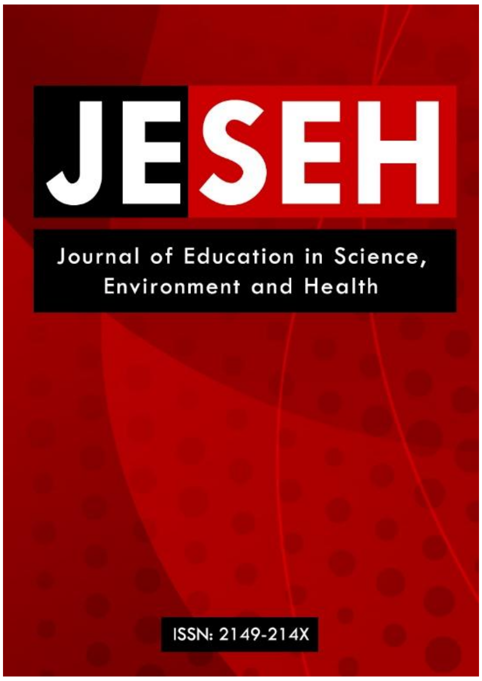

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Argumentation Research in Science Education: Global Publication Trends, Intellectual Structure, and Thematic Transformation (2001–2025)

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Argumentation Research in Science Education: Global Publication Trends, Intellectual Structure, and Thematic Transformation (2001–2025)

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Abstract

Argumentation has become a cornerstone of science education research, essential for fostering evidence-based thinking, scientific reasoning, and scientific literacy. This study employs bibliometric methods to examine global publication trends, intellectual structures, and thematic transformations in argumentation-focused research between 2001 and 2025. A final dataset of 474 peer-reviewed articles, retrieved from the Web of Science Core Collection after applying stringent inclusion and exclusion criteria, was analyzed using the R-based Bibliometrix package. To ensure a holistic interpretation, author keywords were standardized and categorized into overarching themes, allowing the field's conceptual landscape to be mapped in a more integrated manner rather than through fragmented indicators. The results indicate that argumentation studies emerged between 2001 and 2010, experienced rapid growth from 2011 to 2020, and approached a maturation phase by 2025. Early research focused mainly on cognitive argument structures, while later work increasingly engaged with socioscientific issues, epistemic practices, and classroom discourse. During this process, classical models were recontextualized within contemporary pedagogical settings and underwent terminological transformation. By illustrating the transformation of the science education argumentation literature from a pedagogical tool to a foundational epistemic framework, this study offers an empirically grounded perspective that may inform future research directions in the field.

Introduction

Science education aims not only to teach individuals scientific concepts, but also to enable them to question, evaluate, and justify this knowledge based on evidence. In this context, argumentation stands out as a fundamental reasoning process that enables students to support their claims with data and to substantiate these claims through reasoning (Toulmin, 1958). Argumentation-based learning environments support the development of scientific reasoning skills by allowing students to interact with different perspectives (Osborne et al., 2004). Scientific knowledge is recognized as a dynamic process that is socially constructed through classroom discussions and reasoned discourse (Driver et al., 2000). Accordingly, argumentation is positioned not only as a form of expression but also as a central epistemic practice that enables an understanding of the nature of science.

Argumentation-based approaches in science education are considered effective instructional approaches that not only deepen conceptual learning but also support the development of critical thinking and scientific literacy skills (Osborne, 2010). In recent years, there has been a marked increase in the number of studies on this topic, indicating that argumentation is considered not only a teaching strategy but also a comprehensive approach to learning and thinking. This upward trend can be attributed not only to global research dynamics but also to the explicit inclusion of argumentation in science education curricula in some countries. Indeed, the emphasis on scientific reasoning and argumentation in science curricula updated in Turkey since the mid-2010s has shown a parallel development with the increase in academic production in this field. However, individual studies may be limited in revealing the general publication trends, dominant thematic orientations, and intellectual structure of the field. This lack of a holistic perspective in the literature, coupled with the increasing volume of publications, further underscores the need for bibliometric approaches capable of systematically examining its structural characteristics and longitudinal dynamics (Donthu et al., 2021; Zupic & Cater, 2015).

