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Biogas in Science Education: A Systematic Literature Review and Bibliometric Mapping of Trends, Challenges, and HOTS Integration (2015–2024)

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Abstract: Biogas is a renewable, environmentally friendly energy source with significant potential for science education, offering an alternative to the global fossil fuel crisis. This study aims to provide a brief overview of research trends, publication contributions, methodologies used, thematic coverage, and teaching integration in the biogas-based science education literature. This study is a Systematic Literature Review (SLR) with bibliometric analysis, supported by Publish or Perish and VOSviewer, including 720 selected articles from the period 2015 to 2024. The results show that, since 2020, publications related to biogas have increased significantly, with three main research focuses: the use of organic waste for renewable energy development; the application of biogas as an alternative global energy source through technological innovation; and its integration into HOTS learning and education. The majority of the publications come from reputable international journals such as Energies and Sustainability. Case studies and reviews remain the dominant research protocols, while empirical designs such as experiments and surveys are still relatively rare, leaving room for more applied follow-up studies. This review also finds that the application of biogas in science education can support the development of Higher Order Thinking Skills (HOTS). However, this application remains limited in the existing literature. Therefore, the findings highlight the need for further empirical research to more deeply explore the potential of biogas for science education and HOTS development. This study provides new insights that the biogas literature has not fully integrated practical applications for HOTS development, thus requiring further creative and applied research to address this gap.

Keywords: alternative energy, biogas, environmentally friendly, HOTS, science education.

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INTRODUCTION

In the 21st century, global challenges such as the growing demand for sustainable energy and the need for high-quality science education have become critical. The persistent rise in fossil fuel consumption has resulted in numerous adverse environmental effects, including pollution and energy shortages (Borowski, 2022). At the same time, there is a growing call for "green" energy solutions to address the energy crisis and support socio-economic development (Bello, 2015; Acharya, 2025). Biogas generated from organic waste is a promising alternative energy source. The environmental nature of waste and the urgency to develop renewable energy solutions make biogas a key technology not only for addressing environmental issues but also for meeting society's energy needs (Kasavan et al., 2022; Anand et al., 2022).

Biogas production, through processes such as anaerobic digestion (AD), converts food waste into an energy resource that can be used

for cooking or generating electricity (Emetere et al., 2021). This technology has the potential to improve both environmental sustainability and socio-economic conditions by providing affordable energy while addressing waste disposal (Dewi & Roziqin, 2022; Zakhilwal et al., 2024). However, despite its environmental and social benefits, the use of biogas remains relatively underexplored in the context of science education.

Biogas is positioned as a strategic technology to address environmental issues while also obtaining socio-economic and logistical benefits. It is also proposed that biogas can be utilized through recycling and replenishment (Meneses et al., 2023; Rai et al., 2024). It could draw public attention and involvement to the development of an eco-friendly lifestyle. Second, the increase of food waste along the supply chain complicates matters (Kasavan et al., 2022). Characterization and treatment of biogas production. One of the most commonly utilized processes is anaerobic digestion (AD), which converts food waste into biogas (Anand et al., 2022). From this perspective, biogas is clearly not just a low-cost green energy resource but also a strategic instrument that is used to 'man' science education (Biró et al., 2025). Mainstream teaching theories may challenge the 21st-century domain by engaging traditional and contextual thinking, as well as high-order thinking (Safitri et al., 2025).

As global interest in sustainability and renewable energy technologies increases, the application of biogas technology in education presents a unique opportunity to foster higher-order thinking skills (HOTS) in students. While alternative energy research, including biogas-based systems, has surged recently, much of the literature has focused on the technical and environmental aspects of biogas rather than its integration into educational practices (Ali et al., 2023; Kabeyi, 2022). This gap in the literature underscores the need for a more thorough investigation of how biogas can be used as a contextual learning tool to enhance science education and stimulate the development of HOTS in students (Maftuh et al., 2023; Ali et al., 2023; Diab et al., 2017).

The concept of HOTS involves the ability to analyze, evaluate, and create solutions to complex problems, which is essential in the context of energy and environmental issues. Studies have shown that embedding biogas-related concepts in science education can enhance students' understanding of scientific processes and help them apply theoretical knowledge to real-world situations (Haryanto & Arty, 2019; Sutarni & Sutama, 2023). However, the literature remains limited in how biogas can be strategically integrated into curricula to foster these skills. A review of existing studies reveals a critical need to further explore the relationship between biogas and HOTS and to understand how biogas, as a teaching tool, can foster higher-level cognitive engagement among students (Kotsis, 2024; Rahayu et al., 2025). A comparison of our research with other studies from the HOTS generator investigation is based on a study that uses multimedia to generate bioenergy and wind energy materials, providing videos and simulations that cover all STEM subjects. Our primary objective in comparing our findings with those of other studies is to demonstrate the effectiveness of multimedia as an HOTS Generator in Bioenergi and Wind Energy Materials (Suyatna et al., 2019; Diansah et al., 2021).

The science education alternative energy concept may help students confront this problem, as evidenced by cases of investing, critical thinking, creative making, and problem-solving (Hebebci & Usta, 2022). Higher Order Thinking Skills (HOTS) is part of efforts to improve higher-order thinking in students, particularly in science learning, so that they can process and evaluate a wide range of information more deeply (Yanti &

Anas Thohir, 2024). The concept of the alternative energy (Biogas) scene will guide students to understand the process of how science is practiced, including observing, designing, and analyzing data, and proposing solutions that relate to real-world situational problems about energy and environmental crises in a systemic thinking framework (Rubner et al., 2023; Surendra et al., 2015). Project-based education and field-based classes in renewable energy will train students to act as a bridge between theory and practice, evaluating both ecological and social impacts and developing sustainable, innovative ideas (Izzah et al., 2020). In that sense, integrating biogas-based alternative energy as a concept into science learning is not only beneficial for resolving environmental and energy issues but also strategic for enhancing students' quality of HOTS.

