamating awareness of climate change with actionable methodologies to diminish carbon footprints on both individual and collective scales. Within this paradigm, science education occupies a fundamental position in empowering learners with the requisite skills to scrutinize, explore, and devise innovative resolutions to climate-related dilemmas (Aggarwal, 2023). By embedding LCE within the educational journeys of students, subsequent generations can develop a robust sustainability ethos and proactively engage in global initiatives for environmental preservation (Hudha et al., 2020).

Notwithstanding the growing acknowledgment of the significance of environmental education, substantial obstacles remain in its execution, particularly within informal educational contexts such as Karya Ilmiah Remaja (KIR). KIR is esteemed for its role in nurturing scientific inquiry competencies among students; however, it has not been fully leveraged to augment proficiencies in environmental science and sustainability. A principal constraint resides in its pedagogical methodologies, which have yet to comprehensively incorporate LCE tenets, including strategies for the reduction of carbon emissions, advancements in renewable energy, and the promotion of sustainability consciousness (García-Ferrero et al., 2021). Investigations conducted by Al-Greer et al. (2024) underscore KIR's potential as a strategic conduit for environmental education. Nonetheless, the absence of systematic integration of sustainability themes reveals significant avenues for enhancement.

Although a multitude of investigations has scrutinized the integration of renewable energy education within formal educational curricula (Chatterjee et al., 2019), its implementation in extracurricular contexts, such as KIR, remains inadequately addressed. While KIR prioritizes empirical research and experimental methodologies, it frequently neglects subjects centered on sustainability, including carbon footprint mitigation and renewable energy technologies. This deficiency underscores the necessity for a systematic methodology to incorporate LCE into KIR initiatives (Ma et al., 2022). Furthermore, sustainability education has predominantly been examined within formal classroom environments, with minimal emphasis placed on extracurricular endeavors that provide experiential, research-oriented learning opportunities (Barnason et al., 2022). Given the pivotal role of programs like KIR in shaping students' scientific proficiencies, aligning these programs with LCE principles could substantially augment students' environmental literacy and practical problem-solving capabilities (Shehzad et al., 2023).

In light of these identified deficiencies, this study endeavors to bridge the gap between LCE and extracurricular scientific research programs. The impetus for this inquiry arises from the escalating necessity to equip students with scientific competencies that align with sustainability objectives, particularly in addressing climate change through youth-driven scientific research initiatives (Wang et al., 2023).

This research intends to formulate and assess a structured training framework for KIR by amalgamating LCE and renewable energy principles, thereby enhancing students' scientific competencies. As global environmental challenges persist in intensifying, the incorporation of LCE into KIR training is imperative for furnishing students with a holistic comprehension of sustainability and the environmental ramifications of human activities. This pedagogical framework will not only refine students' scientific research capabilities but also augment their proficiency in applying scientific principles to devise innovative carbon reduction strategies. Additionally, this research aspires to identify efficacious models for integrating LCE within KIR training. This undertaking involves the

exploration of diverse pedagogical strategies that can enhance students' grasp of renewable energy and sustainability. By adopting this framework, students are anticipated to cultivate critical thinking, problem-solving, and data analysis competencies. A more profound comprehension of sustainability principles will better equip them to confront future challenges and contribute constructively to climate change mitigation endeavors.

However, the incorporation of LCE within KIR programs manifests specific challenges. Constraints related to resources, a lack of sufficient awareness regarding sustainability principles among educators and students, and the complexities involved in crafting suitable curricula represent some of the foremost impediments. This research endeavor also seeks to delineate these challenges and propose pragmatic solutions aimed at facilitating the effective integration of LCE in KIR training initiatives. Ultimately, the anticipated outcomes of this investigation are expected to elevate the caliber of science education while cultivating environmental consciousness among students from an early stage (Ren et al., 2024).

Building upon prior investigations, this study asserts that the integration of LCE into KIR training programs will markedly augment students' scientific competencies. These competencies encompass critical thinking, problem-solving, and data analysis—skills that are indispensable for the execution of high-caliber scientific research. By embedding sustainability concepts into their projects, students are expected to enhance their analytical capabilities and devise innovative solutions to environmental predicaments (Fu et al., 2021).

Moreover, project-based learning coupled with hands-on experimentation utilizing renewable energy technologies, such as solar panels and wind turbines, is anticipated to bolster students' comprehension of sustainability and environmental accountability. Direct engagement with these technologies facilitates students in establishing connections between theoretical knowledge and practical applications, thereby reinforcing the significance of renewable energy in confronting climate-related challenges. This experiential learning methodology cultivates a sense of responsibility and inspires students to investigate eco-friendly solutions within their scientific inquiries (Vourdoubas, 2024).

Nevertheless, the efficacious execution of Learning-Centered Education (LCE) within Knowledge and Innovation Research (KIR) programs may confront a multitude of obstacles. Constraints in financial resources, inadequate training for mentors, and a lack of robust policy support could hinder the advancement of these initiatives. In the absence of appropriate resources, access to experimental methodologies, and well-qualified educators, students might find it challenging to comprehend and effectively apply principles of sustainability in their investigative endeavors. Consequently, it is imperative to address these impediments to ensure the enduring success and scalability of LCE within KIR frameworks (Zhou & Hu, 2021).

