

The goal of quality education stands out not only as a goal for sustainable development but also as an important element for achieving other goals (Ghulam, 2022; UNESCO, 2020). In particular, SDG 4 (Quality Education) assigns a central responsibility to education systems by aiming to equip individuals with the knowledge, skills, and values necessary for sustainable development (Prieto-Jiménez et al., 2021; United Nations, 2015).

Science education plays a critical role in the realization of the Sustainable Development Goals (SDGs) through education (Maryanti et al., 2022). In this context, physics education holds particular importance as it encompasses topics directly related to many SDGs, such as energy, climate change, environmental sustainability, technology, and industrial development (Al-Barakat et al., 2025). Through physics education, it becomes possible for students to develop a scientifically grounded perspective on issues such as energy efficiency, renewable energy sources, climate systems, and technological innovations (Henriksen et al., 2014). In this respect, physics education is not limited to the transmission of conceptual knowledge but also contributes to the development of students as conscious, critically thinking, and responsible individuals within the context of sustainable development (Eilks, 2015). In recent years, pedagogical approaches and curricula aimed at integrating physics education with the SDGs have attracted increasing international attention, and this trend has been reflected in both educational policies and the academic research agenda (Lozano et al., 2017; Prayogi & Verawati, 2024).

When the literature is examined, the increase in the number of studies in the field of sustainable development and education reveals the intensity of interest in this area (Prieto-Jiménez et al., 2021; Van et al., 2025). Bibliometric analysis can be expressed as an important analysis method used to reveal the research trends, knowledge production dynamics, and structure in areas where this interest is concentrated. Bibliometric studies generally present to readers, in a systematic manner, information about the number of studies in a specific research field, citation intensity, the keywords used, and collaboration networks (Aria & Cuccurullo, 2017; Waltman, 2016). Bibliometric stud-

ies conducted within the scope of sustainable development goals in the field of education reveal that studies in this area have increased rapidly after 2015 and that knowledge production has occurred within the scope of interdisciplinary research (Hallinger & Chatpinyakoo, 2019; Prieto-Jiménez et al., 2021). In addition, it stands out that there has been a significant increase in studies related to SDG 4 among the sustainable development goals (Suluk, 2025). Moreover, it is noteworthy that the number of studies conducted on sustainable development goals within the scope of physics education is limited in literature. Existing studies have generally mapped sustainable development goals through bibliometric analysis in a general manner, and it is seen that studies showing the evolution of keywords used within the scope of physics education over the years, citation dynamics, and collaboration networks are limited (Hallinger & Nguyen, 2020; Prieto-Jiménez et al., 2021). However, since physics education is directly related to sustainable development goals, it should be considered as an important research field (UNESCO, 2017). In this context, it has emerged as an important necessity to examine the SDG-focused physics education literature through bibliometric analysis in order to make the scientific production structure, intellectual core, and thematic orientations of the field visible. Such analyses provide significant insights to the scientific community both for strengthening theoretical frameworks and for enhancing the alignment between the Sustainable Development Goals and science education policies (Hallinger & Chatpinyakoo, 2019; Prieto-Jiménez et al., 2021).

The aim of this study is to comprehensively examine the physics education literature shaped within the context of the Sustainable Development Goals (SDGs) through bibliometric methods, and to reveal the temporal development of the field, its scientific production and impact patterns, its intellectual and social structure, as well as its conceptual/thematic evolution. In this regard, the study seeks to answer the questions of how the physics education literature has developed globally within the SDG framework, around which actors (authors, institutions, countries, and journals) it has concentrated, and through which thematic structures it has been shaped.

Sub-research Questions

1. What distribution do the temporal development trends and citation dynamics of SDG-focused physics education publications exhibit?
2. In the SDG-focused physics education literature, how do scientific production, citation-based impact, and collaboration structures display distribution and organization at the levels of authors, journals, institutions, and countries?
3. Which core studies constitute the intellectual structure of the SDG-focused physics education literature, and how do their global and local citation patterns differ?
4. How has the conceptual structure and thematic evolution of the SDG-focused physics education literature been transformed over time?

METHOD

Within the scope of this study, a bibliometric approach was employed to explore the current state of research conducted on the Sustainable Development Goals (SDGs) in physics education. Through the bibliometric analyses conducted within this framework, research trends in a specific field were identified (Kasemodel et al., 2016), and the relative importance of publications was systematically evaluated (Gimenez et al., 2018). Originating from the fields of library and information science, bibliometric analysis provides comprehensive insights into both research performance and the social and conceptual structure of a given research field through the analysis and mapping of specific indicators related to publications within the literature (Aria & Cuccurullo, 2017; Sun et al., 2020). Furthermore, this type of analysis not only systematically identifies prominent authors, studies, institutions, countries, and journals within a particular research field, but also enables the examination of collaboration relationships among them (Gimenez-Espert & Prado-Gasco, 2019). In brief, bibliometric analysis is a quantitative analytical approach that examines scientific publications and other academic outputs on the basis of numerical data using mathematical and statistical techniques (Dönmez, 2024).

Data Sources

To achieve the aim of the study, Web of Science (WoS) and Scopus were selected as the databases from which articles focusing on the Sustainable Development Goals (SDGs) in physics education would be retrieved. WoS is one of the most widely used and reliable databases in the world, containing numerous academic publications such as articles, books, conference proceedings, and similar works (Birkle et al., 2020). In addition, this database includes publications and journals that meet high academic standards (Garrigos-Simon et al., 2018). For this reason, it is regarded as a high-quality and curated source of literature in many bibliometric analyses (Janik et al., 2020; Pessin et al., 2022). WoS also enables tracking of citation relationships among publications (Birkle et al., 2020). Furthermore, a review of the literature indicates that WoS is frequently preferred as a data source in bibliometric studies due to its widely used citation indexes (Azañedo et al., 2022). Similar to WoS, Scopus is a reliable database with a user-friendly interface that includes peer-reviewed journals, conference proceedings, books, and book chapters published worldwide (Baas et al., 2020). In their bibliometric study, Salleh et al. (2023) describe Scopus as the largest database in the world. Moreover, Janik et al. (2020) emphasize that Scopus is frequently preferred by researchers conducting bibliometric analyses because it provides reliable and comprehensive information on scientific research. For these reasons, and because the data obtained from both databases are compatible with bibliometric analysis software and can be used directly, data for this study were retrieved from these two databases. Additionally, reviewers examining numerous bibliometric studies recommend that data should be collected from multiple databases when conducting such analyses (Öztürk et al., 2024).

In this study, the process of identifying, screening, and including articles addressing the Sustainable Development Goals (SDGs) within the context of physics education was organized in accordance with the PRISMA guidelines (Moher et al., 2010), an internationally recognized standard for reporting systematic reviews. This guideline aims to ensure that the publication selection and reporting

process in meta-analyses, reviews, and bibliometric studies is presented in a transparent, consistent, and reproducible manner (Sarkis-Onofre et al., 2021). Initially, a literature review was conducted to determine the keywords to be used in the databases from which the articles would be retrieved. In this process, several studies related to sustainable development in physics education were examined in the WoS, Scopus, and Google Scholar databases, and the keywords used in these studies were identified. Subsequently, the Sustainable Development Goals were reviewed, and search terms corresponding to these goals were determined.

Using the identified search terms, the search process was conducted in the WoS and Scopus databases on February 20, 2025. Both databases provide various filtering options during the search process. In line with the aim of the study, only the document type “article” was selected as a filter in both databases. The article selection process carried out in accordance with the PRISMA reporting guideline is presented in Figure 1.

Within the scope of the study, before conducting searches in the Web of Science (WoS) and Scopus databases, the “article” option was selected in the filtering section, and then searches were carried out by entering the search keywords listed in Table 1 into the search field, respectively. Within the searches, the articles obtained for each search keyword and their numbers were recorded (for example, for the

search keyword “sustainable education in physics education,” 155 articles were obtained in WoS and 140 in Scopus). Afterwards, the obtained articles were examined in line with the purpose of the study, and the studies outside this scope were excluded. As a result of this examination, for the example search keyword “sustainable education in physics education,” 46 articles remained in WoS and 22 in Scopus. This process was applied to the articles obtained for all search keywords, and the articles suitable for the purpose of the study and their numbers were obtained (the number of articles for WoS was 357, and for Scopus it was 194). The information of these eligible articles was recorded in separate Excel files for each database by considering the analyses to be carried out in the study (citation count, journal name, author information, etc.). Then, the Excel files obtained from the WoS and Scopus databases were examined within themselves, and duplicate records were removed; as a result of this process, the number of articles from WoS decreased to 159, and the number of articles from Scopus decreased to 152. In the final stage, the Excel files of both databases were merged using the RStudio software, and after merging, the resulting dataset was re-examined and duplicate records between the databases were eliminated. Following these procedures, a final Excel dataset containing the bibliographic information of a total of 226 articles representing the aim of the study was obtained.

