Trends in learning global warming materials for supporting sustainable development goals: A bibliometric review

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Abstract
Climate change and global warming are global issues with significant impacts on health, food security, and economic sustainability. This study aims to analyze learning trends related to global warming in support of the Sustainable Development Goals (SDGs) through a bibliometric approach. The research data were obtained from the Scopus database and analyzed using VOSviewer software. The findings indicate a significant increase in publications on global warming education from 2014 to 2024, with the highest number of publications recorded in 2024. Innovative learning models such as Problem-Based Learning (PBL), Project-Based Learning (PjBL), and Context-Based Learning (CBL) have proven effective in enhancing students' scientific literacy, critical thinking, and communication skills regarding global warming issues. Universitas Pendidikan Indonesia has been identified as the leading institution contributing to this field. This study emphasizes the critical role of education in raising awareness and driving concrete actions against climate change. Furthermore, integrating global warming topics into formal education systems is a strategic measure to support climate change mitigation and environmental sustainability.

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1. Introduction

Climate change has significantly impacted ecosystems and societies, and the ongoing global warming is projected to increase risks to health, food and water availability, security, and economic growth (Scheffran & Battaglini, 2011). This issue is internationally recognized as a major global threat, with concerns about it emerging as early as 2013 (Huang, 2019). Alongside rising social anxiety, various parliaments and governments have declared a "climate emergency" to emphasize the need for extraordinary resource mobilization. Meanwhile, some influential politicians still deny climate change and often support disinformation campaigns that generate controversy within society (Hamari, 2021). As climate change becomes an increasingly urgent societal issue, there is a growing need to expand climate literacy among the future generation of decision-makers (Emily Hestness, 2019).

Global warming refers to the increase in the average surface temperature of the Earth (Lineman et al., 2015). The primary cause of global warming is the rising concentration of greenhouse gases in the atmosphere, such as carbon dioxide and methane (Kanginan, 2014). Initially, greenhouse gases played a role in warming the Earth by absorbing energy and trapping heat in the atmosphere (Yan et al., 2016). However, their continuous increase has led to climate change (Manabe, 2019). Rising temperatures are believed to cause disasters such as heatwaves (Baldwin et al., 2019). Furthermore, recent attribution studies have substantiated that the intensification of human-induced greenhouse gas emissions is directly linked to an increase in the frequency and severity of extreme weather events, further endangering both natural ecosystems and human communities (Reed et al., 2022). This escalating crisis underscores the critical importance of international cooperation and swift implementation of comprehensive climate policies to mitigate further ecological and socio-economic disruption.

The impacts of global warming are increasingly felt worldwide, including in Indonesia, which is geographically highly vulnerable to climate change (A. Suryansyah et al., 2021). Climate change intersects with knowledge, values, and individual experiences, particularly regarding awareness of climate change (Hadiapurwa et al., 2024). Concrete actions are always needed to address this issue,

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even though information may be incomplete due to knowledge gaps (Stoeth & Carter, 2023). These knowledge gaps underscore the necessity of climate change education through formal and non-formal education channels. The core principles of climate change education are providing understanding about climate change, adaptation, and mitigation (Arwan et al., 2021). These principles should be supported by learning activities, reflection, and fostering connections between learners and climate-related learning resources (Mochizuki & Bryan, 2015).

The advancements in science and technology in the 21st century have impacted various aspects of life, including education, making it a critical field for developing high-quality human resources (Hasana et al., 2022). Global warming is not only a challenge for Indonesia but also a pressing issue worldwide (Riyanto, 2007). Rising temperatures have implications for the Earth's future and the thinning of the ozone layer, which exacerbates global warming (Sagala et al., 2019). The Earth's warming is driven by insufficient care for and protection of the environment, as well as environmentally destructive actions. One way to protect the environment is through reforestation. Cultivating a love for nature should be developed gradually (Dal et al., 2015), especially in education, as it is a process that can transform students' mindsets. No matter how solid the foundation, without education, addressing long-term environmental damage will be challenging. Fostering environmental awareness should begin early (Yulianti & Prihatin, 2014).

Educational institutions should play a role in addressing these issues. Even small efforts in schools can make a difference (Rafika Rahmi, 2017). Students can more easily internalize environmental values and habits through education (Maulana, 2016), thereby preventing future environmental damage by fostering environmental awareness for future generations (Lasat et al., 2018). Today's environmental crisis extends beyond issues like waste management, pollution, reforestation, or nature conservation alone (Tompodung, Rushayati, & Aidi, 2018). Environmental problems are part of a worldview. These issues relate to human perspectives and attitudes toward their role in the environment (Budiman, Irwansyah & Susilo, 2018).

The current environmental crisis extends beyond waste management and pollution, reflecting a worldview that shapes human interactions with the environment (Karimi et al., 2021; Guevara-Herrero, 2024). This perspective emphasizes the importance of educational institutions in integrating environmental education into their curricula to foster students' attitudes and behaviors toward nature and sustainability (Suarlin, 2023). Furthermore, incorporating critical thinking and systems thinking into environmental education empowers students to address complex environmental issues more effectively (Guevara-Herrero, 2024; Olğun, 2018).