At this point, bibliometric analyses stand out as systematic approaches that aim to reveal the intellectual structure, development dynamics, and research orientations of a field by examining scientific production through quantitative indicators (Donthu et al., 2021). Publication trends over the years, citation structures, prominent journals and authors, and keyword-based conceptual networks can be made visible in a holistic manner through bibliometric analyses. While there are bibliometric studies (Kurtuluş & Yılmaz, 2022; Orhan, 2024; Tang, 2024) focusing on various themes in science education, studies that specifically focus on argumentation and examine the field's temporal development, intellectual foundations, and thematic orientations using up-to-date data remain limited. The volume of publications and thematic diversity achieved in the field necessitate a structural mapping beyond traditional review studies. Indeed, the number of existing bibliometric studies on science education argumentation (Mulyani et al., 2024; Noris et al., 2024; Tosun, 2024; Wang et al., 2023) is relatively small, and there is a clear need for a comprehensive perspective that reveals the current development dynamics and intellectual structure of the literature, particularly including publications after 2020.

The aim of this study is to examine research focusing on argumentation in science education using bibliometric methods in response to the aforementioned methodological gap, and to provide a comprehensive overview of the field's temporal development, intellectual structure, and thematic orientations. Specifically, scientific production trends by year, distributions by country and journal, citation structures, and keyword-based thematic orientations were analyzed using publications indexed in the Web of Science database. One of the primary original contributions of this study is that it covers current data up to the end of 2025 and empirically demonstrates that the science education argumentation literature is approaching a mature stage. At this critical juncture, as the field transitions from an exploratory phase to a more established structure, identifying emerging thematic transformations and potential paradigm shifts is of strategic importance for shaping future research agendas. In this respect, the study aims not only to provide an overview of past developments but also to guide researchers by offering an analytical projection of the sub-fields in which the literature is deepening.

Preliminary analyses conducted to contextualize this expansion process in the science education argumentation literature and to support the methodological rationale of the study reveal that the field exhibits a characteristic growth pattern. The logistic growth model (Figure 1) and the cumulative growth curve (Figure 2) are mathematical approaches used to predict the growth rate, life cycle, and potential saturation level of a research field's publication output based on empirical data. These analyses indicate that research on argumentation in science education emerged between 2001 and 2010, experienced a period of rapid growth between 2011 and 2020, and has begun to approach a phase of maturity as of 2025.

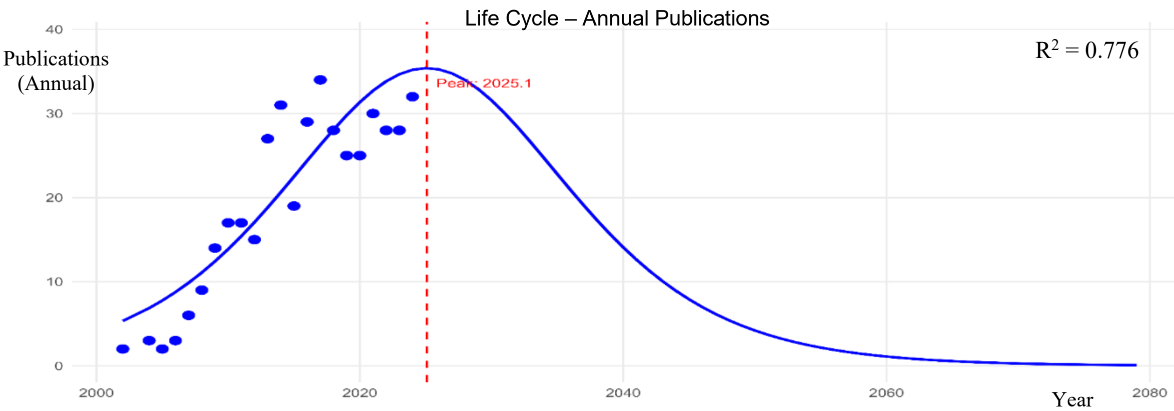

Figure 1. The life cycle of argumentation studies (logistic growth model)