Table 1: Identified Search Terms

Identified Search Terms	
sustainable development and physics education	sustainable development in physics education
sustainable cities and communities in physics education	physics education and sustainable development goals
sustainable education in physics education	renewable energy in physics education
physics education and education for sustainable development	healthy and quality life in physics education
industry and innovation in physics education	clean water in physics education
clean water sustainable development	end poverty in physics education
gender equality in physics education	life on land in physics education
accessible learning in physics education	end hunger in physics education
life below water in physics education	climate change in physics education
affordable and clean energy in physics education	

		Databases WoS and Scopus		
Search Words				
	Identification	Number of articles	WoS: 15	Scopus: 15
			WoS: 115	Scopus: 97
			WoS: 10	Scopus: 2
			WoS: 79	Scopus: 34
			WoS: 155	Scopus: 140
			WoS: 80	Scopus: 36
			WoS: 107	Scopus: 98
			WoS: 4	Scopus: 0
			WoS: 30	Scopus: 23
			WoS: 0	Scopus: 4
			WoS: 16	Scopus: 1
			WoS: 15	Scopus: 1
			WoS: 99	Scopus: 28
			WoS: 16	Scopus: 3
			WoS: 129	Scopus: 83
WoS: 14			Scopus: 0	
WoS: 10	Scopus: 0			
WoS: 110	Scopus: 67			
WoS: 32	Scopus: 0			
Eligibility	WoS: 357 articles		Scopus: 194 articles	
	Exclusion of duplicate publications obtained from each database			
Exclusion criteria	198 articles excluded from WoS			
	42 articles excluded from Scopus			
	WoS: 159	Scopus: 152		
Inclusion criteria	Combining articles obtained from each database and eliminating duplicate publications			
	85 articles excluded			
		Total number of articles: 226		

Fig. 1: Databases, Web and Scopus

Data Analysis

The data obtained within the scope of the study were analyzed in the RStudio environment using Biblioshiny, the interactive interface of the Bibliometrix package. Bibliometrix is a comprehensive analytical tool developed to examine the performance indicators of scientific publications and to conduct science mapping analyses aimed at revealing the structural characteristics of the literature (Aria & Cuccurullo, 2017). Through Biblioshiny, the datasets retrieved from the databases in Excel format were examined in accordance with the research questions of the

study within the framework of two main analytical approaches: “Performance Analysis” and “Science Mapping”. In this context, in order to reveal the structure of the literature focused on the Sustainable Development Goals (SDGs) in physics education, publication productivity at the author, journal, and country levels, temporal publication trends, and total/average citation indicators were analyzed through Performance Analysis. In addition, keyword co-occurrence, co-authorship, and country collaboration networks were created through science mapping.

RESULT

In this section, the bibliometric findings of SDG-focused studies within the scope of physics education are presented systematically through different analytical dimensions. First, the temporal development and citation dynamics of SDG-focused publications were examined in order to reveal the quantitative growth and visibility patterns of the literature over time. Subsequently, scientific production, impact, and collaboration structures at the author, journal, institutional, and country levels were analyzed, and the production centers and relational networks of literature were described. In the following stage, the intellectual structure of the field was examined through citation-based indicators, and the core studies prominent in SDG-focused physics education research were identified. Finally, through analyses based on author keywords, the conceptual structure and thematic evolution of the literature were investigated, revealing the conceptual core of the field as well as the patterns of thematic diversification and transformation that emerged over time.

Temporal Development and Citation Dynamics of SDG-Focused Publications in Physics Education

By examining the changes in the annual number of SDG-focused publications (Figure 2) together with their annual average citation values (Figure 3), the relationship between the production volume of the field and its level of impact was revealed. The findings reflect the temporal development of SDG-focused physics education research and its impact within the literature in a comprehensive framework.

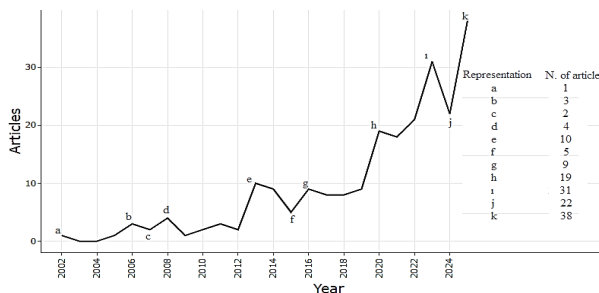


Fig. 2: Distribution of Publications on Sustainable Development Goals in Physics Education by Year

Figure 2 shows the number of publications of SDG-focused studies in physics education by years. It is also seen that the letters (a, b, c, etc.) in the graph curve represent the number of publications and that their numerical values are given in the table on the right side of the graph. In this context, it is understood that the number of SDG-focused studies in physics education was limited between 2002 and 2012. It is observed that there was an increase in the number of related studies between 2012 and 2019, but this increase was limited. In contrast, it has been determined that there has been a significant increase in the number of SDG-focused studies in physics education after 2019. These findings reveal that the number of articles in this field remained limited for a long time, and that in recent years there has been a significant increase in the number of studies with the growing interest in this area.

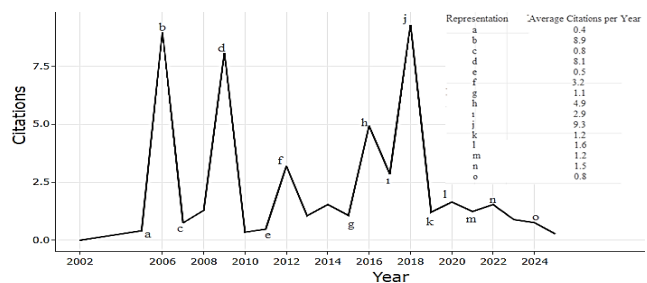


Fig. 3: Yearly Change in Citations to SDG-Focused Publications in Physics Education

Figure 3 illustrates the temporal variation in the annual average citation counts of SDG-oriented studies within the field of physics education. It is also observed that the letters (a, b, c, ...) on the graph represent the annual average citation values, with their corresponding numerical values provided in the table on the right-hand side of the figure. An examination of Figure 3 reveals a fluctuating pattern in the graph. This suggests that the annual average number of citations received by publications in this field does not increase in a steady or linear manner; rather, it exhibits alternating periods of growth and decline. Despite the limited number of publications in the early years (Figure 2), it is evident that these studies received relatively high citation counts during certain periods (Figure 3). In particular, the annual

average citation values reached 8.9 in 2006 and 8.1 in 2009. The highest average citation value was recorded in 2018, with a value of 9.3. Furthermore, although there has been a notable increase in the number of publications in recent years (2020 and beyond) (Figure 2), a decline in the average citation counts of these studies has been observed (Figure 3).

Scientific Production, Impact, and Collaboration at the Author, Journal, Institutional, and Country Levels

The scientific production volume, citation-based impact level, and collaboration patterns of the SDG-focused literature in physics education were examined at the author, journal, institutional, and country levels through bibliometric indicators. The presented findings aim to reveal the central actors of scientific production in the field, the distribution of its impact, and how collaborations are structured through network configurations.

Scientific Production, Impact, and Collaboration at the Author Level

In this subsection, the distribution of production at the author level, citation-based impact indicators, and co-authorship relationships in the SDG-focused physics education literature were examined through bibliometric analyses. By considering annual publication output, authors' impact levels (H-index), and collaboration networks among authors together, it was revealed around which researchers the scientific production of the field is concentrated and within what kind of collaboration structure this production takes place.