Global warming topics are sometimes taught by teachers using lecture methods or by having students study independently (Karpudewan et al., 2014). The lecture method is a traditional approach (Bozdogan, 2011) where there is no interaction among students, and the focus remains solely on the teacher (Al-rawi, 2013). Consequently, students lack enthusiasm for learning. However, global warming is relatively straightforward to discuss as it does not involve equations typically found in physics topics (Zahrotunnisa, 2017). Furthermore, global warming relates to everyday life, making it essential for students to understand because it introduces environmental phenomena and fosters sensitivity to environmental conditions (Marhum & Budiningarti, 2019).

The importance of interactive teaching in the context of global warming cannot be overstated. Learning methods that involve discussions, group projects, and other active teaching strategies can enhance students' understanding of environmental issues and encourage them to become more sensitive to their surroundings (Meehan et al., 2018). Research indicates that when students engage in active learning processes, they are more likely to internalize environmental values and develop positive attitudes toward sustainability (Meehan et al., 2018). Therefore, adopting a more dynamic approach to teaching global warming can help students not only grasp fundamental concepts but also cultivate critical thinking skills and the ability to take responsible actions for the environment (Meehan et al., 2018). Education on global warming should encompass the social and ethical dimensions of climate change, enabling students to understand the impact of their actions on the environment and society (Gharabaghi & Anderson-Nathe, 2018).

Research on global warming education, such as that conducted by A. Suryansyah et al. (2021), revealed that the development of global warming issues has not been well implemented. The

researchers recommended integrating global warming issues into learning activities and training students to study various global warming phenomena through higher-order thinking and problem-solving skills to develop scientific thinking. This study, however, focuses on trends in global warming education. Therefore, the objective of this research is to explore a bibliometric review of global warming education. Previous research on global warming education has not comprehensively examined bibliometric aspects, especially in the analysis of publication trends, geographic distribution, and collaboration patterns between researchers and institutions. In addition, there has been no in-depth exploration of key journals, citation impact, and thematic relationships between concepts in this field. This study aims to fill this gap through a systematic bibliometric approach, so as to provide a deeper understanding of the development and direction of global warming education research (Muhamad,2022).

2. Method

This research is a literature study employing a quantitative bibliometric approach and a qualitative literature review derived from the Scopus database. Scopus was chosen due to its extensive collection of papers and its capability to provide superior citation data (Hasana et al., 2022). Data analysis tools used in this study include Microsoft Excel and VOSviewer software. According to Hakim (2020), bibliometrics is a study that measures the development of research, literature, books, or documents in a specific field, either quantitatively or qualitatively, using statistical methods. Bibliometrics is divided into two major categories: descriptive bibliometrics and behavioral bibliometrics. Descriptive bibliometrics describe the characteristics of a literature, whereas behavioral bibliometrics examine the relationships formed between the components of the literature (Royani, Tupan, & Kusumaningrum, 2019). In this bibliometric approach, it is possible to understand research trends, identify knowledge gaps, and assess the impact of a field of study. This method helps measure the relevance of publications, collaboration patterns, and the development of research topics through citation analysis. In this study, bibliometrics is used to understand the development of literature quantitatively and qualitatively (Sulaiman kurdi,2021). The research flowchart can be seen in Figure 1.

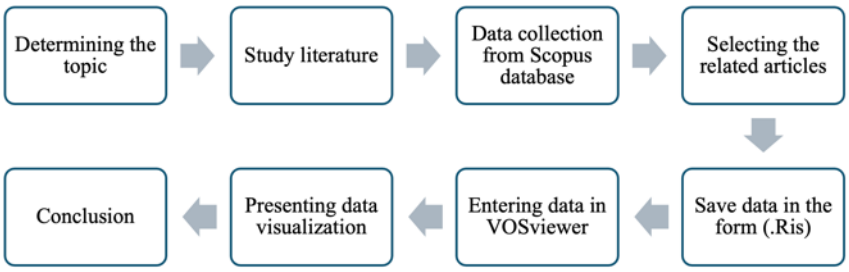

Figure 1. Research flowchart

This study employs a bibliometric approach to analyze research trends in global warming education. Data were collected exclusively from the Scopus database, selected due to its extensive coverage of peer-reviewed literature and comprehensive citation records. The search was conducted using specific keywords related to global warming education, sustainability, and climate literacy, ensuring the inclusion of relevant studies published between 2014 and 2024.

The bibliometric analysis involved several key indicators. Co-citation analysis was performed to identify influential works and research clusters within the field, providing insights into the intellectual structure of global warming education studies. Additionally, keyword trend analysis was conducted using VOSviewer software to examine the evolution of research topics over time. Network visualization techniques were employed to map collaborative relationships among authors, institutions, and countries, highlighting key contributors and research hubs.

To ensure data reliability, duplicate records and irrelevant studies were excluded through a systematic screening process. The results were then interpreted in relation to existing educational frameworks and climate change mitigation strategies, providing a comprehensive overview of how global warming education has evolved and its implications for future research.

3. Results and Discussion

Based on the publication years of the research articles, fluctuations in the number of publications can be observed between 2014 and 2024.

Figure 2 presents the annual distribution of research publications on global warming education from 2014 to 2024. The trend shows fluctuations in publication numbers, with a significant increase in recent years, peaking in 2024. This trend aligns with global educational efforts, emphasizing the role of sustainability education in raising climate awareness.