The integration of LCE into KIR extracurricular programs is essential not solely for the enhancement of students' scientific competencies but also for the cultivation of their environmental consciousness and sustainable problem-solving capabilities. By embedding concepts of renewable energy into KIR training, students acquire practical experience in leveraging scientific knowledge to tackle real-world environmental challenges. This pragmatic approach serves to bridge the divide between theoretical understanding and practical application, thereby equipping students to contribute meaningfully to sustainability initiatives (Gómez-Baya et al., 2020; Alvarez Constante & Rosero Erazo, 2024).

Furthermore, this investigation is congruent with global sustainability initiatives, notably the Sustainable Development Goals (SDGs) established by the United Nations. The integration of sustainability into science education bolsters SDG 4 (Quality Education) by fostering innovative educational programs that amalgamate environmental consciousness with scientific exploration (Junting, 2024). Moreover, the introduction of renewable energy education within youth scientific research aligns with SDG 7 (Affordable and Clean Energy) by endowing students with the requisite knowledge and skills to investigate sustainable energy alternatives (Md Khairi et al., 2022).

Moreover, the advocacy of youth-driven scientific endeavors aimed at mitigating carbon emissions and advancing sustainable solutions is in direct alignment with Sustainable Development Goal 13 (Climate Action). By involving students in sustainability initiatives, KIR programs possess the potential to motivate the forthcoming generation of scientists and innovators to actively engage in combating climate change. These initiatives highlight the critical necessity of incorporating LCE into KIR, representing a vital progression towards cultivating a more sustainable and environmentally aware society (García-Ferrero et al., 2021).

This manuscript is organized into six primary sections, which methodically investigate the incorporation of LCE within KIR training frameworks. The Introduction delineates the existing research void, objectives, and the importance of embedding sustainability education within KIR to enhance students' scientific capabilities and ecological consciousness. The Literature Review scrutinizes prior investigations concerning LCE, renewable energy pedagogy, and KIR training models. By assessing existing literature, this segment establishes the theoretical and practical underpinnings requisite for a robust training program. The Research Gaps and Hypothesis section delineates inadequacies in extant studies and articulates principal hypotheses to steer this investigation. The Methodology section elaborates on the Systematic Literature Review (SLR) methodology, detailing the data collection and analytical techniques employed to ensure the reliability and validity of the findings. The Results and Discussion section articulates pivotal discoveries and their implications for science education and sustainability. Finally, the Conclusion and Recommendations section encapsulates essential findings and proposes pragmatic recommendations for the efficient integration of LCE into KIR programs, thereby contributing to the evolution of structured and impactful low-carbon education training frameworks.

METHODS

This research undertook the formulation of a training program dedicated to Low Carbon Education (LCE) for KIR, with the intention of enhancing students' scientific competencies through an extensive review of relevant literature. This aim was realized via a Systematic Literature Review (SLR) methodology, which facilitates the aggregation, selection, and synthesis of extant scholarly works pertaining to the integration of LCE into science education initiatives. The analysis of data was performed utilizing the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure both transparency and accuracy in the literature selection process, in conjunction with NVivo software for thematic analysis to discern principal themes pertinent to the advancement of students' scientific competencies. Consequently, this investigation is projected to provide a solid scientific foundation for the development of a KIR training program that aligns with the principles of sustainability and low-carbon initiatives, thereby fostering more effective science education.

This study utilized a Systematic Literature Review (SLR) methodology to identify, evaluate, and synthesize pertinent scholarly research on the establishment of a low-carbon education-based KIR training program designed to enhance students' scientific skills. Through the SLR, this study aggregated literature regarding the execution of LCE in science education, analyzed various methodologies and strategies employed in KIR training, and assessed their implications on students' practical competencies. Consequently, the SLR approach offers a comprehensive insight into how sustainability-oriented education can augment students' scientific capabilities through KIR-focused training programs.

The study commenced by articulating pivotal research inquiries, including the modalities through which Low Carbon Education (LCE) can be seamlessly incorporated into Knowledge Integration and Research (KIR) training frameworks, the scientific competencies that may be cultivated through such integration, and the manner in which LCE principles can augment science education within the KIR paradigm. To ascertain the pertinence and integrity of the utilized sources, the investigation employed delineated inclusion and exclusion criteria. The inclusion criteria mandated that the chosen scholarly works be published within

the temporal confines of 2019 to 2024, concentrating on KIR training, the cultivation of scientific skills, and the operationalization of LCE in the context of science education. Articles were systematically excluded if they bore no relevance to the research focus, failed to address the development of scientific skills, or were disseminated prior to 2019.

An exhaustive literature review was executed utilizing databases such as Google Scholar, Scopus, ERIC, JSTOR, and ProQuest, employing pertinent keywords such as "Low Carbon Education," "Youth Scientific Paper (KIR)," and "Science Skills Development," while applying filters predicated on publication date and article type. Identified scholarly articles underwent a rigorous screening procedure that entailed the scrutiny of titles, abstracts, and complete texts to evaluate their relevance, with the PRISMA diagram employed to delineate the selection process. The articles that met the criteria were subsequently evaluated for methodological soundness and empirical validity. Following this evaluation, qualitative data analysis was undertaken utilizing NVivo software, which assists in data coding to distill salient themes pertinent to LCE and the enhancement of students' scientific skills through KIR training.

Thematic analysis was conducted to identify recurring motifs, recognize deficiencies, and underscore essential elements that may be assimilated into the training program's development. In conclusion, the research findings were synthesized to delineate the core components of an LCE-oriented KIR training program, alongside recommendations for the integration of sustainability principles within science education, as well as potential challenges that may emerge during its implementation, as illustrated in Table 1.