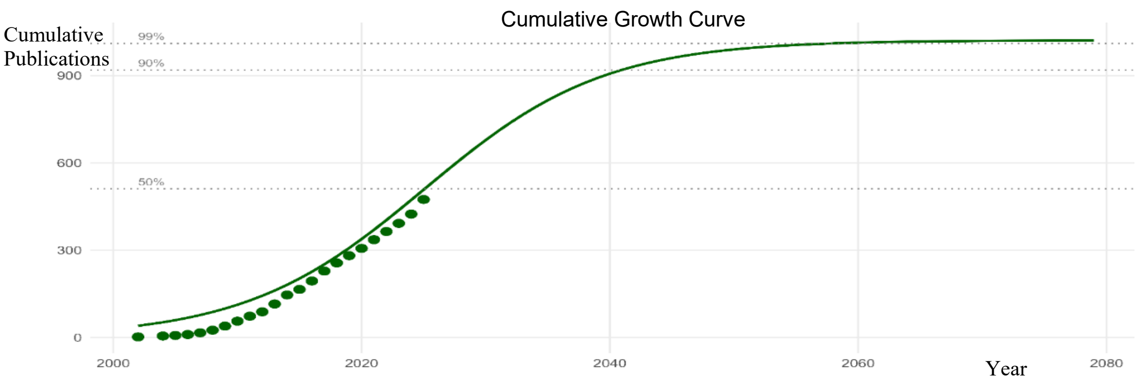

Figure 2. Cumulative growth curve of argumentation studies in science education

The model presented in Figure 2 suggests that the potential saturation level of the field may be reached around 2050, with an estimated total of approximately 1021 publications. This finding indicates that the field has largely moved beyond its exploratory phase and entered a more established stage that is open to thematic deepening and specialization. The visuals and accompanying explanations presented in this section are used descriptively to contextualize the developmental trajectory of the field; detailed quantitative analyses are presented in the Results and Discussion sections.

In this context, the present study, which aims to reveal the intellectual structure, thematic orientations, and global publication trends of argumentation research in science education from a holistic perspective, constitutes a timely and necessary contribution to the current stage of development in the field. Within this scope, the following research questions (RQ) are addressed to systematically achieve the study's objectives:

- RQ1. What are the temporal development and scientific production trends of argumentation studies in science education?
- RQ2. Which journals, authors, countries, and institutions stand out in science education argumentation studies?
- RQ3. How are the citation structures and intellectual foundations of argumentation studies in science education shaped?
- RQ4. What are the dominant thematic orientations, thematic transformations, and research trends in science education argumentation studies?

Method

Data Source and Data Set Formation

The Web of Science Core Collection (WoS) was selected as the data source for this study. WoS is widely used in literature reviews because it covers peer-reviewed journals with high impact values, provides standardized and reliable citation data, and offers structured bibliographic data that enables bibliometric analysis. The research dataset was created from publications selected from the WoS database in accordance with the specified inclusion and exclusion criteria, and the data collection process was completed and updated on January 5, 2026.

Screening Strategy and Inclusion-Exclusion Criteria

The screening process used the WoS Topic field to retrieve studies on argumentation in science education. This field was preferred for its comprehensive dataset, including titles, abstracts, author keywords, and Keywords Plus terms. The search string was "science education" AND "argumentation", aligning with common literature concepts. Using the AND operator ensured both terms co-occurred, increasing result relevance. The decision to include only the term *argumentation* in the search string was adopted to maintain the conceptual focus of the study and to capture core research addressing epistemic and pedagogical argumentation processes in the science education literature.

The retrieved publications were filtered in successive stages based on predefined inclusion and exclusion criteria to construct a dataset that was aligned with the study's purpose, methodologically comparable, and of high academic quality. Accordingly, only research articles published in peer-reviewed journals between 2001 and 2025, indexed in the SSCI, classified under the Education–Educational Research category, and written in English were included in the analysis. Book reviews, conference proceedings, book chapters, and studies outside the SSCI scope or not directly related to the context of science education were excluded from the analysis. The filtering stages applied and the number of publications obtained at each stage are summarized in Table 1.