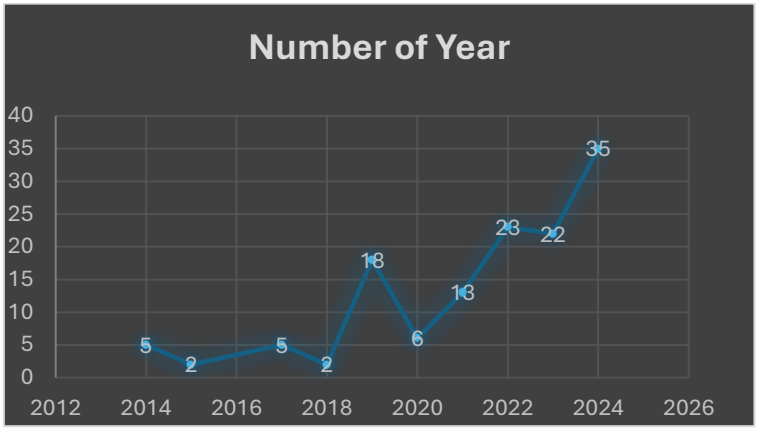

Figure 2. Distribution graph per year of article publications

The highest number of studies utilizing the global warming theory was recorded in 2024, with a total of 35 articles. In contrast, the lowest numbers were observed in 2018 and 2015, each with only 2 articles. However, as 2024 is not yet complete, there is still a possibility for additional articles to be published in that year. It is also evident that many researchers are interested in the global warming theory, as indicated by the increase in articles between 2020 and 2022. Although a decline occurred in 2023, the number of publications in 2023 remains higher than in 2014, demonstrating that the global warming theory continues to attract researchers' interest. The learning model applied in the study of global warming can be seen in Table 1.

Table 1. Learning models applied in global warming studies

Author	Years	Title
Arifa M.F.; Wahdah N.; Fitria T.; Fitria R.; Jumadi J.	2023	PBL-Based PhET Simulations e-Worksheet: Improvement students' Communication Skill on Global Warming in Merdeka Curriculum
Nasution I.B.; Liliawati W.; Hasanah L.	2019	Effectiveness problem-based learning (PBL) with reading infusion strategic to improving scientific literacy for high school students on topic global warming
Piotrowska I.; Cichoń M.; Sypniewski J.; Abramowicz D.	2022	Application of inquiry-based science education, anticipatory learning strategy, and project-based learning strategies
Mukaromah S.H.; Wusqo I.U.	2020	The influence of PjBL model with stem approach on global warming topic to students' creative thinking and communication skills
Ulum A.S.; Basori H.; Suhandi A.; Samsudin A.	2020	Improving the mental model of high school students related to the concept of global warming through the implementation of the context based learning (CBL) model combined with the CM2RA strategy

In 2023, Arifa M.F., Wahdah N., Fitria T., Fitria R., and Jumadi J. conducted a study on the use of PBL-based e-Worksheets with PhET simulations to enhance students' communication skills on the topic of global warming in the Merdeka Curriculum. In 2019, Nasution I.B., Lilianwati W., and Hasanah L. investigated the effectiveness of problem-based learning (PBL) with a reading infusion strategy to improve high school students' scientific literacy on the topic of global warming. In 2022, Piotrowska I., Cichoci M., Sypniewski J., and Abramowicz D. applied inquiry-based science education, anticipatory teaching strategies, and project-based learning strategies. In 2020, Mukaromah S.H. and Wusqo I.U. examined the impact of the PjBL model with a STEM approach on the topic of global warming in enhancing students' creative thinking and communication skills. Similarly, in 2020, Ulum A.S., Basori H., Suhandi A., and Samsudin A. investigated the improvement of high school students' mental models related to global warming concepts through the implementation of context-based learning (CBL) combined with the CM2RA strategy. These studies highlight diverse innovative

approaches in education aimed at enhancing communication skills, scientific literacy, creative thinking, and conceptual understanding among students on the topic of global warming.

The top ten affiliations for research topics on global warming education are presented in Table 2. The most significant contributor to this field of research is Universitas Pendidikan Indonesia. The second-largest author affiliation is the Centre for Environmental Education. These findings align with Table 3. where Liliawati, W. from Universitas Pendidikan Indonesia is identified as the primary author, followed by Boyes, Eddie from the Centre for Environmental Education.

Table 2. Top 10 Leading Institutions in Global Warming Education Research

Institution	Number of documents
University Pendidikan Indonesia	3
Centre for environmental education	2
University of new england	2
Centre for children and young people	2
University of maribor	2
University of liverpool	2
Australian chatolic university	1
Chuncheon national university	1
Ciudad universitaria	1
Ohio state university	1

Table 2 identifies the leading institutions contributing to global warming education research over the past decade. Universitas Pendidikan Indonesia (UPI) ranks as the top contributor, reflecting Indonesia's strong academic focus on climate education. Other notable institutions from Europe, Australia, and the United States highlight the global collaboration in environmental education research.

Table 2 provides several key insights. First, the presence of top-tier universities suggests that climate education is becoming a priority in higher education policies (Lasat et al., 2018). Second, geographical distribution patterns indicate that while Western and Southeast Asian institutions dominate, research from underrepresented regions remains limited. Third, institutions with multiple publications are likely engaged in collaborative and cross-disciplinary research, which has been shown to increase research impact and innovation (Guevara-Herrero et al., 2024).

While these institutions play a significant role in advancing climate literacy research, further efforts are needed to expand global collaboration, particularly by involving universities in regions most affected by climate change. Strengthening these networks can ensure a more inclusive and equitable knowledge production in climate education.