In recent years, the integration of renewable energy in science education has become a growing research focus, particularly in the development of Higher-Order Thinking Skills (HOTS) among students. In addition to biogas, research on the use of solar, wind, and hydroelectric energy as contexts for developing HOTS has also shown significant potential. For example, research by (2021) and Nabilah et al. shows how solar and wind-based projects can engage students in experiments and simulations that stimulate their analytical skills. This project-based approach not only improves students' understanding of renewable energy concepts but also encourages them to think critically in evaluating data and designing solutions based on available information. Thus, renewable energy other than biogas has proven to be an effective tool in science education for developing higher-order thinking skills.

The HOTS framework adopted in this study is Bloom's taxonomy, revised by Anderson and Krathwohl (2001), which divides thinking skills into six levels: Remembering, Understanding, Applying, Analyzing, Evaluating, and Creating. In the context of biogas, these skills can be stimulated through activities that involve analysis, evaluation, and solution creation. For example, students can be invited to analyze the anaerobic process in biogas production, evaluate its environmental impact, and develop solutions to optimize biogas use in the context of renewable energy. This approach not only involves students in learning the basic facts about biogas but also invites them to engage in deep, critical, and creative thinking about the application of this technology in real life.

Although studies link biogas to science education, there remains a significant gap between its technical aspects and its application in developing HOTS. Most of the existing literature focuses more on the technical aspects of biogas production, such as the anaerobic process and the quality of methane produced, without much research on how biogas can be used as a tool to improve higher-order thinking skills among students. This gap highlights the need for further research examining how biogas can be integrated into project-based learning (PjBL) and contextual learning to stimulate HOTS. By incorporating biogas into science education, students not only gain knowledge about renewable energy but are also empowered to think critically and creatively in finding solutions to complex energy and environmental problems.

This study aims to address this gap by conducting a Systematic Literature Review (SLR) with a bibliometric approach to explore the integration of biogas in science education. The research questions guiding this study are as follows:

1. What are the annual research trends in alternative energy, specifically biogas?
2. What are common sources of biogas in alternative energy research?
3. What are the dominant subjects in research

on alternative energy within science education, as revealed through network analysis, overlay, and density visualization?

4. How is biogas integrated into science education, and what impact does it have on enhancing students' HOTS?

METHOD

The purpose of this study is to analyze the research trends and developments in alternative biogas energy within the context of Science Education as a contextual learning resource (Santika et al., 2024; Putri et al., 2024). A Systematic Literature Review (SLR) was chosen for this study due to its capacity to comprehensively synthesize existing literature in a systematic, transparent, and structured manner, enabling findings to be scientifically accounted for (Cabrera et al., 2023). The literature search was conducted using ERIC with the search terms 'Alternative Energy,' 'Biogas,' 'Environmentally Friendly,' 'HOTS,' and 'Science Education.' The complete search string used was: ('Alternative Energy' OR 'Biogas') AND ('Environmentally Friendly' OR 'Sustainable') AND ('HOTS' OR 'Higher Order Thinking Skills') AND ('Science Education'). Quotation marks were used to search for exact phrases, and Boolean operators (AND, OR) were employed to combine the terms effectively. The initial search yielded 720 relevant and applicable articles from a pool of 49,382 citations. A subset of 720 articles was formed from the initial list, consisting of articles directly related to the research question. This process adhered to the SLR protocol, with manual application of inclusion and exclusion criteria (Lame, 2019; Carrion et al., 2018; Boell & Cecez-Kecmanovic, 2015).

Data Analysis

The bibliometric analysis was performed using the Publish or Perish and VOSviewer tools (Ariyanto, 2023). The analysis proceeded through the following stages: (a) Identification of search terms; (b) Extraction of initial results based on these terms; (c) Screening of articles according to inclusion and exclusion criteria; (d) Collection of aggregate statistics on the discovered literature, including trends in publication years and subject areas; and (e) Examination of interrelationships among topic areas, using review keywords generated during the systematic review process itself. The results are illustrated through three bibliometric maps: network visualization, overlay visualization, and density visualization, which describe the relationships, temporal evolution, and focus of research topics.

This systematic review aims to explore the integration of biogas into HOTS learning, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The research flow is illustrated in Figure 1.

Figure 1 shows a PRISMA flowchart illustrating the systematic process for identifying and including studies in a review. Initially, 877 records were identified from Google Scholar, Publisher, and Perish databases, utilizing keywords such as "Alternative Energy," "Biogas," "Environmentally Friendly," "HOTS," and "Science Education" for the years 2015-2024. After removing duplicate records (n=35) and those deemed ineligible by automation tools (n=23), 819 records were screened. Of these, 38 records were excluded for irrelevance or other reasons. Subsequently, 781 reports were sought, of which 20 were not retrievable. Following the eligibility assessment, 761 reports were reviewed, resulting in the inclusion of 720 studies in the final review. This process reflects a thorough, systematic approach to ensuring that relevant and eligible studies are considered for review.