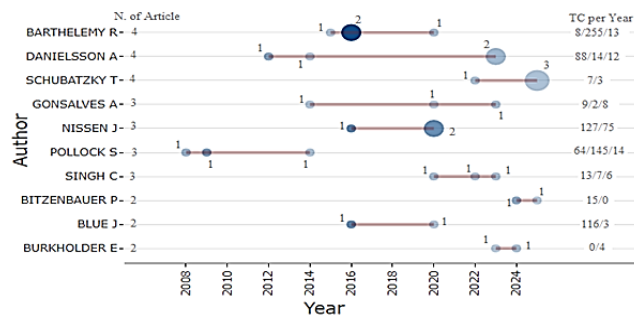


Fig. 4: Authors' Scientific Production by Year and Annual Citation Intensity

Figure 4 presents, in a holistic manner, the annual article production of authors conducting SDG-focused studies within the scope of physics education and the intensity of citations received by these articles. The table on the right side of the graph (for example, the expression 8/255/13 indicates that one study conducted by Barthelemy R. in 2014 received 8 citations, two studies conducted in 2016 received a total of 255 citations, and one study conducted in 2020 received 13 citations) represents the citation counts of the articles published by the relevant author in specific years, respectively. In this context, when Figure 4 is examined, it is determined that the annual article production and citation intensities of the authors are not evenly distributed; on the contrary, article production is concentrated in certain years and citation counts differ significantly. When the number of articles produced by the authors is considered, it is understood that the most productive authors are Barthelemy R., Danielsson A., and Schubatzky T., each with four articles. However, although these authors have the same number of articles, differences are observed in the number of citations they received. The two articles published by Barthelemy R. in 2016 stand out with a total of 255 citations. In general, Figure 4 shows that citations at the author level vary independently of the total number of publications.

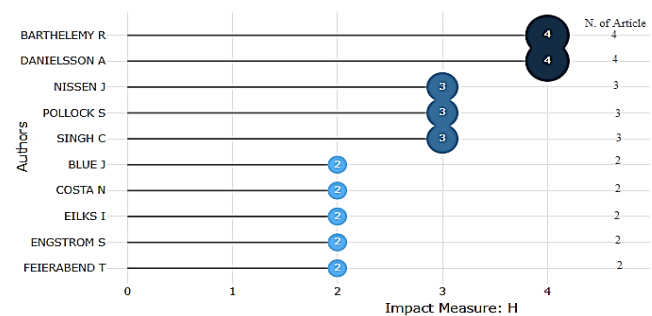


Fig. 5: Authors' H-Index (Impact) Values

Figure 5 presents the impact profiles of authors in the SDG-focused physics education literature based on their H-index values. An examination of Figure 5 indicates that scientific impact differs among authors and is concentrated around a limited number of researchers. The authors with the highest impact levels are Barthelemy R. and Danielsson A., both of whom have reached an H-index of 4.

These authors are followed by Nissen J., Pollock S., and Singh C., each with an H-index of 3. The remaining authors (Blue J., Costa N., Eilks I., Engstrom S., and Feierabend T.) have an H-index of 2. Overall, Figure 5 shows that H-index values among authors range between 2 and 4.

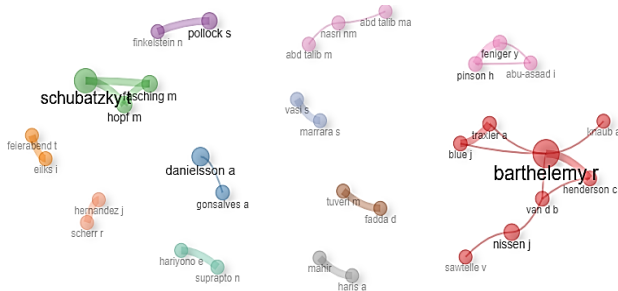


Fig. 6: Author-Level Collaboration Network

Figure 6 illustrates the co-authorship (collaboration) relationships among authors in the SDG-focused physics education literature examined within the scope of the study. An analysis of the network structure indicates that collaboration is organized not as a single integrated structure, but rather as partially differentiated and highly clustered sub-networks.

In the visual representation, the most prominent and densely connected sub-network is formed around Barthelemy R. Barthelemy’s central position within the network is visible through direct connections with Henderson C., Traxler A., Blue J., Van D. B., and Knaub A. The thickness of the link between Barthelemy R. and Henderson C. indicates a stronger co-authorship tie compared to other links in the network. Similarly, in other parts of the network, the relationships established by Schubatzky T. with Fasching M. and Hopf M., as well as the bilateral collaboration between Pollock S. and Finkelstein N., are visible. Across the network, collaborations appear in the form of small-scale clusters composed of a limited number of researchers.

Overall, Figure 6 shows that the author-level collaboration structure is concentrated around several central nodes and consists of multiple small sub-networks.

Scientific Production, Impact, and Collaboration at the Journal Level

The distribution of scientific production at the journal level, citation-based impact indicators, and inter-journal relationship patterns of studies produced in the context of the SDGs in physics education were examined through bibliometric analyses. By jointly evaluating journals’ publication volume, impact levels, and citation relationships among them, it was revealed around which journals the scientific communication of the field is concentrated and how the interaction structure among these journals is organized.

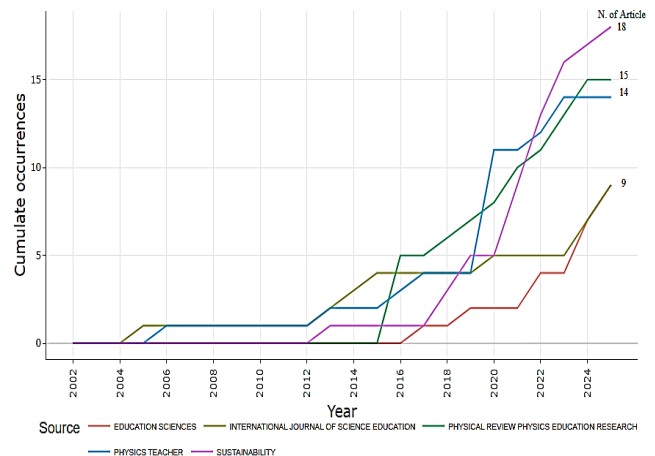


Fig. 7: Cumulative Publication Output of the Most Relevant Journals by Year

Figure 7 shows the cumulative change over time in studies based on the related topic published by leading journals that publish SDG-focused studies within the scope of physics education. When Figure 7 is examined, it is understood that studies on the related topic within the scope of physics education in leading journals began to be published from 2004 and that they published a limited number of studies until 2012. After 2012, it is observed that the studies published on the related topic in these journals increased gradually. It is also seen that the first study on the related topic within the scope of physics education was published in 2005 by the International Journal of Science Education. Despite this, it has been determined that the journal Sustainability, which published its first article in 2012, has published 18 articles on the related topic to date (until the

end of 2024) and is the journal that has published the highest number of articles on this topic. Within the scope of the study, it is understood that among the prominent journals, the journal in the field of sustainability has shown a rapid increase in production on the related topic in a short time, while journals in the field of physics and science education have followed a more stable and gradual production trend since earlier years. In this context, it has been revealed that the cumulative increase in publications of journals publishing on the related topic differs.

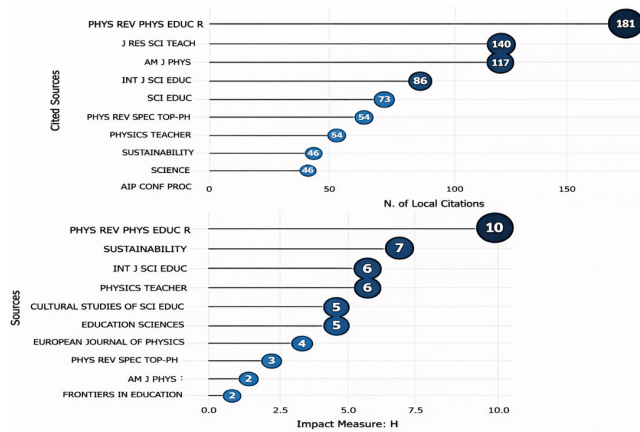


Fig.8: Journals' Local Citation Performance and H-Index Values

Figure 8 consists of two graphs showing the local citation values of the leading journals in which SDG-focused studies within the scope of physics education are published and the H-index effects based on these citation values. When the local citation values shown in the first graph are examined, it is determined that the journal Physical Review Physics Education Research has the highest citation value in this field with 181 citations, while the Journal of Research in Science Teaching has the second highest citation value with 140 citations. When the H-index values shown in the second graph are examined, it is seen that Physical Review Physics Education Research has the highest impact intensity with an H-index of 10, while the journal Sustainability has the second highest impact intensity with an H-index of 7. In this context, it has come to the fore that the citation values of journals are related to their impact intensity, but are not the only factor.