Table 1. Data set creation process: Filtering stages and publication counts

Stage	Applied Filter / Criterion	Remaining Publication Count
1	Keywords: "Science Education" (topic) AND Argumentation (topic)	835
2	Document type: Article	729
3	Publication year: 2001–2025	724
4	WoS category: Education–Educational Research	618
5	Index: SSCI	477
6	Language: English	474

Data Cleaning Process

Prior to the analyses, the dataset underwent a cleaning process to enhance the accuracy, conceptual consistency, and reproducibility of bibliometric results. In this process, variations in author names (e.g., first name–last name order and abbreviations), institutional name formats, singular–plural usage in keywords, and spelling inconsistencies were identified using tools provided by the Bibliometrix package. Where automated procedures were insufficient, manual corrections were performed under researcher supervision to ensure consistency.

Keyword Standardization and Conceptual Integration

To increase the conceptual validity of the thematic mapping and network analyses, a comprehensive keyword standardization and conceptual integration procedure was applied following data cleaning. This stage aimed not only to correct formal inconsistencies but also to analytically harmonize concept clusters representing shared theoretical and pedagogical frameworks in the science education argumentation literature. Accordingly, keywords with high conceptual overlap were grouped under superordinate concepts by considering spelling variants, singular–plural forms, and contextual similarity across all author keywords. This consolidation was guided primarily by lexical proximity and recurrent contextual usage patterns rather than by constructing a formal ontological taxonomy. When lexical variants referred to the same pedagogical construct, practice, or theoretical framework, as indicated by their recurrent usage within similar research contexts, they were grouped under a common superordinate term. This approach prioritizes the preservation of emergent thematic structures over rigid a priori classifications. While certain terms could be conceptually distinguished at a finer theoretical level, the objective here was to reduce terminological fragmentation while preserving thematic coherence within the analytical framework.

In this process, 396 variants identified among 1,074 author keywords were consolidated under 51 superordinate conceptual terms, each comprising between 2 and 25 sub-terms. The complete list of these keyword consolidations and their corresponding variants is provided in Appendix 1 to ensure methodological transparency and reproducibility. Following consolidation, each superordinate term reached a minimum frequency threshold of five or more ($f \geq 5$), suggesting a relatively stable presence within the field. Of the remaining 678 keywords that could not be meaningfully grouped, 592 had a frequency of one ($f = 1$), while 86 appeared with frequencies ranging from two to four. To reduce conceptual noise and emphasize more robust thematic structures, keywords with a frequency of one were excluded from the thematic mapping and network analyses. Consequently, the final analytical framework consisted of 137 keywords, formed by the combination of 51 superordinate terms and 86 individual keywords with frequencies of two or higher. These units are hereafter referred to as “refined terms”.

During the conceptual consolidation process, merging variant forms also increased the representational strength of the related superordinate concepts. For instance, the keyword *collaboration*, which initially appeared with a frequency of one, was merged with 12 related variants, resulting in a cumulative frequency of 19. Similarly, although the term *argument* exhibited a moderate standalone frequency ($f = 8$), it was grouped under the superordinate concept of *argumentation* together with related variants such as *arguments*, *scientific argumentation*, *socio-scientific argumentation*, and *science argumentation*, reflecting its role within a broader theoretical framework. In contrast, 11 technical variants representing structural components specific to the Toulmin Model (e.g., rebuttal, warrant, and claim) were separated from the general argument category and grouped under the umbrella term *Toulmin*. These consolidations, along with the establishment of the overarching category of *socioscientific issues* through the integration of 13 variants (e.g., socio-scientific issues, socioscientific, socio-scientific issue, local socioscientific issues), constitute the core outcomes of the standardization process. Overall, this procedure eliminated redundancy while preserving contextual meaning, yielding a thematically coherent structure that supports analytical reliability.

Data Analysis

The R-based Bibliometrix package, specifically developed for bibliometric studies, was used to analyze the dataset (Aria & Cuccurullo, 2017). Bibliometrix was selected because it enables the integration of performance analysis and scientific mapping approaches within a single analytical framework, allowing the simultaneous examination of both the conceptual and intellectual structures of the field. Two main analytical approaches were adopted: performance analysis and scientific mapping. Within the scope of performance analysis, scientific production trends by year, the most productive countries, authors, institutions, and journals, as well as citation-based indicators, were examined. Logistic and cumulative growth curve analyses were applied to reveal the temporal development and growth dynamics of argumentation research in science education; these analyses enabled the quantitative modeling of the field's emergence, acceleration, and maturation phases.