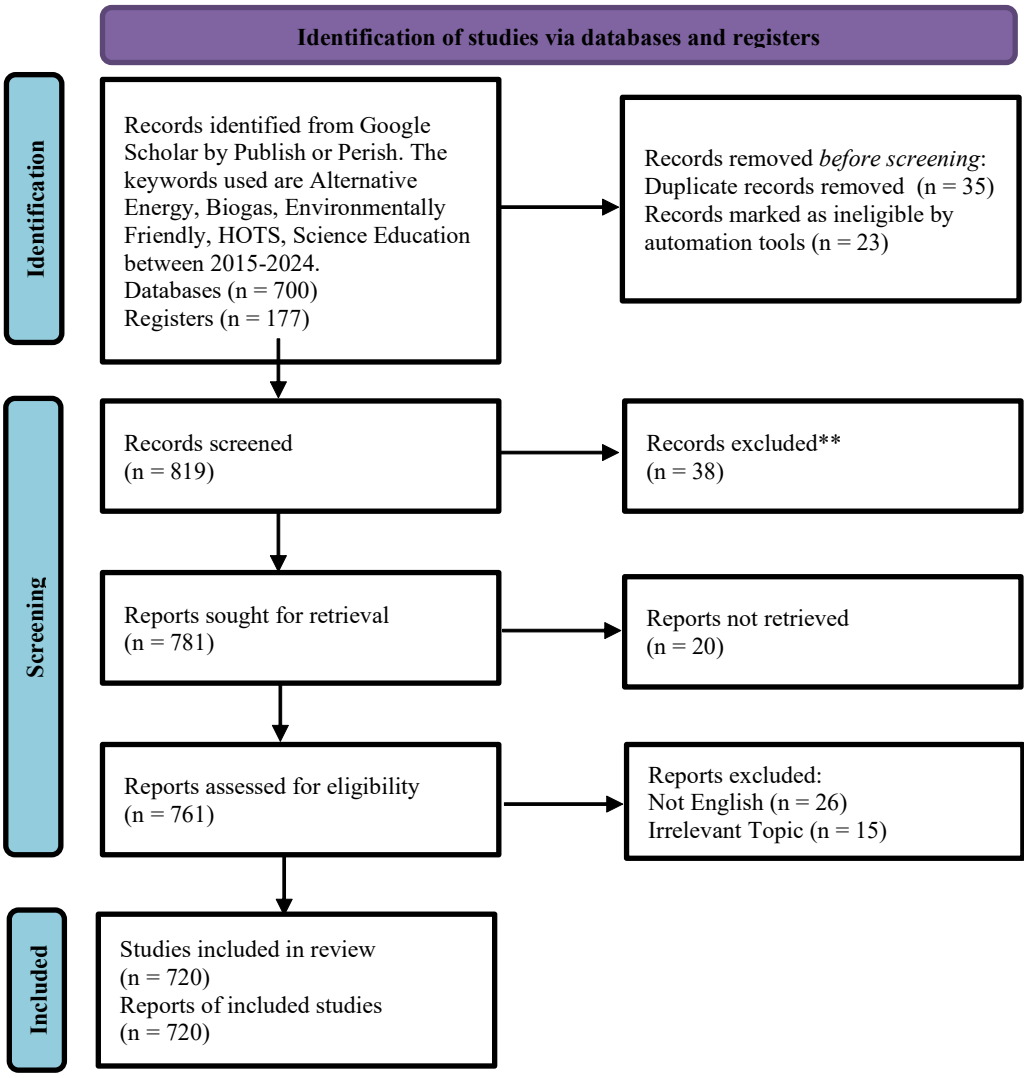

Figure 1. Research flow with PRISMA

Research Design

The study's data extraction design focused on identifying key elements of biogas integration and its impact on HOTS in science education. Articles were reviewed with a focus on: (a) Research methodology: identifying the type of research used (qualitative/quantitative/mixed-methods) and the research design, (b) Educational models: Understanding how biogas was integrated into science education, such as project-based learning, inquiry-based learning, or hands-on experimental methods, (c) Instruments for measuring HOTS: Identifying specific tools or scales used to measure higher-order thinking skills, such as problem-solving tests, critical thinking assessments, or conceptual understanding tools, and (d) Instruments for measuring HOTS: identifying specific tools or scales used to measure higher-order thinking skills, such as problem-solving tests, critical thinking assessments, or conceptual understanding tools.

In qualitative data analysis, this study uses a thematic analysis approach to explore the integration of biogas in science education and its impact on the development of Higher Order Thinking Skills (HOTS). The analysis began by

identifying the main themes that emerged from the reviewed articles, including the learning models applied and the use of biogas in the context of science education. These themes were analyzed to reveal patterns indicating how biogas integration can stimulate HOTS, including analytical, evaluative, and problem-solving skills. Thematic analysis enables this study to draw more in-depth conclusions about the effectiveness of various learning models in the context of biogas, providing clearer insights into practical ways to enhance HOTS through context-based learning approaches.

The sample size of 720 articles is sufficient to represent the emerging research trends in biogas and science education over the past decade. This number serves as a reliable bibliometric group for studying trends and keyword networks, providing certainty in the analysis of author and journal contributions. Furthermore, the sample size is adequate for generalizing the study's results (Sherka et al., 2024; Ghag et al., 2025). Presenting these numbers emphasizes the diversity and size of the literature considered, thereby supporting the legitimacy of the SLR results and affirming the use of current, scientifically credible knowledge. Following the selection, the extracted publication records were transferred and organized using Mendeley, a reference management software, to facilitate data extraction (Ivey, 2018).

Inclusion Criteria

The inclusion criteria were defined based on the focus on biogas, its integration into science education, and its relationship to HOTS. The selected articles had to meet the following criteria: (a) Content relevance: The article must discuss the integration of biogas energy or alternative energy sources into science education or the development of HOTS, (b) Publication timeframe: only articles published between 2015–2024 were included to reflect current trends in research, (c) Language: articles must be published in English to ensure accessibility and consistency in data analysis, (d) Peer-reviewed: only peer-reviewed journal articles or post-conference proceedings were included, ensuring the quality of the research, (e) Education-focused: articles that focused primarily on the technical aspects of biogas without educational context were excluded, and (f) Exclusion of non-scientific reports: editorials, opinions, non-peer-reviewed publications were excluded from the review.