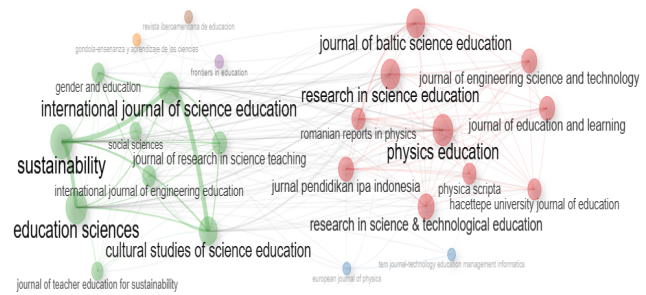


Fig. 9: Journal-Level Citation/Relationship Network

Figure 9 shows the citation relationship network among the leading journals that publish SDG-focused studies within the scope of physics education. In the figure, each node represents a journal, while the size of the node reflects the relative central position of that journal within the citation relationship network. The connections between the nodes represent the citation relationships among the journals, and the thickness of the connections represents the strength of the citation interaction, that is, the high or low number of citations they make to each other.

When Figure 9 is examined, it is seen that the journals are grouped into two clusters. In one cluster, the journals International Journal of Science Education, Sustainability, Education Sciences, and Cultural Studies of Science Education are located at the center of the network, while in the other cluster, the journals Research in Science Education, Physics Education, and Journal of Baltic Science Education are located at the center. It is determined that the journals at the center of the first cluster have strong citation relationships with each other. However, although the journals at the center of the second cluster are in citation relationships with each other, it is understood that this relationship is weak. In addition, it has come to the fore that the journals located around the clusters are represented by smaller nodes and exhibit fewer citation connections within the network.

Scientific Production, Impact, and Collaboration at the Institutional Level

The distribution of scientific production at the institutional level, citation-based impact indicators, and inter-institutional collaboration networks of

studies produced in the context of the SDGs in physics education were examined through bibliometric analyses. By jointly considering institutions' publication volume, impact levels, and co-production relationships, it was revealed around which institutional structures the scientific production of the field is concentrated and how these structures interact within the literature.

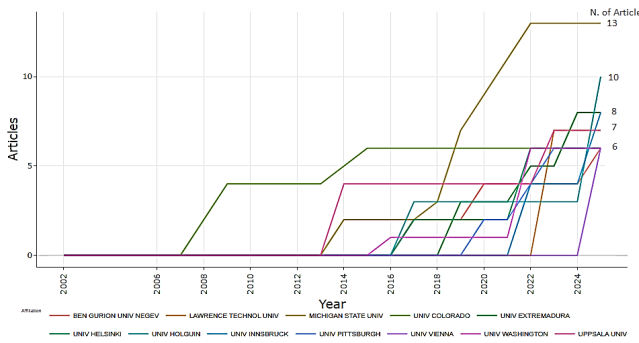


Fig. 10: Temporal Production Patterns of Institutions in SDG-Focused Physics Education Publications

Figure 10 presents the temporal publication output of institutions conducting SDG-oriented research within the field of physics education. An examination of Figure 10 indicates that institutions initiated their research on this topic at different points in time. When the publication trajectories are considered, it is observed that University of Helsinki produced the earliest study in 2007; however, its subsequent publication output remained relatively limited. In contrast, although Michigan State University published its first study in 2016, it demonstrated a rapid increase in publication output in the following years, emerging as the most productive institution with a total of 13 publications. Furthermore, it is evident that most institutions began publishing SDG-oriented studies in physics education around 2013, with a marked acceleration in research output after 2020. Additionally, while some institutions exhibited a gradual and sustained increase in publication output from earlier years, others entered the field at a later stage but achieved higher levels of productivity within a relatively short period.

Figure 11 illustrates the co-authorship-based collaboration relationships established among institu-

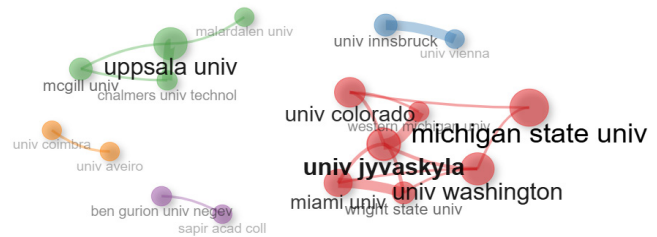


Fig. 11: Institutional Collaboration Network

tions in the publications examined within the scope of the study. The network structure shows that institutional collaborations are concentrated around multiple clusters rather than a single centralized structure, with relatively limited direct connections between these clusters.

The most dominant institutional cluster located at the center of the network consists of the University of Colorado, Michigan State University, the University of Jyväskylä, and the University of Washington. These institutions are represented by larger nodes and higher connection density. The thick links among these universities indicate strong co-authorship ties. Western Michigan University, Miami University, and Wright State University are directly connected to this cluster.

On the left side of the network, a second prominent cluster is formed around Uppsala University. Within this cluster, connections are observed with Chalmers University of Technology, McGill University, and Mälardalen University. In addition, the bilateral connection between the University of Innsbruck and the University of Vienna represents a small but dense sub-cluster within the network.

Overall, the figure shows that institutional collaboration is organized around several high-density clusters, alongside smaller and relatively separate sub-networks.

Scientific Production, Impact, and Collaboration Structure at the Country Level

In this subsection, the country-level distribution of production, citation-based impact profiles, and international collaboration patterns of studies produced in the context of the SDGs in physics education were examined through bibliometric

indicators. By jointly considering countries' publication volume, impact levels, and collaboration networks among them, it was revealed how the scientific production of the field is geographically structured and around which countries' international interactions are concentrated.

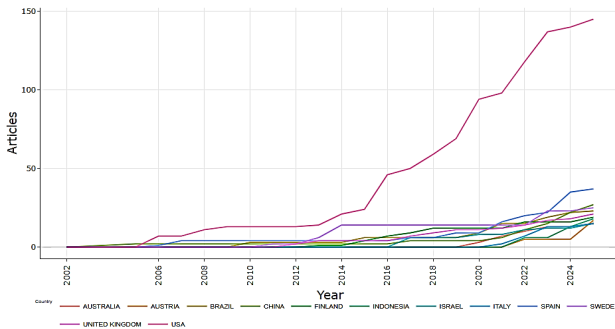


Fig. 12: Cumulative SDG-Focused Publication Output of Countries by Year

Figure 12 presents the change in countries' cumulative publication output over time in the SDG-focused physics education literature. The graph shows that the United States reached the highest cumulative publication count compared to other countries throughout the entire period. After 2015, an increase is observed in the cumulative production curve of the United States, with a more pronounced rise after 2020. The United Kingdom and Sweden display steady growth in cumulative publication counts over time. The production curves of Spain, Finland, and China show increases after 2016, with a clearer upward trend following 2020. Countries such as Australia, Austria, Brazil, Indonesia, and Israel maintain comparatively lower cumulative production levels; however, an upward trend is also observable in these countries after 2020. Overall, the figure

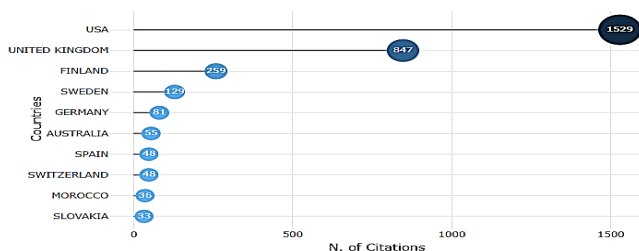


Fig. 13: Total Citation Impact of Countries (N. of Citations)

shows differences in cumulative publication output among countries, with increasing publication levels in several countries particularly after 2015.

Figure 13 presents the total number of citations received by countries in the SDG-focused physics education literature. According to the values shown in Figure 13, the United States ranks first in terms of total citation count, clearly distinguishing itself from other countries with 1,529 citations. The United States is followed by the United Kingdom (n = 847), while Finland ranks third (n = 259). When the cumulative publication output data presented for countries are considered together with the citation counts, they have received, it becomes evident that the distribution of total citations does not always correspond directly to publication volume. In this context, although Finland does not rank among the leading countries in terms of publication output, it stands out in terms of total citation count. This finding indicates that some countries, despite having relatively limited publication volume, can achieve high levels of citation impact.