Table 3 presents the top 10 most productive researchers in global warming education, highlighting key contributors based on the number of published documents. The data indicate that Liliawati, W. is the most prolific author, with five publications, followed by Boyes, Eddie; Skamp, Keith; Stanisstreet, Martin; Samsudin, A.; and Sulisworo, Dwi, each contributing four publications. The presence of these authors in multiple studies reflects their significant role in advancing research on climate change education and promoting effective learning strategies.

Table 3. Top 10 Most Productive Writers in Global Warming Learning

Authors	Number of documents
liliawati, w.	5
boyes, eddie	4
skamp, keith	4
stanisstreet, martin	4
samsudin, a.	4
sulisworo, dwi	4
hasanah, l.	3
kusumaningtyas, dian artha	3
gonzález, darío a.	3
winarno, n.	3

Several important observations emerge from this data. First, the dominance of Liliawati, W., along with other researchers from Universitas Pendidikan Indonesia, suggests Indonesia's strong engagement in climate education research. This aligns with the increasing focus on integrating environmental literacy into formal education systems in Southeast Asia. Second, frequent co-authorship among these researchers highlights the importance of collaboration and interdisciplinary approaches in studying climate change education. Joint publications indicate that educational strategies for climate literacy require expertise from multiple disciplines, such as science education, psychology, and environmental policy.

Furthermore, the presence of researchers like Boyes and Stanisstreet, who have extensively studied students' perceptions of global warming, demonstrates the global reach of this field. Their research, primarily conducted in the UK, provides valuable insights into how students understand climate change and what educational interventions are most effective. Additionally, the inclusion of researchers from various regions suggests a growing global interest in enhancing climate literacy through innovative pedagogical methods, such as Problem-Based Learning (PBL), Project-Based Learning (PjBL), and Inquiry-Based Science Education (IBSE).

Overall, the findings in Table 3 emphasize the importance of academic leadership, research collaboration, and global engagement in climate education studies. Future research should foster stronger international partnerships to ensure equitable knowledge distribution and to develop policy-driven educational frameworks that effectively address climate change education worldwide. Their correlation is illustrated in the following Figure 3 & Figure 4.

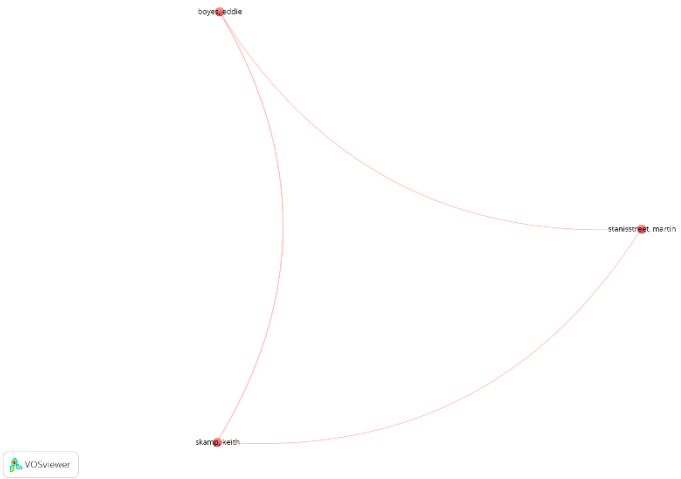

Figure 3. Three researchers often publish research results together

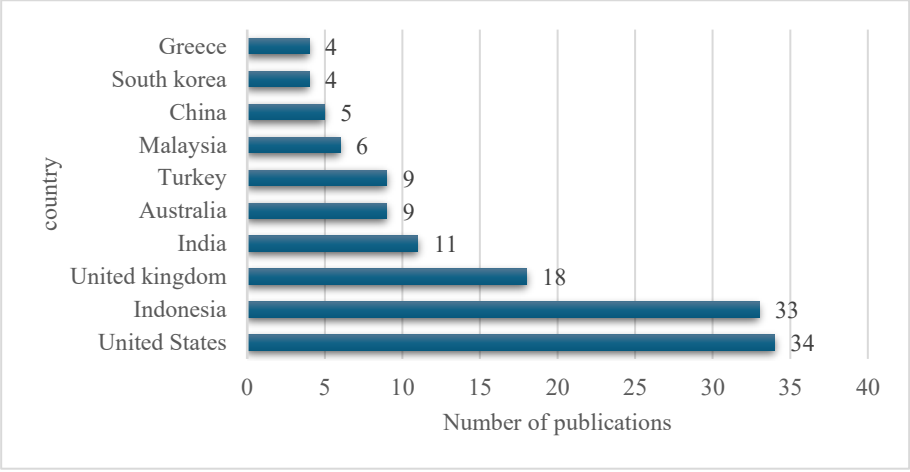

Figure 4. Top global warming learning publications by country

Figure 4 illustrates the distribution of global warming education research publications by country, highlighting the leading contributors in this field. The data indicate that the United States ranks as the top contributor, followed by several European and Asian countries. This pattern suggests that climate change education is receiving significant attention in countries with well-established research institutions and strong governmental policies supporting sustainability education.