Relevance Evaluation

The steps to determine relevance included: (a) Articles that discussed issues related to alternative biogas energy, environmentally friendly practices, science education, or HOTS, published within the 2015–2024 timeframe, to reflect current research trends; and (b) Only full-text English articles published in peer-reviewed scientific journals or post-proceedings were included. Conversely, papers were excluded if: (a) they focused primarily on the technical aspects of biogas without a connection to the field of education; (b) they were categorized as non-scientific reports (such as editorials or opinions); (c) they lacked peer review; or (d) they were duplicates of other publications. After initial screening, 720 relevant articles were retrieved and analyzed. The 49,382 references cited in these articles were used to evaluate the academic influence and global research trends of biogas-based alternative energy in the context of Science Education, based on the WOS Science Education database.

■ RESULT AND DISCUSSION

What are the annual research trends in alternative energy, specifically biogas?

Identification of annual research trends in alternative energy, especially biogas, was conducted using VOSviewer analysis, which revealed correlations among keywords.

Vosviewer assisted analysis

The correlation between keywords was analyzed using Publish or Perish and VOSviewer.

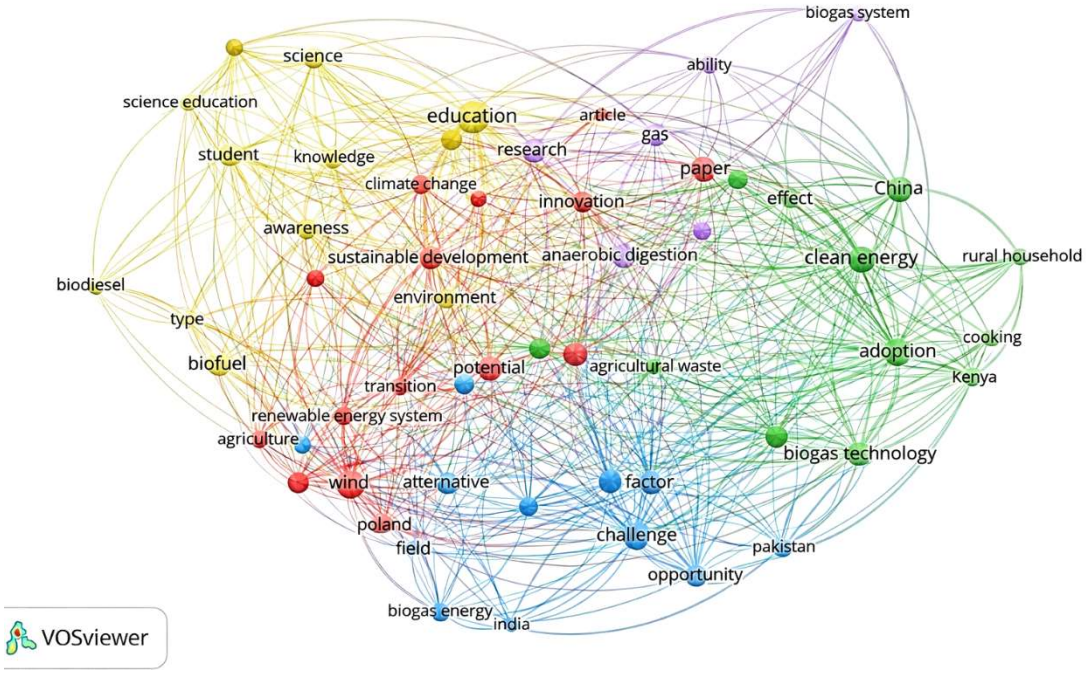

Figure 2. VOSviewer assisted analysis results

The outputs from VOSviewer, as illustrated in Figure 2, reveal an increasing trend in research interest surrounding alternative energy, biogas, environmentally friendly solutions, Higher Order Thinking Skills (HOTS), knowledge, and science education. Each dot represents a keyword, and connecting lines indicate relationships or co-occurrences between these keywords in relevant articles. Keyword clusters are distinguished by color, with topics including education, clean energy, biogas technology, and challenges to biogas adoption across different countries. Keywords such as "sustainable development," "clean energy," and "biogas technology" indicate that these topics are frequently discussed in research on the potential and challenges of using biogas as a renewable energy source in developing countries, including China, India, Pakistan, and Kenya.

Upon examining the VOSviewer results, three main clusters emerge: (a) Education and awareness in sustainable energy, (b) Biogas system and its potential for clean energy adoption, and (c) Biogas technology and its application in rural households. Notably, the cluster on "education" and "sustainable development" has become particularly dense. This density can be attributed to the growing emphasis on raising awareness about renewable energy and climate change, alongside the increasing need for sustainable energy solutions in rural and agricultural settings. As global demand for clean energy rises, biogas has attracted attention for its potential in waste-to-energy systems, particularly in countries such as China, India, and Kenya. Technological advancements in biogas systems, along with research on agricultural waste and the transition to cleaner energy alternatives, have fueled this surge in biogas-related studies. Furthermore, policy shifts supporting the adoption of clean energy technologies have significantly contributed to the expansion of this field. The adoption of green energy frameworks and waste-to-energy initiatives has played a significant role in driving research and development in these fields (Yamaji et al., 2024).

Research in this area has evolved beyond its initial technical focus to encompass broader

environmental and educational dimensions. The integration of biogas technology into science education has gained momentum, with a growing emphasis on its potential to develop students' HOTS through hands-on learning experiences (£ukomska & Witaszek, 2025). This reflects a broader shift towards the inclusion of real-world, context-based examples in the educational curriculum, aiming to foster a deeper understanding of sustainable practices among future generations.