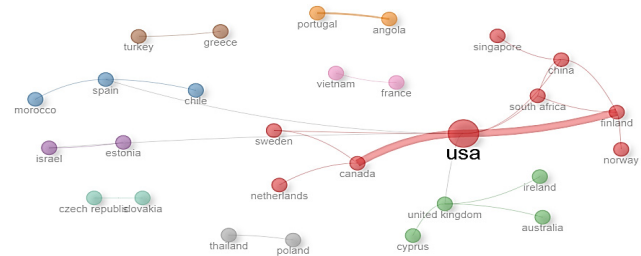


Fig. 14: Inter-Country Collaboration Network

Figure 14 shows the collaboration network based on co-authorship among countries publishing SDG-focused studies within the scope of physics education. When Figure 14 is examined, it is determined that the USA is located at the center of the network and establishes direct collaboration with many countries. In addition, it is found that, compared to other countries, the USA has stronger collaboration with Canada and Finland. It is observed that there are separate and different groups within the network structure. It is determined that the USA, which is at the center of the network, collaborates with some small groups, while it does not have any collaboration with some others. Moreover, it has come to the fore

that it establishes connections with the countries located at the center of the groups with which it collaborates.

Intellectual Structure: Core Cited Studies

In this section, the intellectual structure of SDG-focused studies within the scope of physics education has been examined through citation relationships. By considering the global and local citation patterns of the studies, it was identified which works stand out as core references in the field's knowledge production and how these references are positioned within literature.

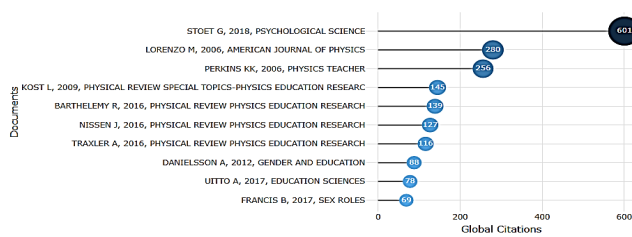


Fig. 15: Top 10 Studies with the Highest Global Citations

Figure 15 presents the top ten publications with the highest global citation counts in the SDG-focused physics education literature examined within the scope of the study. According to the data shown in Figure 15, Stoet's 2018 study published in Psychological Science has the highest global citation count (n = 601). This publication is followed by Lorenzo (2006), published in the American Journal of Physics (n = 280), and Perkins (2006), published in The Physics Teacher (n = 256). After the top three publications, the global citation values of the remaining studies range between 69 and 145 citations. Most of the publications in this group were published in journals such as the American Journal of Physics, The Physics Teacher, and Physical Review Physics Education Research.

Figure 16 shows the top 10 studies with the highest local citation values among SDG-focused studies within the scope of physics education. This type of citation indicates the number of citations that the studies included in the sample receive from other studies within the same sample, that is, from each other. Since this citation value represents

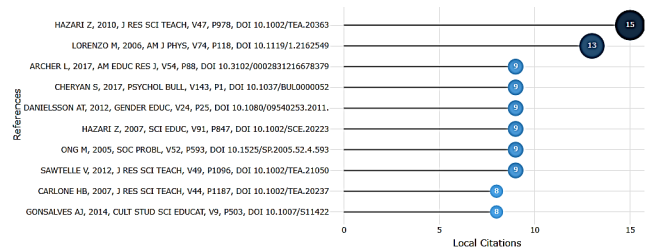


Fig. 16: Top 10 References with the Highest Local Citations within Sample

an indicator of preference during the conduct of SDG-focused studies within the scope of physics education, it provides important information in revealing the intellectual core (intellectual studies) within the sample. When Figure 16 is examined, it is determined that the study published by Hazari in 2010 in the Journal of Research in Science Teaching has the highest local citation with 15 citations within the sample. Secondly, it is determined that the study published by Lorenzo in 2006 in the American Journal of Physics received the second highest local citation (local citation: 13). It is also seen that the local citation values of the other studies are mostly 9.

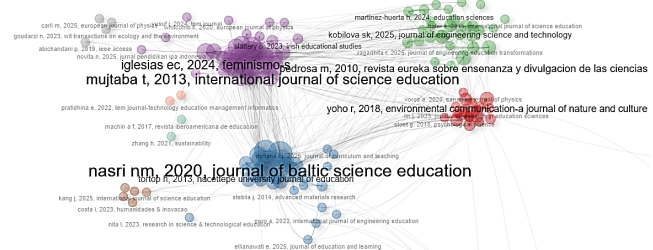


Fig. 17: Document-Level Citation/Relationship Network

Figure 17 presents the network structure showing the citation relationships among SDG-focused publications within the scope of physics education included in the study. Within the network, each node represents a publication, while the links between the nodes represent citation relationships. The size of the node indicates the centrality of the publication within the network, and the thickness of the link shows the strength of the citation relationship. When Figure 17 is examined, it is determined that publications are clustered around four centers within the network structure. It is also understood that the

studies conducted by Mujtaba (2013), Nasri (2020), and Iglesias (2024) are located at central positions in the network and have strong citation relationships with other studies. In addition, it has come to the fore that publications such as Yoho (2018) and Pedrosa (2010), although not as central as these studies, still occupy an important place in the network and have effective citation relationships with other studies. In general, it is determined that there are many clusters within the network, both large and small, and that the publications within these clusters establish citation relationships both with different studies within their own cluster and with studies in other clusters.

Conceptual Structure and Thematic Evolution

In this section, the thematic development over time of SDG-focused studies within the scope of physics education based on the keywords used has been examined. In this context, detailed information has been provided about the usage trends of the keywords used in the relevant studies over time, their visibility, and the transformations they have undergone.

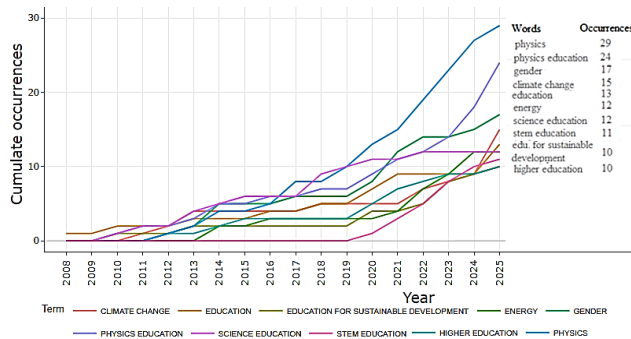


Fig.18: Cumulative Usage Trends of Author Keywords by Year (Top 10)

Figure 18 presents the cumulative usage curves over the years of the ten most frequently used author keywords in SDG-focused studies within the scope of physics education. The table on the right side of the graph shows the total usage values of the author keywords in studies on the related topic up to 2025. When the table is examined, it is seen that the keyword “physics” is the most frequently used author keyword (n:29). When the cumulative usage curves of the author keywords are examined, it is understood that

the frequency of use of these keywords has increased significantly after 2015. In addition, it is determined that the frequency of use of some author keywords has increased even more after 2020. Moreover, it has come to the fore that the author keywords “physics” and “physics education” have consistently had a high frequency of use in all periods, while keywords within the scope of SDGs such as climate change, education for sustainable development, and energy have shown an increased frequency of use in recent years.

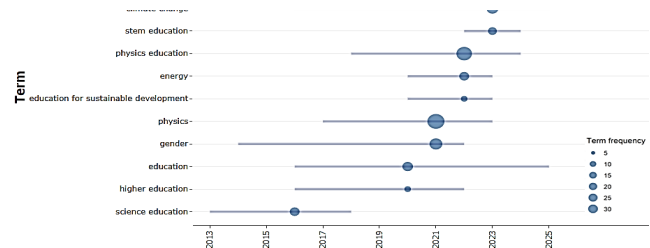


Fig. 19: Temporal Visibility and Intensity of Author Keywords (Trend Topics)

Figure 19 shows the visibility and usage intensity of author keywords used in SDG-focused studies within the scope of physics education over time. In the graph, horizontal lines represent the visibility of author keywords, while the size of the nodes represents their usage intensity. For example, it is understood that the author keyword “energy” was visible between 2020 and 2023 and, since it is represented by a small node in 2022, its usage intensity was low. When Figure 19 is examined, it is determined that the author keywords “climate change” and “education” were visible for approximately 10 years between 2016 and 2025 and are the most visible author keywords. Following these keywords, it is determined that the author keyword “gender” remained visible for approximately 9 years between 2014 and 2022. In addition, it has come to the fore that the author keyword “science education” has the earliest visibility. Moreover, when the nodes representing the usage intensity of author keywords are examined, it is determined that the author keywords “physics” and “physics education” reached the highest usage intensity in certain periods (in 2021 and 2022, respectively). It is also understood that the author keywords “higher education” and “sustainable development” had the lowest usage intensity in 2020 and 2022.