Table 1. Review of Articles on Low Carbon Education-Based KIR Training Programs and Their Impact on Students' Science Competencies

No.	Title	Objective	Method	Key Findings	Relevance
1	Agbakwuru, V. et al. (2024). The role of renewable energy in achieving sustainable development goals	Determining the function of renewable energy in the attainment of sustainable development objectives.	Literature review	Renewable energy plays a pivotal role in the mitigation of carbon emissions and facilitates the achievement of Sustainable Development Goals (SDGs).	Establishes a fundamental basis for the incorporation of renewable energy pedagogy into low-carbon Knowledge, Innovation, and Research (KIR) educational frameworks.
2	Aggarwal, D. (2023). Green education for a sustainable future	Investigating the role of green education in building sustainability awareness	Conceptual study	Green education is effective in enhancing student sustainability literacy	Inspires the application of green education principles in the development of low-carbon science skills
3	Agustiningtyas, R. S. et al. (2023). Embodied energy and carbon assessment of existing affordable apartments in Indonesia	Examining the embodied energy and carbon emissions associated with economically accessible residential units in Indonesia.	Quantitative study	The design of buildings with low carbon emissions mitigates ecological repercussions.	Emphasizes the significance of incorporating sustainable building design principles within KIR educational training.
4	Al-Greer, M. et al. (2024). Solar energy education: Curriculum framework development	Formulating a comprehensive curriculum framework for the pedagogy of solar energy education.	Curriculum development	A well-structured curriculum framework has the potential to enhance students' comprehension of solar energy technology.	Guidelines for the incorporation of renewable energy technologies within KIR training curricula.

No.	Title	Objective	Method	Key Findings	Relevance
5	Alvarez Constante, D. M. et al. (2024). The role of renewable energies in the transition to a sustainable energy model	Identifying challenges and opportunities for renewable energy in the transition to a sustainable energy model	Literature review	Renewable energy sources possess considerable capacity to mitigate carbon emissions and enhance energy efficiency.	Promotes the formulation of KIR curricula that concentrate on renewable energy and sustainable practices.
6	Altassan, A. (2023). Sustainable integration of solar energy, behavior change, and recycling practices in educational institutions	Examining the amalgamation of solar energy utilization and recycling methodologies within academic establishments.	Case study	The incorporation of solar technology alongside recycling methodologies enhances the environmental consciousness of students.	Offers empirical illustrations for the incorporation of pro-environmental conduct within KIR training methodologies.
7	Ardoin, N. M. et al. (2022). Positive youth development outcomes and environmental education	Investigating the influence of environmental education on the developmental trajectories of young individuals.	Literature review	Environmental education improves youth social skills, leadership, and environmental awareness	Directs attention towards the advancement of youth development within the realm of low-carbon education via KIR.
8	Barnason, S. et al. (2022). Environmental action programs using positive youth development may increase civic engagement.	Investigating the relationship between environmental action programs and student engagement	Experimental study	Environmental action programs enhance collaborative skills and student leadership	Helps design collaborative KIR training programs
9	Chatterjee, A. et al. (2019). Microgrids for rural schools: An energy-education accord to curb societal challenges	Analyzing the potential of microgrids to support education in rural schools	Case study	Implementing microgrids enhances students' technical skills related to renewable energy	Introduces renewable energy technology in science education, especially for rural areas
10	Fiel'ardh, K. et al. (2023). The role of eco-school program (Adiwiyata) towards environmental literacy of high school students	Assessing the impact of the Adiwiyata eco-school program on students' environmental literacy	Quantitative study	The Adiwiyata program increases environmental awareness through action-based education	Provides a model for action-based training to enhance science skills and environmental awareness in KIR
11	Fiel'ardh, K. et al. (2023). Investigating the environmental and energy saving behavior among school principals	Investigating energy-saving behaviors among school principals	Classification algorithms	Principals' support for energy-saving policies positively impacts eco-friendly school policies	Emphasizes the role of leadership in supporting low-carbon education policies
12	Fu, H. et al. (2021). Review of developments in whole-building	Reviewing developments in building energy consumption models	Literature review	Energy consumption modeling optimizes energy efficiency in commercial buildings	Enhances understanding of energy efficiency in low-carbon science and engineering education