Research trends indicate a growing shift from a purely technical approach toward incorporating environmental and pedagogical concerns. For example, research on technology configurations and operational parameters has become increasingly common. Moreover, while early studies primarily focused on bioenergy production, there is now a broader exploration of by-products and sustainability (García et al., 2024). This transition is highlighted in the study titled "Research Trends in By-Products Recovery from Organic Waste Treated by Anaerobic Digestion: A 30-Year Bibliometric Analysis." This broader approach offers significant opportunities to integrate HOTS and science education, particularly by fostering practical work, local applications, and addressing socio-environmental issues, thereby enriching students' critical thinking skills (Kumar et al., 2024). These evolving research trends are well reflected in the increasing number of publications (Figure 3).

Publications related to alternative energy, biogas, environmentally friendly, hots, science education

Figure 3 illustrates the trend of research publications from 2015 to 2024. During the first

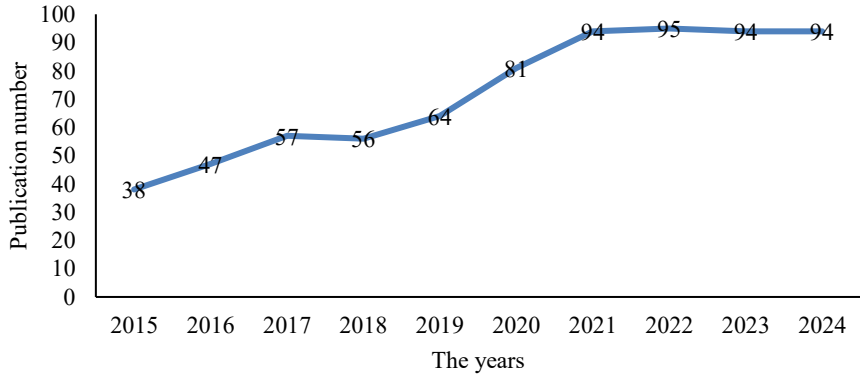

Figure 3. Publications number related to alternative energy, biogas, environmentally friendly, HOTS, science education

period (2015–2018), the publication outputs fluctuated and reached a nadir around 2015–2016. In 2020, the number of published articles continued to rise, reflecting the increasing interest in the field. This trend indicates that research on alternative energy, particularly biogas, has become an active component of academic research, with over 50 articles, similar to around 90 during 2020-2024.

The rise in publications could suggest that alternative energy, including biogas, is no longer seen solely from technical and environmental perspectives. It is also being recognized as a platform for fostering students' critical thinking (Putri et al., 2025; Alim et al., 2025). This aligns with the findings of Erdiwansyah et al. (2021), which emphasize the significant energy potential of renewable sources, surpassing that of fossil

fuels. The growing body of research indicates that green energy technologies, such as biogas, not only address environmental issues but also provide a practical context for developing students' critical thinking.

However, this study has some limitations, including being restricted to articles published in English and indexed in ERIC, which may overlook literature in other languages or from non-indexed sources. Additionally, the bibliometric analysis provides an overview of research trends without assessing the quality or methodology of the individual studies in detail.

What are common sources of biogas in alternative energy research?

Several materials used to produce biogas are described based on a bibliometric analysis of international articles. Bibliometric analysis indicates that international biogas research primarily focuses on utilizing abundant organic matter in the natural environment for clean waste treatment and energy production (Javed et al., 2016; Arora et al., 2018).

Biogas Materials Often Used in Alternative Energy Concepts

Food waste predominates on feedstock's relatively high availability in the household and food industry sector; on the other hand, animal manure, such as cow manure, pig manure, goat dung, chicken excreta, and other types of these fertilizers, are usually considered due to their microbial content having potential for promoting anaerobic digestion (Anand et al., 2022). Water hyacinth has attracted considerable interest as a potential raw material due to its rapid growth and potential to control water pollution (Bello, 2015). Another common source of biogas feedstock is fish waste, fruit and vegetable waste, and agricultural waste (such as straw, rice husks, and corn stalks). These wastes are often used due to their high organic content and their ability to degrade anaerobically (to yield methane gas, which can be used as an environmentally low-impact alternative fuel).

The trend suggests that integrating biogas into science teaching can motivate students' core learning by focusing on sustainability and context-based problem-solving in environmental contexts (Purwaningsih & Wulandari, 2024), while fostering Higher Order Thinking Skills and enabling students to envision and implement changes that utilize wasted energy. Moreover, the findings of this analysis suggest that alternative energy and biogas are not only viewed as technical issues in energy but also as effective, sustainable solutions from an environmental perspective (Lyytimäki et al., 2021).

What are the dominant subjects in research on alternative energy within science education, as revealed through network analysis, overlay, and density visualization?

Network analysis, overlay, and density visualization show that the dominant subjects in alternative energy research within science education are biogas energy, renewable energy technology, and sustainable development. These topics focus on enhancing higher-order thinking skills (HOTS) through project-based learning (PjBL).