Several key insights can be drawn from this Figure 4. First, the dominance of the United States in global warming education research reflects the country's extensive investment in environmental studies and climate policies. The US government, universities, and research institutions have actively supported climate literacy programs, leading to a higher volume of publications in this field. This aligns with previous findings that emphasize the role of government funding and institutional support in shaping research output (Lasat et al., 2018).

Second, the presence of European nations among the top contributors suggests that climate education is deeply integrated into their national curricula, aligning with the European Union's strong commitment to sustainability and climate action policies. Prior studies have shown that policy frameworks such as the EU Green Deal and UNESCO Climate Education Guidelines significantly influence the emphasis on sustainability education in European research (Guevara-Herrero et al., 2024).

Additionally, the inclusion of Indonesia among the leading contributors underscores the country's growing engagement in climate change education. As an archipelagic nation highly vulnerable to the impacts of global warming, Indonesia has shown an increasing commitment to integrating climate literacy into education policies and research initiatives (Arwan et al., 2021). This aligns with the country's participation in global environmental agreements and its emphasis on environmental education programs at various academic levels.

However, the Figure 4 also highlights a research gap in certain regions, particularly in developing countries with limited access to climate change education resources. Studies have found that barriers such as lack of funding, insufficient research infrastructure, and weak policy enforcement often limit the ability of lower-income countries to contribute to climate education research (Karimi et al., 2021). While climate education is expanding globally, some nations still face challenges related to funding, policy support, and institutional capacity to conduct extensive research on this subject.

Future efforts should focus on enhancing international collaboration and providing research opportunities for underrepresented regions to ensure a more equitable distribution of climate education research worldwide. Expanding access to open-access journals, research grants, and global academic partnerships could help address these disparities and promote a more inclusive approach to climate literacy research. Table 4 presents the top 10 most cited articles on global warming education published in the last decade, highlighting key studies that have shaped the field. The articles listed in this Table 4 have significantly influenced the understanding of students' perceptions of climate change, effective learning models, and the role of education in climate action.

Table 4. Top 10 articles of global warming learning in the last 10 years

Authors	Tittle	Source	Number of documents
Sadler T.D.; Chambers F.W.; Zeidler D.L.	Student conceptualizations of the nature of science in response to a socioscientific issue	International Journal of Science Education	291
Boyes E.; Stanisstreet M.	The 'Greenhouse Effect': Children's perceptions of causes, consequences and cures	International Journal of Science Education	291
Shepardson D.P.; Niyogi D.; Choi S.; Charusombat U.	Seventh grade students' conceptions of global warming and climate change	Environmental Education Research	168
Groves F.H.; Pugh A.F.	Elementary pre-service teacher perceptions of the greenhouse effect	Journal of Science Education and Technology	95
Herman B.C.	The Influence of Global Warming Science Views and Sociocultural Factors on Willingness to Mitigate Global Warming	Science Education	82
Boyes E.; Stanisstreet M.	Students' perceptions of global warming	International Journal of Environmental Studies	74

Authors	Tittle	Source	Number of documents
Summers M.; Kruger C.; Childs A.; Mant J.	Understanding the science of environmental issues: Development of a subject knowledge guide for primary teacher education	International Journal of Environmental Studies	49
Fernández Galeote D.; Hamari J.	Game-based Climate Change Engagement: Analyzing the Potential of Entertainment and Serious Games	Proceedings of the ACM on Human-Computer Interaction	33
Sagala R.; Nuangchalerm P.; Saregar A.; El Islami R.A.Z.	Environment-friendly education as a solution to against global warming: A case study at Sekolah Alam Lampung, Indonesia	Journal for the Education of Gifted Young Scientists	31
Chhokar K.; Dua S.; Taylor N.; Boyes E.; Stanisstreet M.	Indian secondary students' views about global warming: Beliefs about the usefulness of actions and willingness to act	International Journal of Science and Mathematics Education	27

A key observation from this Table 4 is the dominance of research focusing on students' conceptual understanding of global warming. Studies by Sadler et al. (2004) and Boyes & Stanisstreet (1993), which are among the most cited, emphasize how students perceive the causes, consequences, and possible solutions to climate change. These findings align with constructivist learning theories, which suggest that students build knowledge based on their prior experiences and misconceptions (Piaget, 1950).

Another significant theme in this Table 4 is the role of environmental literacy in shaping students' willingness to engage in climate action. Research by Herman (2015) and Chhokar et al. (2012) explores the connection between scientific knowledge and behavioral change, showing that students who understand climate science are more likely to adopt sustainable behaviors. This supports Ajzen's Theory of Planned Behavior (1991), which posits that knowledge and attitudes toward an issue influence one's intention to act.

The presence of research on pre-service and in-service teachers' perceptions (e.g., Groves & Pugh, 2002) indicates a growing recognition of teacher preparedness in delivering climate change education. Studies have found that teachers' confidence, pedagogical strategies, and access to quality teaching resources significantly impact students' climate literacy (Meehan et al., 2018). This suggests that professional development programs for educators should emphasize scientifically accurate content and inquiry-based teaching methods to enhance student engagement with climate topics.

Additionally, the integration of technology and game-based learning approaches in climate education is an emerging research area. Fernández Galeote and Hamari (2021) investigated the use of digital games to engage students in climate change discussions, demonstrating the potential of interactive learning strategies to increase motivation and understanding of global warming concepts. This aligns with previous studies on game-based learning, which highlight its effectiveness in simulating real-world environmental challenges (Gee, 2003).