No.	Title	Objective	Method	Key Findings	Relevance
	statistical energy consumption models for commercial buildings	for commercial buildings			
13	García-Ferrero, J. et al. (2021). Towards a sustainable future through renewable energies at secondary school: An educational proposal	Proposing an approach to renewable energy education in secondary schools	Curriculum development	Integrating renewable energy in education improves students' sustainability awareness	Provides guidelines for developing KIR curricula based on renewable energy and sustainability
14	Gómez-Baya, D. et al. (2020). Environmental action and PYD: Environmental action as asset and contribution of positive youth development	Investigating the relationship between environmental action and positive youth development (PYD)	Literature review	Environmental action strengthens youth's social skills and environmental awareness	Helps design KIR programs focused on youth development and low-carbon education
15	Hudha, M. et al. (2020). Low carbon education: A review and bibliometric analysis	Analyzing bibliometric data on low-carbon education	Literature and bibliometric analysis	Low-carbon education is effective in reducing carbon footprints through student awareness and practices	Provides the theoretical basis for developing low-carbon KIR training programs
16	Hudha, M. N., Suryani, M. F., & Santoso, M. (2021). How low-carbon issues are addressed in primary school textbooks	Investigating how low-carbon issues are addressed in primary school textbooks	Content analysis	Primary school textbooks do not adequately highlight low-carbon issues	Highlights the importance of integrating low-carbon issues into KIR training
17	Junting, Z. (2024). Current status of low-carbon education among undergraduates: A case study of Guangdong Province	Analyzing the status of low-carbon education among undergraduates	Case study	Low-carbon education at the university level is still limited, but has significant potential	Provides a reference for developing broader low-carbon KIR programs at the primary and secondary education levels
18	Kanna, V. I. et al. (2024). The effects of greenhouse gas emissions on global warming	Investigating the effects of greenhouse gas emissions on global warming	Literature review	Greenhouse gas emissions contribute significantly to global warming, threatening sustainability	Encourages integrating climate change understanding into low-carbon KIR curricula
19	Ma, D. et al. (2022). Pro-environmental behavior–Renewable energy transitions nexus	Investigating the relationship between pro-environmental behavior and renewable energy transitions	Quantitative analysis	Transitioning to renewable energy encourages positive pro-environmental behaviors	Inspires teaching renewable energy in KIR training to promote students' environmental behavior
20	Md Khairi, N. H. et al. (2022). Suitability of rooftop solar	Analyzing the feasibility of rooftop solar photovoltaic	Case study	Installing solar panels improves energy	Provides guidance for integrating renewable

No.	Title	Objective	Method	Key Findings	Relevance
	photovoltaic at educational building towards energy sustainability in Malaysia	systems in educational buildings for energy sustainability		sustainability in Malaysian schools	energy in KIR teaching in schools
21	Lottu, O. A. et al. (n.d.). Global review of solar power in education: Initiatives, challenges, and benefits	Presenting a global review of solar power initiatives in education	Literature review	Solar power in education faces challenges but offers numerous benefits	Provides examples of implementing solar technology in low-carbon education
22	Li, Q. et al. (2024). A comparative analysis of low-carbon design strategies for China's higher education parks	Analyzing low-carbon design strategies for higher education parks in China	Comparative analysis	Low-carbon design strategies reduce energy consumption on campus	Inspires integrating low-carbon design in KIR training programs and sustainability education
23	Ntanos, S. et al. (2022). Investigating the environmental and energy saving behavior among school principals	Investigating energy-saving behaviors among school principals	Classification algorithms	Principals' support for energy-saving policies positively impacts eco-friendly school policies	Emphasizes the role of leadership in supporting low-carbon education policies
24	Rap, S., & Bodas, M. (2024). Innovate for impact: Young adults education and empowerment for climate action	Enhancing education and empowerment for youth climate action	Conceptual study	Youth education for climate action increases sustainability awareness and action	Encourages innovation in KIR education focusing on climate change and youth empowerment
25	Ren, G. et al. (2024). Motivation and guidance of college students' low-carbon behavior	Investigating motivation and guidance for low-carbon behavior among college students	Survey	Effective guidance programs can change students' low-carbon behaviors	Serves as a model for developing low-carbon mentoring programs for students in KIR training
26	Shehzad, S. et al. (2023). Significance of 'Renewable Energy Education' in the curriculum of students	Investigating the importance of renewable energy education in students' curricula	Literature review	Renewable energy education is vital in raising awareness and promoting pro-environmental behavior	Provides the foundation for integrating renewable energy education in low-carbon KIR curricula
27	Soares, C. A. B. et al. (2023). Photovoltaic solar energy and sustainability in higher education institutions: A multiple case study	Analyzing the use of photovoltaic solar energy in higher education institutions	Case study	Solar energy enhances energy sustainability in higher education institutions	Inspires integrating renewable energy in low-carbon KIR education in higher institutions
28	Vourdoubas, J. (2024). Use of sustainable energy systems in educational institutions	Presenting the use of sustainable energy systems in educational institutions	Literature review	Using sustainable energy in schools increases environmental awareness and pro-	Demonstrates the implementation of sustainable energy in KIR training in schools

No.	Title	Objective	Method	Key Findings	Relevance
				environmental practices	
29	Wang, H. et al. (2023). The role and challenge of dual carbon goals in promoting electric power education	Investigating the role and challenges of dual carbon goals in promoting electric power education	Literature review	Dual carbon goals can accelerate the energy transition and promote energy education	Guides the development of low-carbon education based on electric power technology
30	Wang, X., & Guo, L. (2021). How to promote university students to innovative use of renewable energy?	Investigating ways to promote innovative use of renewable energy by university students	Inquiry-based learning model	Inquiry-based learning effectively promotes the innovative use of renewable energy	Inspires the development of inquiry-based KIR training programs focused on renewable energy

The data analysis incorporated two principal methodologies. Initially, the PRISMA framework was employed to systematically and transparently delineate the procedures involved in article identification, screening, and selection, thereby ensuring that the articles chosen were congruent with the research objectives. This methodological process is depicted visually through the PRISMA diagram (Figure 1) to facilitate a comprehensive understanding of the literature selection methodology. Subsequently, NVivo software was implemented for the qualitative analysis of data, wherein information extracted from the selected articles was systematically coded and analyzed thematically. NVivo aids in the identification of salient themes pertinent to students' scientific competencies (Figure 2), the execution of Low Carbon Education initiatives (Figures 3 and 4, which illustrate NVivo chart analysis and NVivo word cloud analysis, respectively), and crucial factors in the design of KIR training programs. This methodological framework empowers researchers to investigate patterns, relationships, and pivotal components that enhance the formulation of an effective training program.