Overlay Visualization Mapping

The overlay visualization analysis presented in Figure 4 reveals the evolving trends in biogas research from 2019 to 2021. In the early stages, around 2019, the research focused primarily on the environmental benefits of biogas, with terms such as "biofuel" and "biodiesel" dominating the discourse. As the timeline progresses into 2020, there is a noticeable shift towards the exploration of biogas systems, with increased focus on "biogas technology" and its applications in clean energy. This period also saw a rise in discussions around "sustainable development" and "agricultural waste," reflecting the growing importance of biogas as an alternative renewable

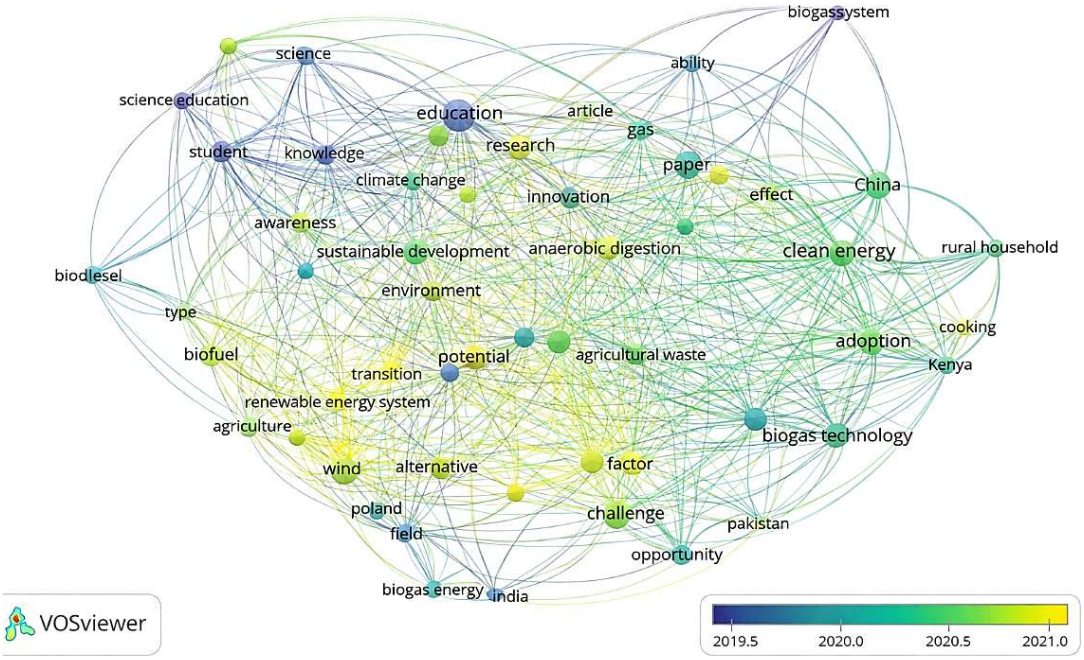

Figure 4. Keywords of overlay visualization mapping

energy source in agricultural and rural contexts. By 2021, research trends indicate a more diversified interest in the "adoption" of biogas technology, particularly in countries such as China, Kenya, and Pakistan. The growing interest in biogas also signals an opportunity to integrate this field into science education, fostering Higher Order Thinking Skills (HOTS) by engaging students with real-world environmental problems related to renewable energy (Biró et al., 2025; Ali et al., 2023).

These findings align with previous research, such as that by Li et al. (2015) and Anand et al. (2022), which suggest that biogas offers green energy benefits and could serve as a context for science teaching to foster higher-level cognitive development. However, it is important to note that not all studies on integrating biogas into education yield consistent results, and some may highlight limitations in its practical application in classrooms. A comparison with trends in other renewable energy research fields, such as wind and solar energy, shows that while biogas is rapidly growing, it still faces greater technical and pedagogical challenges than other, more established renewable energy sources in science education.

Density Visualization Mapping

Figure 5 illustrates the density of studies on biogas as a renewable energy source, with a particular focus on its applications in clean energy and sustainable development. The brighter clusters, notably around terms such as "education," "clean energy," "adoption," and "biogas technology," highlight areas where research is concentrated, showing a high interest in how biogas can be integrated into educational contexts and adopted in rural settings, particularly in countries like China and Kenya. The clustering of keywords such as "innovation," "agricultural waste," and "transition" in the central regions of the map reflects ongoing research on biogas technology's potential to address environmental challenges and energy needs. These areas of high research density indicate that biogas is increasingly viewed not only as an alternative energy source but also as an essential part of the global energy

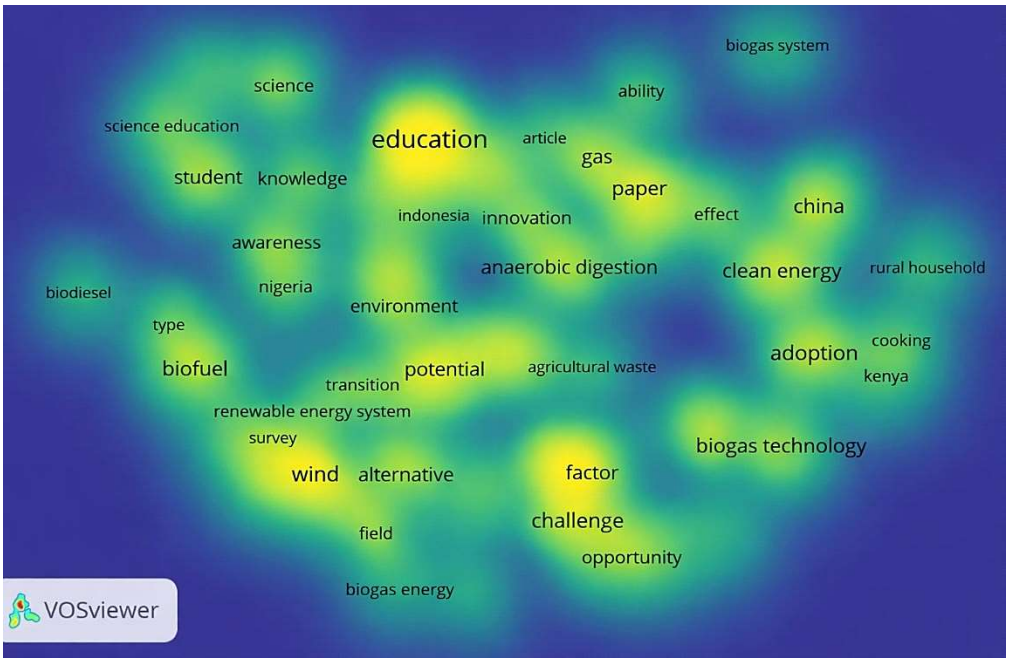

Figure 5. Density visualization mapping

transition. Moreover, the keywords "challenge" and "opportunity" signal that, while significant progress has been made, there is still considerable room to overcome barriers to adoption and expand its role in sustainable energy systems. This suggests an ongoing opportunity to implement biogas technologies, particularly in educational frameworks that foster higher-order thinking skills (HOTS) by engaging students with real-world environmental issues (Hsu & Wu, 2023).