Despite these advancements, the Table 4 also highlights gaps in research. Most highly cited studies focus on students from developed countries, with limited representation of climate education in developing regions, where climate change impacts are often more severe. Future research should address this imbalance by conducting cross-cultural studies to compare climate literacy levels across different educational contexts. Expanding research collaborations and increasing access to climate education resources in underserved regions can contribute to a more inclusive and globally relevant climate education framework.

Figure 5 presents a keyword clustering visualization of global warming education research, highlighting distinct thematic areas that characterize the field. This bibliometric mapping helps identify the main research focuses and interdisciplinary connections in global warming learning.

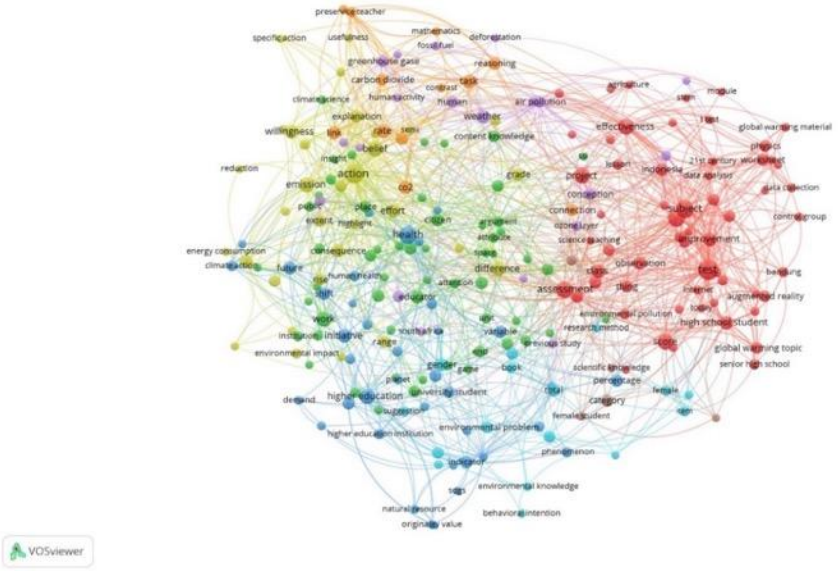

Figure 5. Visualization of global warming learning

The red cluster represents education, assessment, and student engagement, indicating a strong emphasis on how climate change topics are integrated into formal curricula. This aligns with constructivist learning theories (Piaget, 1950), which suggest that students' prior knowledge and experiences influence their understanding of complex issues like global warming.

The green cluster focuses on climate action, health, and behavioral change, emphasizing the role of environmental psychology and social responsibility in climate education. Studies such as Herman (2015) and Chhokar et al. (2012) have demonstrated that students' awareness of health and environmental risks associated with climate change influences their willingness to take action. This supports Ajzen's Theory of Planned Behavior (1991), which suggests that knowledge and attitudes significantly impact an individual's decision to adopt sustainable behaviors.

The yellow cluster highlights climate science, greenhouse gas emissions, and mitigation strategies, reinforcing the necessity of strong scientific literacy in climate education. Research by Manabe (2019) has shown that understanding CO_2 levels and the greenhouse effect is fundamental to grasping the broader implications of climate change. The presence of this cluster underscores the importance of STEM-based education approaches, where students engage with data analysis and real-world environmental case studies to deepen their understanding of climate science.

The blue cluster focuses on higher education institutions and environmental management, illustrating the role of universities and research centers in advancing climate education. Universities play a crucial role in shaping climate literacy through specialized curricula, sustainability initiatives, and policy-driven research (Lasat et al., 2018). The integration of sustainability science into higher education has been identified as a key driver for preparing future decision-makers and professionals to address climate-related challenges.

The purple cluster pertains to research methodologies and empirical studies, highlighting the reliance on scientific data collection, experimental research, and observational studies in global warming education research. This is in line with findings by Meehan et al. (2018), which emphasize that evidence-based pedagogical strategies are essential for improving climate literacy outcomes.

This visualization confirms that climate change education is an inherently multidisciplinary field, intersecting with science, policy, psychology, and environmental management. The findings suggest that future studies should focus on expanding interdisciplinary collaborations, particularly between scientists, educators, and policymakers, to enhance the effectiveness of global warming education programs. Figure 6 illustrates the variable relationship visualization.