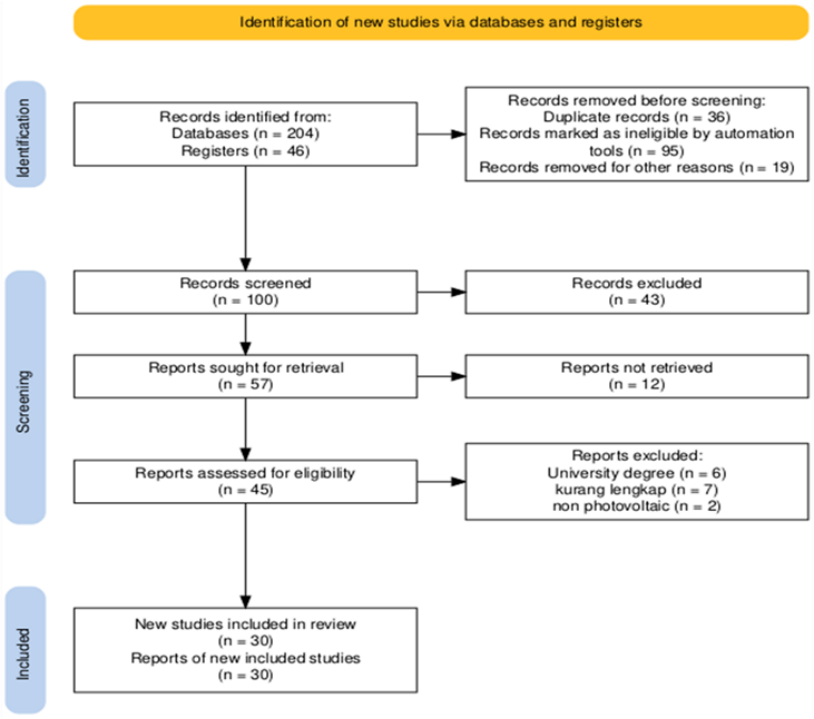

Figure 1. Article Analysis Using the PRISMA Method

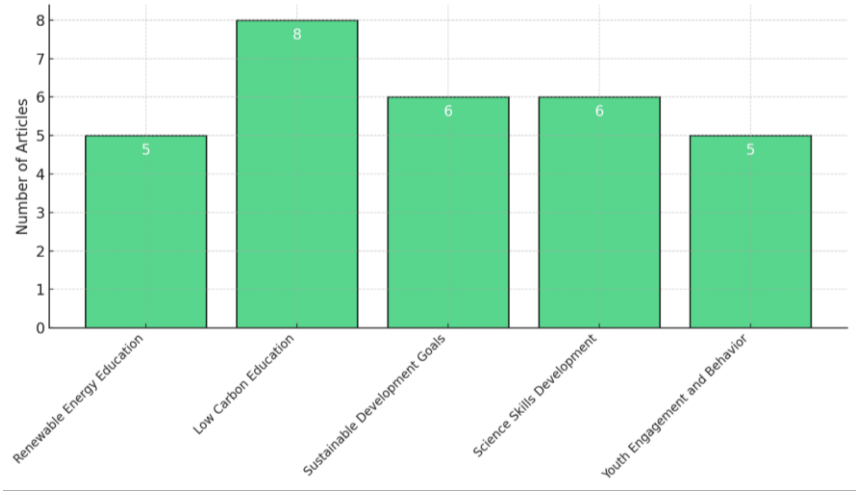

Figure 2. Article Analysis Diagram Using the NVivo Method

Figure 3. Article Analysis Using NVivo Word Cloud Method

A meticulously organized KIR training program grounded in LCE is anticipated to significantly augment students' scientific abilities by incorporating the tenets of renewable energy and sustainability within their academic framework. A multitude of empirical research studies suggest that the execution of this program can enhance students' comprehension of renewable energy technologies, including photovoltaic systems, microgrid infrastructures, and low-carbon energy alternatives, whilst concurrently nurturing practical competencies through experiential learning and scientific projects centered on ecological solutions.

To attain maximum efficacy, the curriculum ought to be structured to encompass a project-based learning paradigm, thereby actively involving students in endeavors pertinent to clean energy technologies and the mitigation of carbon footprints. Moreover, the program should promote behavioral transformations by heightening students' awareness regarding the significance of energy conservation and environmental sustainability. The success of this training initiative is contingent upon collaborative alliances among educational institutions, industry stakeholders, and governmental entities, alongside the provision of sufficient infrastructure, such as the installation of solar panels in educational settings and the incorporation of digital platforms for ICT-enhanced learning. The predominant challenges that necessitate attention include financial limitations, particularly in resource-constrained regions, as well as the imperative to alter behavioral patterns among both students and educators, which

necessitates a comprehensive and sustainable approach.

RESULTS AND DISCUSSION

The concept of LCE can be utilized to augment students' scientific competencies through the integration of sustainability and energy efficiency principles across all domains of science education. In this framework, experiential and project-based pedagogical approaches assume a pivotal role in enriching students' comprehension of theoretical constructs while concurrently facilitating their application in practical, real-world contexts. For example, students may partake in initiatives centered around renewable energy, such as the design and construction of sustainable solar power systems or wind energy installations. These tactile experiences profoundly engage students in the application of scientific and technological principles pertinent to carbon reduction.