This is because research in this area, particularly regarding the connection between biogas and the broader context of alternative energy and technological advancements, is quite advanced (Tagne et al., 2021). Overall, this map confirms that biogas research has focused on reusing organic waste and sustainability, but also highlights that there may still be opportunities in its practical implementation, as well as in educational science (Muvhiiwa et al., 2017). This is an opportunity for researchers to apply biogas and to teach HOTS lessons to students through environmental context-based learning problems and learning about renewable energy.

Other bibliometric studies in the field of renewable energy education, such as those by Senthil (2022), show that, in recent years, there has been a significant increase in publications focusing on integrating renewable energy into higher education curricula. This study highlights the dominance of topics such as "Renewable Energy Education" and "Energy Transition" in the scientific literature. This focuses more on university-level renewable energy education policies and on developing curricula that encompass all types of renewable energy, not just biogas. Meanwhile, as seen in Figure 4, despite progress in research related to biogas and education, the primary focus remains limited to the specific biogas energy sector. It has not yet fully integrated with broader renewable energy topics.

Annual Evolution of Research Topics in the Biogas Context

Figure 6 illustrates the evolution of research topics related to biogas and science education from 2015 to 2024. The chart highlights the

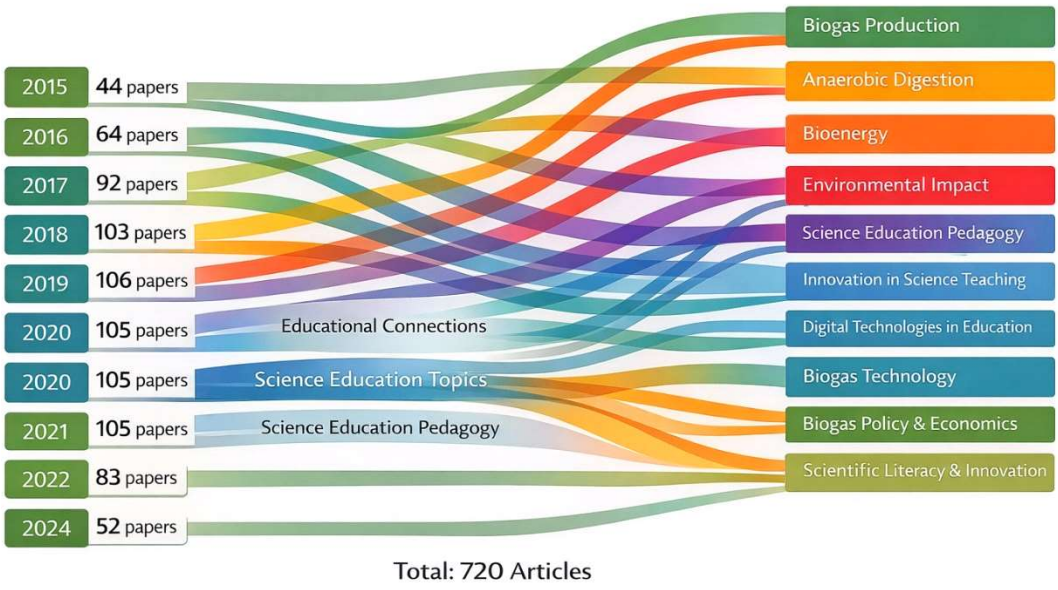

Figure 6. Annual evolution

growing prominence of "Biogas Production" and "Anaerobic Digestion" in the early years, with a noticeable increase in publications from 2015 to 2019. From 2020 onwards, a shift toward integrating biogas-related topics with "Science Education Pedagogy" and "Science Education Topics" can be observed, signaling a trend toward connecting biogas research with educational frameworks. The steady presence of topics such as "Bioenergy," "Environmental Impact," and "Biogas Technology" throughout the years reflects a continued focus on the environmental benefits and technological advancements of biogas. However, in 2022, there was a slight decline in publications, particularly in "Biogas Policy & Economics," suggesting a potential gap in policy-driven research. Overall, this timeline suggests that biogas research is increasingly integrated into educational contexts, reflecting efforts to foster scientific literacy and innovation through real-world applications in energy and sustainability.

How is biogas integrated into science education, and what impact does it have on students' HOTS?

This article explores the potential of integrating Project-based Learning (PjBL), Science, Technology, Engineering, and Mathematics (STEM) approaches, and contextual learning strategies to enhance students' Higher Order Thinking Skills (HOTS). These strategies are particularly effective in addressing alternative energy issues, such as converting organic waste into eco-friendly biogas (Sutarni & Sutama, 2023). Specifically, integrating biogas into science education can deepen students' understanding of energy concepts while engaging them in analytical, problem-solving, and critical thinking activities.

Integration of Biogas as an Alternative Energy in Learning

Previous research indicates that multimedia tools, including bioenergy-based videos and STEM-themed wind energy simulations, are effective in improving HOTS in renewable energy. Similarly, the present study confirms that integrating biogas into science education has high potential to foster context-based, practice-oriented learning, thereby enhancing energy literacy and 21st-century skills, and supporting sustainable development (Anand et al., 2022; Li et al., 2015). This is further supported by research demonstrating the effectiveness of multimedia in stimulating HOTS in bioenergy and

wind energy education (Suyatna et al., 2019; Diansah et al., 2021).