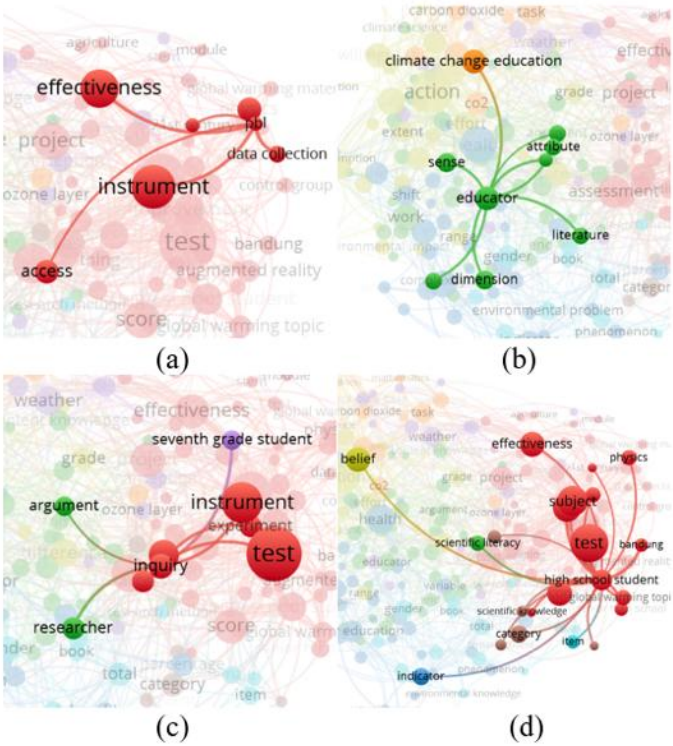

Figure 6. Visualization of each cluster

Figure 6 (a) presents a keyword network visualization that highlights several key terms related to a specific topic. The most dominant and prominent terms are "effectiveness," "instrument," and "access." Other keywords visible in the network include "PBL" (problem-based learning), "data collection," and "project." "Effectiveness" is directly connected to "PBL" and "data collection," indicating that the topic of effectiveness is frequently discussed in the context of problem-based learning and data collection. Similarly, "instrument" is linked to "access" and "effectiveness," suggesting that specific tools or instruments play a role in measuring both effectiveness and access.

Figure 6 (b) shows the visualization of educator-related keywords. These keywords are directly connected to other terms such as "attribute," "dimension," "sense," and "literature." This connection suggests that in the context of climate change education, educators play a crucial role related to various educational attributes and dimensions, as well as their understanding or sense of the material being taught. Figure 6 (c) displays the keyword "inquiry," which is closely tied to processes like testing, instrument usage, the role of the researcher, argument development, and student involvement. This highlights how inquiry becomes an integral part of academic and research activities, particularly in science education. Figure 6 (d) visualizes the keyword "high school student." This visualization reveals that high school students are engaged in various aspects of education, including testing, learning specific subjects, scientific literacy, global warming topics, and scientific knowledge. It emphasizes the importance of a comprehensive approach to secondary education to prepare students for both academic challenges and global environmental issues.

The next result, namely the Overlay Visualization (Figure 7), illustrates the variation in publication years of the articles used by the researchers. This visualization indicates that the farthest distance from the main opportunities represents the greatest potential in research.

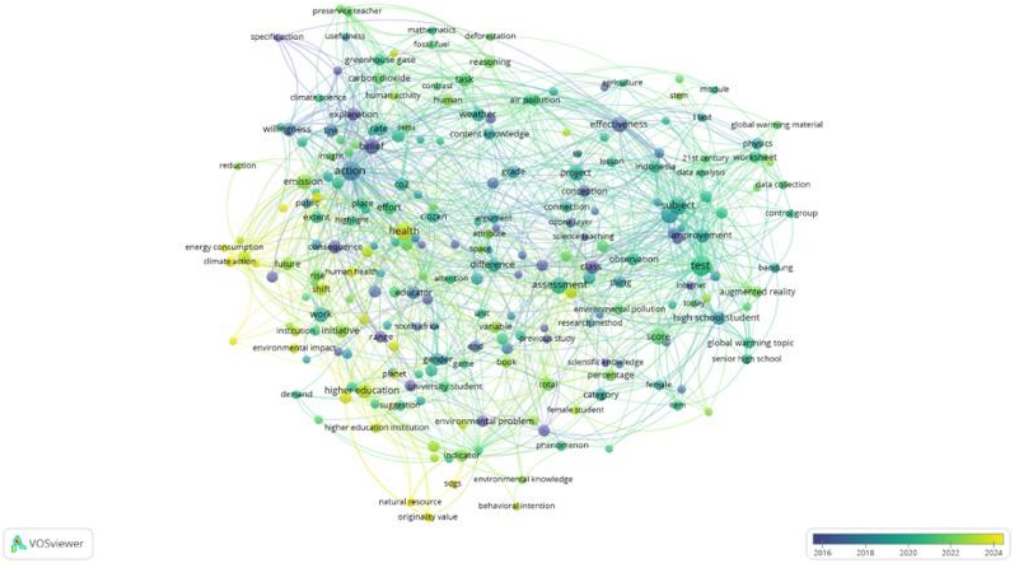

Figure 7. Overlay Visualization

The nodes and lines are color-coded based on a timeline from 2016 to 2024, as shown by the color bar in the bottom-right corner of the image. Purple represents older terms (around 2016), transitioning through blue, green, and yellow, with yellow representing newer terms (up to 2024). The nodes tend to cluster together, forming more interconnected groups. Each cluster may represent thematic areas or specific topics within the broader field. By observing the color transitions, we can infer the evolution of research topics over time. For instance, terms dominated by yellow or green colors indicate emerging or current research trends, while nodes in purple and blue signify well-established or older research areas.

Key terms prominently displayed in this network include "health," "climate action," "education," "global warming," "project," "test," "assessment," and others. These terms likely represent significant topics or focal areas within the field of research. The interconnectedness of terms like "global warming," "climate change," "education," and "health" suggests a multidisciplinary approach or intersectional research areas.

This visualization highlights a strong research focus on environmental and climate change education, integrating terms related to health, scientific knowledge, behavioral intentions, and educational methods. There is also an emphasis on practical applications and assessment methods in education, as indicated by terms such as "project," "test," "assessment," and "improvement". Overall, the VOSviewer network visualization demonstrates the relationships and evolution of terms related to climate action, health, and education from 2016 to 2024. The color coding helps identify the research timeline, with newer terms highlighted in yellow, indicating areas gaining recent attention.