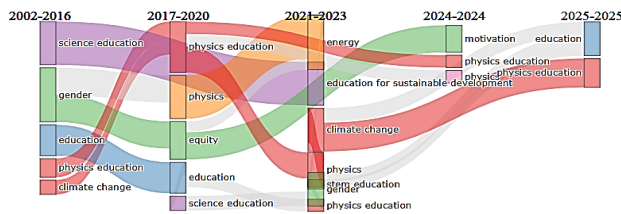


Fig. 20: Thematic Evolution: Inter-Period Thematic Transformation

Figure 20 illustrates the distribution of author-keyword-based themes across different time periods and the flows connecting these themes between successive intervals. The figure presents the temporal transitions of prominent concepts within literature. During the 2002-2016 period, the thematic structure includes science education, gender, education, physics education, and climate change. Flows from the themes of education and gender extend into subsequent periods. In the 2017-2020 period, the themes of physics and physics education appear prominently, with equity and education connected to these themes. During the 2021-2023 period, additional themes such as energy, education for sustainable development, climate change, gender, and STEM education are visible, alongside continuing flows from physics education. In the more recent intervals (2024-2024 and 2025-2025), physics education remains present, while themes such as motivation and education appear in the latest period.

(relevance) and density (development). In the map, the horizontal axis represents the degree of relational centrality of themes within the field, while the vertical axis reflects their internal density. The themes located in the upper-right quadrant “energy,” “sustainable development,” and “science” are positioned in the motor themes area of the map, characterized by relatively high centrality and density values. In the lower-right quadrant, “environmental education,” “renewable energy,” and “critical thinking” are located in the basic themes area, characterized by higher centrality and comparatively lower density values. Themes such as “engineering education” and “critical physics teaching,” located in the upper-left quadrant, appear in the niche themes area, reflecting higher density but lower centrality values. Finally, themes positioned in the lower-left quadrant, such as “climate change,” “teacher education,” and “physics education,” are located in the emerging or declining themes area, where both centrality and density values are comparatively lower within the map.

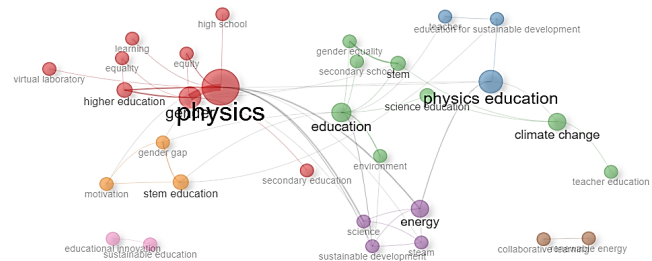


Fig. 22: Thematic Map: Positioning of Themes According to Centrality and Development Level

Each node within the network represents a keyword, and the size of these nodes represents the frequency of use of the keyword. In addition, the connections between the nodes indicate the co-occurrence of two keywords. When Figure 22 is examined, the fact that the node sizes of the keywords “physics” and “physics education” are larger than those of other keywords shows that these keywords are located at the center of the network. It has also come to the fore that these two keywords are directly connected to each other. In addition, when the connections made by the centrally positioned keywords are examined, it is understood that they establish connections with many keywords

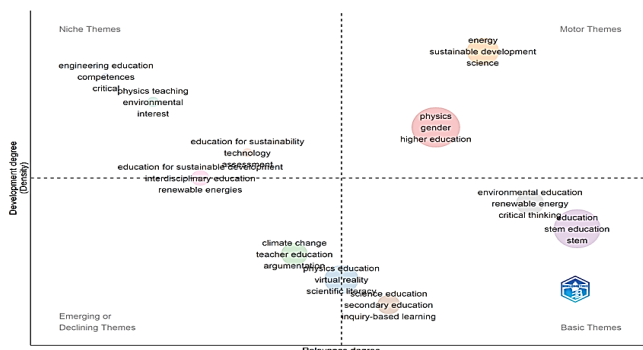


Fig. 21: Thematic Map: Positioning of Themes According to Centrality and Development Level

Figure 21 illustrates how themes derived from author keywords are positioned on a two-dimensional thematic map according to their levels of centrality

in different clusters. In particular, it has been determined that the keyword “physics” establishes a direct and strong connection with the keyword “gender,” which has a large node size. It has drawn attention that this connection is the strongest among the keywords in Figure 22. In general, it is understood that the network consists of several clusters, that SDG-themed keywords are located around the central keywords, and that they establish connections with these keywords.

DISCUSSION AND CONCLUSION

In this section, the findings obtained within the scope of the study have been addressed in relation to the research questions, and the conclusions reached have been evaluated in detail.

Discussion and Conclusions on the Temporal Development and Citation Dynamics of SDG-Focused Physics Education Research

In this subsection, the changes in annual publication output and the citation-based impact patterns of SDG-focused physics education literature are discussed within the framework of the bibliometric findings and the relevant body of literature, and conclusions regarding these findings are evaluated. The study revealed that SDG-focused studies within the scope of physics education did not exhibit a linear growth trend until 2019 and that the level of production was limited, whereas after 2019 there has been a significant increase in the number of studies on this topic. This situation is thought to be due to the delayed reflection of the SDGs, adopted by the UN General Assembly in 2015, on education policies and the agenda of academic research. When the literature is examined, it is observed that bibliometric studies conducted in the fields of sustainability and education between 2018 and 2022 show similar results (Hallinger & Nguyen, 2020; Prieto-Jiménez et al., 2021). Within the scope of the study, it was determined that the average citation values of studies conducted on the related topic in recent years remained lower compared to previous years. In this context, it was concluded that the increase in the number of publications in recent years has not simultaneously been reflected

in citation indicators. This trend can be explained by the concept of “citation delay,” which refers to the increase in the visibility of newly published studies over time and, accordingly, the increase in their citation counts over time (Aksnes et al., 2019; Milfont & Page, 2013; Waltman, 2016). In this context, it can be stated that the SDG-focused physics education literature has grown quantitatively but is in a period in which its scientific impact will emerge over time. However, it has also been determined that in certain periods when the number of publications is relatively limited, higher average citation values are observed. This situation is thought to be due to the concentration of studies in the field on certain works with high scientific impact and visibility. The literature emphasizes that studies with a strong methodology, a problem-focused approach, and that provide consistent information to readers have high visibility and citation potential (Bornmann & Daniel, 2008; Kelley et al., 2003). The number of citations a publication receives is an indicator of its impact and quality in the field (Van Leeuwen et al., 2003). It can be argued that highly visible articles not only reach a wider audience but also directly influence the field by providing more useful and readable information (Karaçöp & İnaltekin, 2023).

Discussion and Conclusions on Scientific Production, Impact, and Collaboration Structures in the SDG-Focused Physics Education Literature

Under this heading, the bibliometric findings regarding scientific production, citation-based impact, and collaboration structures in the SDG-focused physics education literature are discussed at the levels of authors, journals, institutions, and countries within the framework of the relevant literature, and the conclusions drawn from these findings are evaluated.

Discussion and Conclusions on Scientific Production, Impact, and Collaboration at the Author Level

The findings regarding scientific production and citation patterns at the author level revealed that scientific influence in the SDG-focused physics education literature has been constructed around a limited number of highly impactful studies published during

specific periods. This result aligns with studies in the bibliometric literature indicating that the relationship between publication output and scientific impact is often weak, contextual, and non-linear (Aksnes et al., 2019; Waltman, 2016). The significant variation in citation impact among authors with the same number of publications suggests that scientific visibility is associated not merely with quantitative productivity, but rather with the conceptual centrality of studies within the field and their capacity to function as key references. In particular, the high citation counts concentrated within a single publication year in the cases of Barthelemy R. and Pollock S. indicate that what are defined in the literature as “high-impact core publications” can disproportionately shape authors’ impact profiles. Similarly, Aksnes et al. (2019) demonstrate that in many scientific fields, total citation impact is concentrated in a limited number of highly visible publications, which in turn become decisive in shaping authors’ scientific impact profiles. Moreover, such publications can be said to exert a strong scientific influence on subsequent research in the field (Van Eck & Waltman, 2017). In contrast, the more balanced distribution of citation impact across multiple publication years observed for authors such as Danielsson A. and Gonsalves A. corresponds to what has been described in the literature as a “sustainable academic impact” model. Rather than reflecting short-term citation peaks, such profiles indicate that research produced through sustained engagement with the field generates cumulative impact over time (Bornmann & Leydesdorff, 2014). This pattern suggests that the SDG-focused physics education literature has not yet reached a fully homogenized impact structure at the author level; instead, it appears to be structured around highly influential core studies, characteristic of an early maturation stage. The concentration of author-level impact indicators within a narrow range and the organization of collaboration networks around central cores such as Barthelemy R. and Schubatzky T. indicate that new studies are being integrated into the existing intellectual core and reproduced through continuity. This structure points to a development dynamic consistent with the “core-periphery” model of scientific collaboration frequently reported in interdisciplinary research

fields (Newman, 2001; Waltman, 2016; Wagner et al., 2015). Studies examining scientific communication and collaboration networks demonstrate that intellectual orientation in academic fields is often shaped by a core group of researchers, and that this core determines the rhythm of knowledge production in the field (Newman, 2001). Previous bibliometric analyses conducted in physics education similarly emphasize that the studies forming the reference framework of the field are predominantly produced under the leadership of particular researchers (Docktor & Mestre, 2014).