However, the claim to "integrate biogas into learning" remains too general. Based on the literature cluster analysis, more specific recommendations can be made. For instance, integrating biogas into education could focus on hands-on activities, such as biogas production labs where students use organic waste to generate biogas, allowing them to experience the process firsthand and understand its application in renewable energy generation. Additionally, biogas technology simulations could be employed, enabling students to explore the efficiency of various biogas plants and understand their role in sustainable energy systems (Heiker et al., 2021). Case studies based on local biogas production and its role in waste management could also be integrated into the curriculum, fostering a deeper connection between the students' learning and their community's environmental challenges (Olawale & Oladapo, 2024; Rasimphi et al., 2022). These specific approaches not only enhance the understanding of biogas as a renewable energy source but also provide students with opportunities to engage in practical, context-driven learning.

These more targeted recommendations, based on findings from cluster analysis, provide a clearer path for integrating biogas into science education. This approach aligns with broader educational goals of fostering critical thinking, problem-solving abilities, and sustainability awareness. The implications of this study emphasize that renewable energy research should adopt both conceptual and experimental perspectives, making them relevant to education and societal needs (Hu, 2024). Overall, biogas and alternative energy research in science education holds significant promise, as evidenced by high-quality publications and diverse methodologies driven by context-based, practice-oriented learning approaches that enhance HOTS.

The integration of biogas as an alternative energy source into science education has significant potential to improve energy literacy and 21st-century skills, and to support sustainable development. However, despite this clear potential, the reasons why biogas integration into science education remains limited remain underexplored in the existing literature. One pedagogical implication to consider is the dominance of the technical cluster in research focused on practical applications and biogas experiments, while a more pedagogical cluster, emphasizing how biogas can be understood within the context of science learning, remains limited. Teachers often fall into a technical approach that emphasizes the experimental aspects and applications of technology, without linking them to the development of critical and contextual thinking skills, which should be the primary focus of science education. This suggests that while hands-on experiments and simulations can enrich learning, there is still a gap in equipping teachers to integrate this technical knowledge into instruction focused on developing students' higher-order thinking skills (HOTS). Therefore, it is crucial to develop teacher training that combines technical approaches with the development of analytical and problem-solving skills, which should be at the core of science education.

In the existing literature, analysis of barriers to biogas integration into science curricula is often underexplored. One of the most obvious barriers is rigid and inflexible curricula, which often do not allow for changes or adjustments to incorporate new topics such as biogas. The tightly structured curriculum makes integrating renewable energy topics, including biogas, a significant challenge, especially at the primary and secondary levels. Furthermore, the lack of teacher training in the use of the latest technologies and context-based teaching methods, such as biogas simulations and hands-on experiments,

exacerbates this situation. Many teachers lack the skills to design and implement experiment-based learning on biogas, as they have not received sufficient training in teaching renewable energy and in using multimedia in science instruction. Furthermore, limited facilities, such as adequate laboratories for conducting biogas experiments or access to software for biogas technology simulations, also pose significant barriers. Therefore, to overcome these barriers, a more integrated approach is needed, including curriculum updates, more intensive teacher training, and the provision of supporting facilities to enable the more effective implementation of biogas and renewable energy teaching in the classroom.

CONCLUSION

Research on biogas as an alternative energy source has seen significant growth over the past decade, with a steady increase in publications in leading journals such as Energies and Sustainability. This study has provided a comprehensive overview of key research areas, including food waste, anaerobic digestion, biogas technology, and sustainable development. The integration of biogas into science education, particularly through approaches such as project-based learning (PjBL) and contextual learning, has been explored. However, experimental and survey-based studies in this area remain limited. This gap indicates an important opportunity for future research to further investigate the practical applications of biogas in educational settings, with a focus on developing methods to integrate biogas as a tool for promoting Higher Order Thinking Skills (HOTS) and addressing global challenges such as sustainability and renewable energy.

This study holds both theoretical and practical implications for the field of science education. Theoretically, integrating biogas into science education could enhance existing educational models by incorporating hands-on learning experiences, enabling students to engage with real-world issues such as waste management and energy sustainability. In practice, it provides educators with an innovative way to address sustainability and energy literacy while fostering students' critical thinking and problem-solving skills. However, it is important to acknowledge that this study, based on bibliometric data, does not provide direct evidence of the educational impact of biogas integration. Future research should examine experimental studies that assess how biogas education influences students' cognitive development and environmental awareness. Specifically, studies should focus on classroom interventions that incorporate biogas into curriculum designs, using measurable outcomes to assess improvements in HOTS and sustainability knowledge.

The originality of this study lies in its interdisciplinary approach, merging biogas technology with science education. It provides valuable insights into how biogas can be utilized to enhance teaching practices, offering potential applications for fostering 21st-century skills. The primary contribution of this study is its exploration of biogas as both a sustainable energy source and an educational tool, suggesting ways to integrate it into science education to address current global challenges while enriching the learning experience. The study's findings are particularly relevant for educators seeking innovative ways to incorporate sustainability and environmental issues into their teaching, offering practical guidance for designing curricula that engage students in real-world problem-solving.

Ultimately, this study differs from previous research by focusing on the dual role of biogas: both as an alternative energy source and as a tool for developing students' cognitive and environmental literacy. The integration of biogas into science education represents a novel approach that holds promise for improving

educational outcomes while contributing to sustainability goals. This research paves the way for further exploration into the practical applications of biogas in classrooms, offering new opportunities for educators and researchers to develop more effective teaching strategies that align with contemporary educational and environmental challenges.

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