Lastly, the Density Visualization, which is the final visualization of the VOSViewer system, illustrates that the brighter the color associated with a variable, the more frequently that variable has been researched, as shown in Figure 8. The terms that appear with brighter colors indicate those that have been explored most often in the literature, reflecting their prominence and significance in the research area.

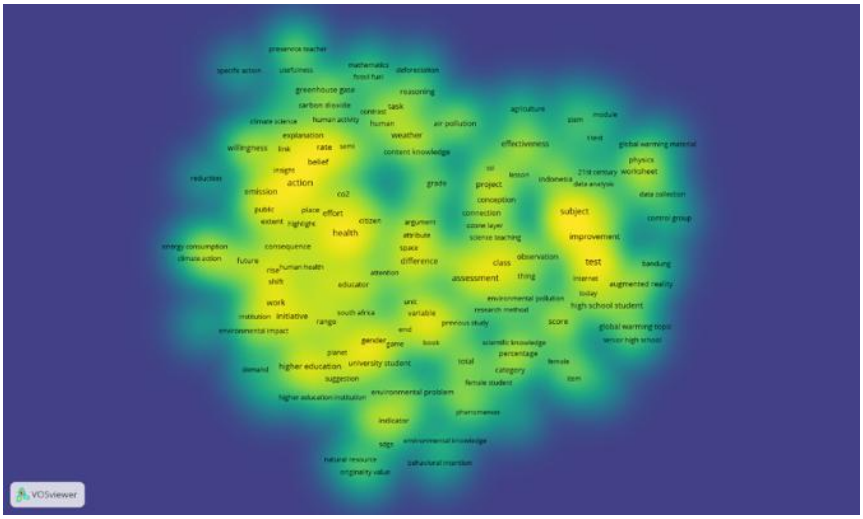

Figure 8. Density Visualization

In Figure 8, various keywords are represented by dots of different colors based on the intensity or frequency of their occurrence. The yellow color indicates the most frequently appearing and most relevant terms, while green and blue represent words that appear less often. Some of the frequently appearing and relevant keywords include "health," "climate change," "action," "carbon dioxide," "greenhouse gas," "emission," and "education." These terms highlight the focus on environmental issues such as climate change, greenhouse gas emissions, and education related to health and the environment. Despite providing valuable insights into the trends of global warming education in support of the Sustainable Development Goals (SDGs), this study has several limitations that should be acknowledged. First, the research relies solely on data from the Scopus database, excluding other potential sources such as Web of Science and Google Scholar, which may contain relevant studies. Second, while bibliometric analysis offers a comprehensive overview of research trends, it does not directly assess the effectiveness of learning models in enhancing students' understanding of climate change, greenhouse gas emissions, and education related to health and the environment. Third, contextual variables such as educational policies across different countries and socio-economic factors have not been thoroughly examined. Therefore, further research is required to address these limitations and provide a more in-depth understanding of the actual impact of learning models in environmental and health education.

Additionally, there are keywords related to evaluation and teaching methods, such as "assessment," "test," "score," and "effectiveness." This suggests an emphasis on how these environmental topics are taught and evaluated within the educational context. Overall, this image provides an overview of the main themes in the analyzed dataset, with a focus on environmental issues, education, and evaluation.

Additionally, the presence of keywords related to assessment, such as 'test,' 'score,' and 'effectiveness,' highlights the role of evaluation in environmental education. This finding aligns with Bloom’s Taxonomy, which emphasizes evaluation as a critical stage in learning, ensuring that students can analyze and assess environmental issues effectively. Furthermore, according to Constructivist Learning Theory, meaningful assessments help students integrate environmental knowledge with real-world applications. These insights suggest that educators should adopt more formative assessments, such as project-based evaluations, to enhance students’ engagement with climate-related topics. Policymakers, in turn, should develop standardized environmental literacy assessments to measure the effectiveness of climate education programs at various academic levels. Overall, this bibliometric analysis underscores the need for robust assessment strategies in environmental education.

Thus, the synthesis of these findings leads to the understanding that research not only highlights environmental issues but also emphasizes the crucial role of education in fostering environmentally responsible awareness and behavior. This is achieved through a systematic evaluative approach, ensuring that environmental education programs effectively instill sustainable practices and attitudes among learners (Gifford & Nilsson, 2014).

4. Conclusion

The bibliometric analysis results reveal a significant upward trend in research on global warming education from 2014 to 2024, with the highest surge in publications occurring in 2024. Universitas Pendidikan Indonesia emerges as the most prominent contributing institution, highlighting the crucial role of educational institutions in enhancing climate literacy.

Innovative learning models such as PBL, PjBL, and CBL have been shown to be highly effective in improving students' understanding of global warming and their critical thinking and communication skills. A multidisciplinary approach to climate education, encompassing aspects of health, climate change mitigation, and carbon emissions, reflects the complexity of global warming issues.

Additionally, this study identifies the United States and Indonesia as the leading contributors to global warming education research, demonstrating a global commitment to the role of education in climate change mitigation efforts. Further research is needed to explore the effectiveness of these learning approaches across broader and more diverse educational contexts to enhance climate literacy and environmental awareness at various academic levels.

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