Discussion and Conclusions on Scientific Production, Impact, and Citation Relationships at the Journal Level

The findings indicate that SDG-focused physics education publications are concentrated around specific journals, and that this concentration accelerated particularly after 2014-2015, turning into a marked increase in publication output in some journals after 2020. Studies examining SDG literature over an extended period demonstrate that the adoption of the Sustainable Development Goals in 2015 constituted a structural turning point in publication production, followed by rapid growth (Hallinger & Chatpinyakoo, 2019; Mishra et al., 2024; Yumnam et al., 2024). This alignment suggests that the more visible integration of the SDG theme into the physics education literature may reflect the broader growth dynamics observed in the SDG/ESD literature. The concentration of journal-level production within a limited number of outlets can be explained by the commonly observed pattern of “core journal clustering” in scientific communication. Bibliometric studies show that, particularly in emerging or interdisciplinary research areas, it is expected that publications cluster around certain journals (Bradford, 1934; Waltman, 2016). In this context, the rapid emergence of journals such as Sustainability as core publication venues for SDG-related research and their role in increasing the visibility of the field is consistent with previously reported trends (Prieto-Jiménez et al., 2021; Yumnam et al., 2024). In contrast, the earlier and more stable production patterns observed in discipline-specific journals such

as Physical Review Physics Education Research and The Physics Teacher suggest that the SDG theme was integrated into these outlets through a process of continuity rather than sudden expansion. Bibliometric analyses focusing on the physics education literature emphasize that the methodological and theoretical reference framework of the field has largely been constructed through such discipline-oriented journals, which assume a “foundational intellectual role” (Docktor & Mestre, 2014). This finding indicates that the SDG theme has diffused within the physics education literature simultaneously through both interdisciplinary publication platforms and discipline-specific journal ecosystems.

The journal-level impact indicators reveal that there is no linear relationship between publication volume and scientific impact. This result is consistent with bibliometric approaches emphasizing that scientific influence is determined not solely by the number of publications, but also by the position of those publications within the field and their function in knowledge circulation (Aksnes et al., 2019; Waltman, 2016). The concentration of local citation counts in well-established journals such as Journal of Research in Science Teaching, American Journal of Physics, and International Journal of Science Education indicates that these journals hold high visibility in terms of generating references and guiding knowledge flows within SDG-focused physics education research. Similarly, previous studies on education research and field-specific journals have demonstrated that such journals, through their high citation values, play a determining role in shaping the intellectual agenda of the field (Hallinger & Chatpinyakoo, 2019; Zawacki-Richter et al., 2019). Synthesis studies in physics education likewise emphasize that these journals shape theoretical and methodological orientations within the discipline (Docktor & Mestre, 2014). The positioning of journals such as International Journal of Science Education, Sustainability, Education Sciences, and Research in Science Education at the center of the citation network suggests that the SDG-focused physics education literature is organized around a core journal structure. The scientific network literature highlights that such central nodes accelerate knowledge flow across fields and serve

as bridges between different thematic orientations (Newman, 2001; Wagner et al., 2015). In particular, the strong reciprocal citation relationships established by Sustainability with both education-oriented and physics education-focused journals indicate that the SDG theme has been integrated into the physics education literature largely through interdisciplinary publication channels. On the other hand, the fact that field-specific journals such as Physical Review Physics Education Research produce high H-index values despite relatively limited publication volume demonstrates that scientific impact can be constructed not only through quantity but also through intensity and continuity. This finding aligns with previous studies reporting that core journals in the physics education literature generate sustainable scientific influence through a limited number of high-impact publications (Jamali et al., 2015; Suprpto et al., 2021). Conversely, the observation that rapid publication growth in some journals does not immediately translate into comparable citation density is consistent with bibliometric literature indicating that, in interdisciplinary and emerging research areas, impact indicators follow a cumulative and time-dependent stabilization process (Aksnes et al., 2019; Waltman, 2016).

Discussion and Conclusions on Scientific Production, Impact, and Collaboration at the Institutional Level

This study reveals that institutional contributions within the SDG-focused physics education literature are not evenly distributed and that certain universities emerge as guiding centers of the field. The fact that production became visible in a significant number of universities after 2015 and accelerated markedly after 2020 is consistent with previous studies indicating that, following the adoption of the SDGs, sustainability themes were more strongly incorporated into higher education research agendas (Hallinger & Chatpinyakoo, 2019; Prieto-Jiménez et al., 2021). This suggests that SDG-focused research in physics education has been shaped not merely by individual academic preferences but also by the strategic orientations and research priorities of universities (Venkataraman, 2009). The clear

prominence of Michigan State University in terms of publication volume demonstrates that certain institutions can assume the role of institutional hubs within the SDG-focused physics education literature. Bibliometric literature emphasizes that, in emerging or interdisciplinary fields, production often concentrates around a limited number of leading institutions, which play a guiding role in the early development of the field (Wagner & Leydesdorff, 2005; Leydesdorff & Wagner, 2008). At the same time, the rapid increase in publication output observed in some universities that entered the field at a later stage indicates that institutional contribution is shaped not only by early adoption but also by institutional strategy, funding mechanisms, and collaboration capacity.

The findings regarding the institutional collaboration network indicate that collaborations within the SDG-focused physics education literature are organized not around a single center but around multiple core clusters. The strong and sustained ties observed among institutions such as the University of Colorado, Michigan State University, the University of Jyväskylä, and the University of Washington are consistent with findings in the scientific collaboration literature, which highlight that core institutional networks play a central role in knowledge production within a field (Newman, 2001; Leydesdorff & Wagner, 2008). Similarly, bibliometric studies focusing on sustainability research in higher education demonstrate that the intellectual structure of the field is shaped and sustained through long-term institutional contributions (Hallinger & Chatpinyakoo, 2019). However, the multi-centered and fragmented network structure observed in this study does not fully align with some studies suggesting that collaborations in sustainability and education research tend to become more integrated over time (Adams, 2013; Wagner & Leydesdorff, 2005). In particular, the regional collaboration cluster formed around Uppsala University and the strong bilateral ties observed between certain universities suggest that institutional collaborations continue to be shaped by thematic, regional, and historical contexts, and that the field has not yet achieved a fully integrated network structure. This finding is consistent with literature emphasizing that scientific collaborations

develop not only through global dynamics but also through contextual and regional factors (Hoekman et al., 2010; Newman, 2001).

Discussion and Conclusions on Scientific Production, Impact, and International Collaboration at the Country Level

The findings at the country level indicate that scientific production and impact in the SDG-focused physics education literature do not display a balanced global distribution, and that certain countries assume guiding roles in the development of the field. In particular, the clear superiority of the United States in terms of the acceleration observed in its cumulative production curve indicates that the country adopted SDG-themed physics education research at an early stage and systematically incorporated it into its research agenda (Leydesdorff & Wagner, 2008). This finding is consistent with studies reporting that the period after 2015, following the adoption of the SDGs, corresponds to a marked acceleration in global research production within the SDG literature (Hallinger & Chatpinyakoo, 2019; Prieto-Jiménez et al., 2021). At the same time, the conclusion that there is no linear relationship between publication output and scientific impact at the country level confirms the production-impact divergence frequently emphasized in the bibliometric literature (Aksnes et al., 2019; Waltman, 2016). Finland's ability to generate high total citation counts despite a relatively limited publication volume demonstrates that some countries can attain a central position in the literature not through quantitative output, but through highly visible and strongly referenced publications. This suggests that scientific impact at the country level is determined not solely by publication volume, but also by the position of publications within citation networks and their level of integration into international scientific circulation (Waltman, 2016).