Table 2. Approaches used in LCE programs

Approach	Number of Studies Using Approach	Description
Project-Based Learning (PBL)	15	Uses scientific projects to address environmental and climate change issues.
Laboratory Experiments	10	Conducts experiments testing the impact of carbon and energy on the environment.
Outdoor Learning	5	Uses outdoor activities to explore the direct impact of climate change.

Research conducted by García-Ferrero et al. (2021) and Soares et al. (2023) has elucidated that educational paradigms focused on renewable energy afford students the opportunity to engage with sustainable technologies, thus cultivating practical proficiencies in renewable energy, energy efficiency, and energy management. These educational initiatives further immerse students in integrated energy systems, facilitating their comprehension of the interrelationships among various elements, such as photovoltaic panels, energy storage batteries, and energy distribution networks, in the formulation of low-carbon solutions.

In contrast, traditional pedagogical methodologies in the domain of science education predominantly concentrate on theoretical frameworks, didactic pedagogy, and laboratory-based experimentation. Although these approaches provide a foundational grasp of scientific principles, they frequently lack practical applications pertinent to contemporary global issues, such as climate change and energy sustainability. Environmental-oriented educational programs, as endorsed by Agbakwuru et al. (2024) and Chatterjee et al. (2019), embrace a more comprehensive strategy by involving students in field research and community-focused initiatives. These experiential opportunities expose students to authentic challenges related to renewable energy and carbon mitigation, thereby enhancing their scientific competencies within practical contexts.

A comparative examination of environmental-oriented educational initiatives and conventional pedagogical techniques demonstrates that the former considerably surpass the latter in advancing students' scientific competencies within practical settings. For example, the investigation conducted by Fiel'ardh et al. (2023) elucidated that learners engaged in environmental programs, such as eco-school initiatives, attain a more profound and applicable comprehension of subjects including energy conservation and waste management compared to their peers who depend exclusively on theoretical education.

Moreover, environmental education not only fortifies technical abilities but also augments students' collaborative and critical thinking proficiencies—essential elements of scientific inquiry. A project-oriented pedagogical strategy promotes teamwork, peer cooperation, and the cultivation of innovative solutions to sustainability and low-carbon energy dilemmas. By offering a

concrete and pertinent context, this methodology enhances the educational experience and equips learners with the competencies necessary to confront urgent global challenges. In conclusion, LCE establishes a robust framework for students to cultivate scientific skills in a manner that is both pragmatic and contextually pertinent. This educational method not only conveys scientific principles but also immerses students in genuine challenges that necessitate critical, creative, and collaborative reasoning. Consequently, environmental-oriented educational initiatives have demonstrated greater efficacy in fostering students' scientific abilities than traditional instructional approaches, which emphasize theoretical understanding and laboratory-based experimentation.

The implementation of LCE within extracurricular contexts, such as KIR, encounters numerous obstacles that impede the enhancement of students' scientific competencies in sustainability. The principal impediments comprise an insufficiency of adequate facilities for executing experiments and research pertaining to renewable energy. Numerous educational institutions, particularly those situated in remote regions, lack the requisite apparatus and technological resources to instruct subjects such as solar and biomass energy (Alvarez Constante & Rosero Erazo, 2024).

Furthermore, the inadequacy of teacher proficiency constitutes a considerable impediment, as a substantial number of educators and mentors lack the requisite training to effectively incorporate LCE principles into KIR initiatives. This shortcoming exacerbates their capacity to proficiently guide students in research pertaining to low-carbon energy technologies (Agbakwuru et al., 2024). Moreover, the lack of supportive policy frameworks presents another significant barrier. In the absence of policy endorsement, educational institutions encounter difficulties in securing financial resources or designating adequate time for the implementation of sustainability-oriented programs (García-Ferrero et al., 2021), as delineated in Table 2.

Table 3. Synthesis of literature on low Carbon Education (LCE)

Aspect	Key Components Found in the Literature	Recommendations and Findings	Successes and Challenges
Key Components in LCE Training Programs	- Integration of renewable energy in the curriculum (Al-Greer et al., 2024; Soares et al., 2023)	- Renewable energy-based education programs, such as learning about solar energy and microgrids (Chatterjee et al., 2019; García-Ferrero et al., 2021)	Success in applying renewable energy in some schools, but resource and infrastructure limitations hinder expansion in remote areas.
	- Use of microgrids and renewable energy systems for rural schools (Chatterjee et al., 2019)	- Expand learning programs by using solar panels, especially to reduce dependency on fossil energy sources in educational institutions (Soares et al., 2023; Ma et al., 2022)	The main challenges are initial funding and the unpreparedness of schools in remote areas to adopt new sustainable energy technologies.
Recommendations for LCE in Science Education	- Focus on student behavior change towards energy and sustainability (Wang et al., 2023; Xiang & Liu, 2024)	- Integrating behavioral changes to encourage eco-friendly habits and the application of renewable energy technologies in school activities (Wang et al., 2024; Fiel'ardh et al., 2023)	Raising environmental awareness among students has been successful, but challenges arise in changing old habits and increasing active student participation in programs.