The international co-authorship network demonstrates that collaboration in the SDG-focused physics education literature is not organized around a single center, but rather exhibits a multi-centered structure shaped around key actors and differentiated along regional lines. The positioning of the United States at the center of the network and its direct

connections with a large number of countries highlight its function as a global hub of collaboration. Similarly, Saka and İnaltekin (2021), in their bibliometric study, report that the United States occupies a central position in international collaboration networks. The scientific collaboration literature emphasizes that such central actors function as key nodes that accelerate knowledge circulation and enhance the global integration of a field (Newman, 2001; Leydesdorff & Wagner, 2008). The strong ties between the United States and Finland, as well as between the United States and Canada, indicate that countries producing high scientific impact may simultaneously maintain intensive and sustained international collaborations. On the other hand, the presence of clearly identifiable regional sub-clusters in the network underscores that international collaboration has not yet reached a fully homogeneous and globally integrated structure. The United Kingdom-Ireland-Australia axis, Spain-centered Latin connections, and clusters formed around China, South Africa, and Finland demonstrate that collaborations continue to be influenced by geographical, historical, and cultural contexts. This finding only partially aligns with studies suggesting that scientific collaborations become increasingly integrated over time (Adams, 2013; Hoekman et al., 2010; Wagner & Leydesdorff, 2005). Instead, the results indicate that collaboration structures in the SDG-focused physics education literature continue to develop through regional and thematic clustering patterns. This outcome is consistent with studies emphasizing that scientific collaborations are sustained not only through global hubs but also through regional networks and bilateral relationships (Hoekman et al., 2010; Newman, 2001).

Discussion and Conclusions on the Intellectual Structure of the SDG-Focused Physics Education Literature: Core Studies and Citation Patterns

In this section, the core studies that constitute the intellectual structure of the SDG-focused physics education literature, along with their global and local citation patterns, are discussed within the context of the bibliometric findings and the relevant literature, and the structural implications of these

findings are evaluated. The document-level findings reveal that scientific influence in the SDG-focused physics education literature does not display a unidimensional structure and that a clear divergence exists between global visibility (global citations) and intra-field referential positioning (local citations). The prominent position of Stoet's (2018) study in the global citation distribution indicates that the intellectual structure of the field is not confined solely to the core of physics education; rather, highly visible interdisciplinary studies can play a decisive role in the global circulation of the literature through the SDG theme. This observation is consistent with classical bibliometric findings demonstrating that citation distributions in most scientific fields are highly skewed and that a small number of publications account for a large proportion of total citations (Seglen, 1992; Waltman, 2016). In contrast, the central positioning of studies such as Hazari (2010) and Lorenzo (2006) in the local citation distribution indicates that knowledge circulation within the SDG-focused physics education literature is organized around a narrower and more selective core group of references. Because local citations reflect direct reference relationships among the studies included in the sample, this indicator is considered particularly functional in revealing the internal intellectual structure and foundational knowledge base of a field (Garfield et al., 2003; Aria & Cuccurullo, 2017). The concentration of local citations on a limited number of studies suggests that consistent with the relatively recent integration of the SDG theme into the physics education literature, the field has not yet developed a broad and diversified reference pool. Nevertheless, certain studies appear to function as a backbone, ensuring theoretical and methodological continuity. The integration of new studies into this intellectual core in order to gain visibility suggested that the field did not exhibit fragmented growth, rather, it is reproduced through continuity while preserving its core structure. In particular, the fact that studies such as Hazari (2010), despite having limited global visibility, receive high levels of local citation underscores that theoretical and methodological orientations within the field are largely shaped through such core publications.

The lack of full overlap between global and local citation indicators demonstrates the existence of two distinct impact mechanisms operating at different levels within literature. While some studies achieve high global visibility through interdisciplinary circulation, others contribute to the intellectual core by being intensively referenced within the field itself. This divergence aligns with evaluation literature that cautions against interpreting citation indicators alone as direct measures of “scientific quality” or “centrality” (Aksnes et al., 2019; Waltman, 2016). Accordingly, the findings suggest that scientific influence in the SDG-focused physics education literature should be assessed through context-sensitive and multidimensional indicators. The document-level citation network analysis further supports this multilayered structure. The concentration of the network around a limited number of central publications, such as Mujtaba (2013), Nasri (2020), and Iglesias (2024), is consistent with the core-periphery pattern of intellectual organization frequently reported in the literature (Garfield et al., 2003; Waltman, 2016). The fact that these central publications assume a bridging role by bringing together citation links from different sub-clusters indicates that the knowledge structure of the field evolves not in a linear manner, but through a network-based development. At the same time, the presence of secondary clusters and the integration of recent studies into the existing core suggest that the SDG-focused physics education literature is not static; rather, it develops through a continuously expanding intellectual network characterized by structural continuity.

Discussion and Conclusions on the Conceptual Structure and Thematic Evolution of the SDG-Focused Physics Education Literature

The conceptual structure and thematic evolution of the SDG-focused physics education literature are discussed within the framework of bibliometric findings based on author keywords and the relevant literature, and the results are evaluated from a comprehensive perspective. Keywords play a significant role in reflecting the content of articles

and in revealing the trends and patterns of academic research (Badaluddin et al., 2021). The findings related to conceptual structure and thematic evolution indicate that the SDG-focused physics education literature exhibits temporal expansion without random conceptual dispersion. The strong concentration around the axes of “physics” and “physics education” demonstrated that the SDG theme has been incorporated into the literature not as an independent sustainability discourse, but rather through integration into a discipline-centered core of physics education. This observation is consistent with studies emphasizing that the integration of sustainability themes into different fields often occurs through existing disciplinary structures (Lozano et al., 2019). In particular, although the keywords “physics” and “physics education” became visible relatively later, their rapid increase in usage intensity suggests that the conceptual center of the field has become more clearly defined over time.

Temporal visibility analyses highlight that general educational concepts such as science education and education have been present in literature since the early stages, whereas sustainability-themed concepts such as climate change, energy, and education for sustainable development emerged at a later stage but achieved longer-term visibility. This pattern indicates that sustainability themes initially entered the literature through broader educational discussions and gradually evolved into more specific and enduring thematic structures within the context of physics education. The fact that similar transition processes have been reported in the sustainability literature in higher education suggests that this transformation reflects a shared maturation dynamic across disciplines (Hallinger & Chatpinyakoo, 2019; Lozano et al., 2019; Prieto-Jiménez et al., 2021). In this respect, the conceptual concentration observed in the SDG-focused physics education literature points not to fragmented thematic expansion, but rather to a maturation process in which the disciplinary core is preserved and progressively deepened.

The thematic evolution analysis reveals that core themes in the literature exhibit continuity across periods, while new themes expand the thematic structure by integrating into the existing core rather

than replacing it. This finding supports the “cumulative thematic expansion around core themes” model frequently emphasized in bibliometric studies (Aria & Cuccurullo, 2017; Waltman, 2016). At the same time, the fact that this pattern does not fully align with the rapid and fragmented thematic proliferation reported in some sustainability education studies suggests that in fields with strong disciplinary boundaries, such as physics education, thematic transformation progresses in a more controlled and core-centered manner (Hallinger & Chatpinyakoo, 2019; Docktor & Mestre, 2014). The findings from the thematic map indicate that themes such as energy and sustainable development are positioned at the center of the field as motor themes, while themes such as environmental education and STEM education, despite their high centrality, function as basic themes characterized by relatively limited conceptual depth. In contrast, niche themes such as engineering education and critical physics teaching, although exhibiting high levels of development, maintain more limited connections with the overall thematic structure of the field. This clearly illustrates the distinction between thematic specialization and centrality within the field (Aria & Cuccurullo, 2017; Callon et al., 1991).

The keyword co-occurrence network demonstrates that the literature is organized around two main conceptual backbones (physics and physics education), and that sustainability themes are structured through their integration into this backbone (Radhakrishan et al., 2017). This structure suggests that the SDG-focused physics education literature maintains disciplinary continuity while simultaneously enabling interdisciplinary expansion through an integrated conceptual organization. This finding aligns with studies arguing that, in interdisciplinary fields, conceptual coherence can be sustained through a strong disciplinary core (Newman, 2001; Lozano et al., 2019).

IMPLICATIONS

This study has shown that the number of SDG-focused studies within the scope of physics education has increased in recent years and that its conceptual and intellectual structure has been shaped mainly around the author keywords “physics” and “physics

education.” This situation has brought to the fore the necessity for future research to focus more on SDG-oriented (such as climate change, renewable energy, quality education, and similar) problem contexts and to conduct interdisciplinary studies. In addition, within the scope of the study, the current state of collaboration networks among authors, institutions, and countries has been revealed by utilizing bibliometric analyses. It is considered that conducting studies in the future that will reveal which factors or relationships influence the formation of this current state (collaboration among authors, institutions, and countries) will make a significant contribution to the literature.

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