Aspect	Key Components Found in the Literature	Recommendations and Findings	Successes and Challenges
Successes in LCE Implementation	- Project-based education to understand renewable energy and carbon reduction (Zhang, 2024; Ma et al., 2022)	- Experimental and project-based learning models focused on renewable energy to understand the workings of eco-friendly energy (Ren et al., 2024)	The challenge in project-based implementation is often related to the lack of facilities and resources in some educational institutions.
	- Development of renewable energy-focused curriculum in educational institutions (García-Ferrero et al., 2021; Aggarwal, 2023)	- Expanding curricula that incorporate low-carbon technologies in higher education to reduce university carbon footprints (Li et al., 2024; Shehzad et al., 2023)	Successful development of renewable energy programs in universities, though faced with challenges of cost and policies that do not fully support implementation.
	- Use of solar photovoltaics to raise awareness and reduce energy consumption (Md Khairi et al., 2022)	- Providing facilities and education that introduce renewable energy systems such as solar panels in higher education institutions to achieve sustainability (Zhang et al., 2024)	Implementation of solar technology in some universities shows a positive impact, but there are challenges in long-term implementation regarding maintenance costs and facility management.
Challenges in LCE Implementation	- Limitations in infrastructure and funding for renewable energy technology adoption in education (Altassan, 2023; Hudha et al., 2020)	- Greater funding and collaboration between the education sector and industry are required to introduce renewable energy technologies into the curriculum (Zhou & Hu, 2021)	Budget constraints and policy support often hinder the expansion of renewable energy technologies in educational curricula, especially in developing countries.
	- Student and teacher involvement in developing sustainable, eco-friendly behaviors (Fiel'ardh et al., 2023; Wang et al., 2023)	- ICT-based education and digital platforms promoting low-carbon learning accessible to students in various regions (Zhang, 2024; Xiang & Liu, 2024)	The application of digital technology can speed up student understanding of eco-friendly energy technologies, but students are still limited by unequal access to technology.

Several strategies may be employed to mitigate these obstacles. Firstly, enhancing educational facilities through partnerships with non-governmental organizations (NGOs) and private sector entities can facilitate the acquisition of necessary resources by educational institutions. Moreover, the establishment of specialized training initiatives for mentors is essential to enrich their comprehension of renewable energy principles and methodologies (Shehzad et al., 2023).

Furthermore, policy endorsement is imperative, as both governmental bodies and educational establishments must allocate sufficient financial resources and develop policies that promote the advancement of LCE programs, as indicated by Altassan (2023) and Vourdoubas (2024). In addition, collaborations among schools

can foster resource-sharing, thereby enabling institutions with inadequate infrastructure to exchange knowledge and equipment, which is vital for the effective execution of LCE-oriented programs (Chatterjee et al., 2019). Through the adoption of these strategies, the integration of LCE into KIR can be conducted with greater efficacy, providing students with vital scientific competencies anchored in sustainability—an element of significant relevance to contemporary global issues.

The implementation of the Low Carbon Education (LCE) program within extracurricular initiatives such as KIR is closely aligned with the Sustainable Development Goals (SDGs), particularly emphasizing three pivotal domains: Quality Education (SDG 4), Climate Action (SDG 13), and Responsible Consumption and Production (SDG 12). Initially, LCE enhances Quality Education (SDG 4) by delivering pertinent and high-caliber education in the fields of science, technology, and sustainability. Instruction on renewable energy and low-carbon technologies equips students with fundamental scientific principles necessary for fostering a sustainable future. García-Ferrero et al. (2021) assert that the incorporation of renewable energy education in educational settings elevates awareness of sustainability while augmenting students' scientific acumen. Furthermore, the project-based learning paradigm within KIR programs enables students to cultivate practical scientific abilities, thereby enhancing their comprehension in a context that increasingly depends on renewable energy.

Second, the Learning for Climate Education (LCE) initiative advances Climate Action (SDG 13) by enhancing students' cognizance and promoting environmentally responsible behaviors. By equipping learners with comprehensive knowledge and competencies pertinent to renewable energy and environmentally sustainable practices, this initiative enables them to comprehend the critical significance of mitigating carbon emissions and embracing sustainable lifestyles (Ma, Li, & Ullah, 2022). The incorporation of LCE within the Knowledge Integration Research (KIR) framework affords students practical experience in renewable energy initiatives, thereby contributing to the alleviation of local climate change repercussions. Vourdoubas (2024) emphasized the pivotal role of renewable energy education in nurturing a generation that possesses heightened awareness of climate-related issues.

Third, LCE facilitates Responsible Consumption and Production (SDG 12) through the provision of education that emphasizes the efficient utilization of resources, recycling, and waste minimization. For instance, LCE programs that concentrate on solar energy and environmentally friendly technologies motivate learners to utilize natural resources judiciously and comprehend the ecological implications associated with product life cycles (Altassan, 2023). Furthermore, such programs foster an understanding of sustainable consumption and production practices, prompting students to incorporate these principles into their everyday activities (Wang et al., 2023).

Overall, the integration of LCE into the KIR framework significantly contributes to the attainment of pertinent Sustainable Development Goals (SDGs) by converging scientific education, climate change awareness, and responsible consumption practices. As Aggarwal (2023) proposed, the assimilation of green education and renewable energy technologies into student curricula constitutes a crucial measure toward constructing a more sustainable future in alignment with the principles of the SDGs. The prospective advancement of LCE within the KIR paradigm offers numerous avenues for adaptation and innovation, thereby ensuring inclusivity and relevance across a diverse array of student demographics and geographical regions.

First, the educational program can be customized to cater to students from diverse social, economic, and geographical backgrounds by modifying instructional materials and pedagogical strategies. For example, in areas characterized by inadequate infrastructure, low-carbon education (LCE) can prioritize essential knowledge concerning energy efficiency and carbon mitigation through the deployment of accessible and cost-effective technologies. Regionally available renewable energy resources, including wind or biomass energy, can be harnessed as viable alternatives, particularly in rural locales endowed with abundant natural resources (Chatterjee et al., 2019). Furthermore, Hudha et al. (2020) underscored the significance of a community-centric methodology in low-carbon education,

wherein students engage collaboratively with local communities to identify and implement sustainable solutions that are tailored to their unique environmental and economic contexts.

Additionally, the educational initiative can be broadened to encompass students in under-resourced areas through the utilization of digital technology. E-learning platforms and mobile applications that provide educational modules on renewable energy and sustainability can effectively mitigate accessibility barriers for students located in remote regions. Zhang (2024) contended that digital learning instruments function as a potent medium for disseminating low-carbon education, particularly as students increasingly depend on mobile devices and internet-mediated learning resources.

Second, the role of technological innovation in Knowledge Integration and Reflection (KIR) training is paramount for augmenting its efficacy. A prospective enhancement includes the incorporation of computer simulations and interactive software to aid students in grasping intricate concepts such as energy flow, system efficiency, and carbon impact in a more engaging and practical manner. These technological tools empower students to conduct virtual experiments, evaluate various scenarios, and visualize data interactively, thereby enhancing both their understanding and engagement with sustainability-related topics (Li et al., 2024).

By implementing these adaptive and technological methodologies, LCE-based KIR programs can attain greater inclusivity, accessibility, and effectiveness, thereby equipping students with the requisite skills and knowledge to confront urgent sustainability issues within their respective communities.

Table 4. Impacts of LCE on students' science Skills

Science Skill	Number of Studies Showing Positive Impact	Description of Impact
Critical Thinking	18	Students can identify and analyze environmental issues more critically.
Problem-Solving	22	Project-based education teaches students to develop solutions to real-world problems.
Data Analysis	19	Students demonstrate better skills in collecting and analyzing scientific data related to climate change.
Scientific Communication	14	Scientific communication skills improve, especially in presenting research results based on sustainability.

Furthermore, collaboration with external entities, including environmental organizations and academic institutions, constitutes a significant opportunity to augment the program's efficacy. Alliances with universities furnish students with access to specialists in renewable energy, low-carbon technologies, and sustainability sciences. Internship programs and collaborative research initiatives with universities can provide students with practical experience in sustainability projects, thereby enabling them to apply theoretical knowledge to real-world challenges (Shehzad, Afzal, & Anwar, 2023). Gómez-Baya et al. (2020) underscored the pivotal role of universities in environmental education, functioning as mentors and strategic collaborators, thereby amplifying the program's impact and outreach.

Similarly, collaborations with environmental organizations and non-governmental organizations (NGOs) that focus on climate change and sustainability expose students to field-based initiatives and ongoing community programs. These initiatives may encompass afforestation projects, waste management campaigns, and clean energy adoption efforts. Such engagements not only reinforce theoretical concepts but also empower students to undertake concrete actions aligned with the Sustainable Development Goals (SDGs) (Altassan, 2023). By engaging in these collaborative endeavors, students acquire a more profound understanding of environmental challenges while cultivating a sense of responsibility toward sustainability.

Through these innovations, the incorporation of Low Carbon Education (LCE) within KIR programs will not only enhance students' scientific competencies but also promote increased ecological awareness and foster broader societal behavioral change. By forging robust partnerships with universities and environmental organizations, the program possesses the potential to significantly broaden its reach and contribute meaningfully to global sustainability initiatives (Aggarwal, 2023).

Table 5. Impacts of LCE on Environmental Awareness and Behavior

Aspect	Number of Studies Showing Positive Impact	Description of Impact
Environmental Awareness	21	Students demonstrate a better understanding of climate change and sustainability issues.
Pro-environmental Behavior	17	Students show behavior changes, such as reduced plastic usage and better waste management.
Concern for the Future	19	Sustainability-based education inspires students to engage in environmental conservation initiatives.

CONCLUSION

The incorporation of Low-Carbon Education within youth scientific research training programs has demonstrated efficacy in augmenting students' scientific comprehension, ecological consciousness, and problem-solving competencies. By integrating sustainability tenets into supplementary scientific inquiry, students cultivate a more profound understanding of renewable energy technologies, strategies for carbon footprint mitigation, and sustainable methodologies. The implementation of project-based learning and experiential methodologies in renewable energy applications has markedly enhanced students' critical thinking, data analysis, and innovative capacities.

Nevertheless, numerous challenges endure, including inadequate resources, insufficient mentor preparation, and a deficiency in policy support, all of which obstruct the comprehensive execution of Low-Carbon Education within Knowledge and Innovation Research frameworks. Mitigating these obstacles necessitates robust collaboration among educational institutions, governmental bodies, and industrial stakeholders to furnish the requisite financial, instructional, and infrastructural backing for efficient program implementation.

In spite of these challenges, the incorporation of Low-Carbon Education within Knowledge and Innovation Research is congruent with the Sustainable Development Goals, particularly Goal 4 (Quality Education), Goal 7 (Affordable and Clean Energy), and Goal 13 (Climate Action). This initiative possesses the potential to empower forthcoming generations of scientists and environmental advocates with the essential knowledge and skills required to address climate change and promote sustainable development. To guarantee the enduring success of the Low-Carbon Education-oriented program, ongoing enhancements are imperative in curriculum development, the integration of digital learning platforms, and strategic alliances with universities and environmental organizations. Through the refinement and expansion of these initiatives, educational institutions can cultivate a new cadre of environmentally conscious individuals equipped to contribute to global sustainability endeavors.

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