In the scientific mapping phase, analyses were conducted on keyword co-occurrence networks, co-citation structures, thematic maps (based on the dimensions of centrality and density, including basic, motor, niche, and emerging/declining themes), trend topics (key concepts that rise or decline over time), and three-field plots (Figure 7). These analyses revealed the conceptual structure of the field and its transformation over time. Keywords Plus data were used in the three-field plot, which illustrates the intellectual structure of argumentation studies in science education, in order to reflect broad conceptual networks and terminological links with referenced sources in a comprehensive manner. In this context, while author keywords were preferred to capture micro-level research foci in thematic mapping and word cloud analyses, Keywords Plus was employed to represent the intellectual flow and macro-level conceptual bridges of the discipline. Accordingly, the three-field plot made large-scale relationships among authors, sources, and concepts visible in a holistic way.

Within the scope of the fourth research question, the analysis aimed to identify thematic shifts and research trends in the literature by reflecting researchers' theoretical and pedagogical positions. For this purpose, author keywords were used in the thematic map analysis, as they constitute the primary micro-level data source by directly reflecting how researchers position their studies within the field, demonstrating sensitivity to science education terminology, and revealing conceptual traces of thematic change. In the thematic map analysis, the minimum cluster frequency threshold was set to 20 to optimize the readability of the conceptual network derived from 474 articles and to represent the intellectual structure of the literature at a meaningful level of resolution. Preliminary tests showed that a threshold value of 10 increased bibliometric noise, dispersed thematic focus, and amplified immature or transient trends as if they were dominant. In contrast, threshold values of 30 and above excluded critical niche themes such as *dialogue*, *pedagogy*, and *decision-making*, which represent methodological and pedagogical depth in the science education argumentation literature. Therefore, a threshold value of 20 was adopted to achieve an analytical balance between basic and motor themes (e.g., argumentation and science education), which constitute the conceptual backbone of the field, and emerging themes (e.g., socioscientific issues and reasoning) that signal developmental directions. Through this threshold selection, terms with limited representation or dispersed contextual relevance were eliminated, and the dominant thematic orientations, transformation tendencies, and research strategies in science education argumentation were presented in a coherent, comparable framework based on "refined terms".

In parallel, during the visualization of conceptual networks, a minimum edge threshold of 4 was applied to balance relational strength among keywords with the overall intellectual density of the network. Experimental testing indicated that threshold values of 6 and above excessively simplified conceptual transitions, substantially reducing the visibility of secondary concepts connected to basic themes such as *socioscientific issues* and *argumentation*. By contrast, the selected threshold preserved strong connections among central concepts while enabling secondary conceptual relationships to be mapped with a higher level of analytical precision.

Within this framework, to examine the intellectual structure of the field and patterns of knowledge production in a multidimensional manner, analyses of keyword co-occurrence networks (Figure 8), thematic maps (Figure 9), and prominent research topics over time (Figure 10) were conducted. Consequently, a holistic view of argumentation research in science education was obtained at both the micro level, through author-focused conceptual representations based on author keywords, and the macro level, through intellectual flows and conceptual linkages across the literature captured by Keywords Plus. This dual perspective provided a systematic and comparable analytical foundation for addressing all research questions.

Results

RQ1. What are the Temporal Development and Scientific Production Trends of Argumentation Studies in Science Education?

When examining Figure 3, which shows the distribution of argumentation research in science education over time, it is observed that scientific production remained below 10 publications per year between 2001 and 2005. A steady increase began in 2006 and continued through 2010. Although fluctuations were observed in publication output between 2011 and 2022, the overall trend remained upward. After 2022, this upward trend strengthened again, reaching the highest publication volume during the 2024–2025 period. Overall, the results indicate that scientific production in the field has followed a consistently increasing trajectory from its early stages to the present.

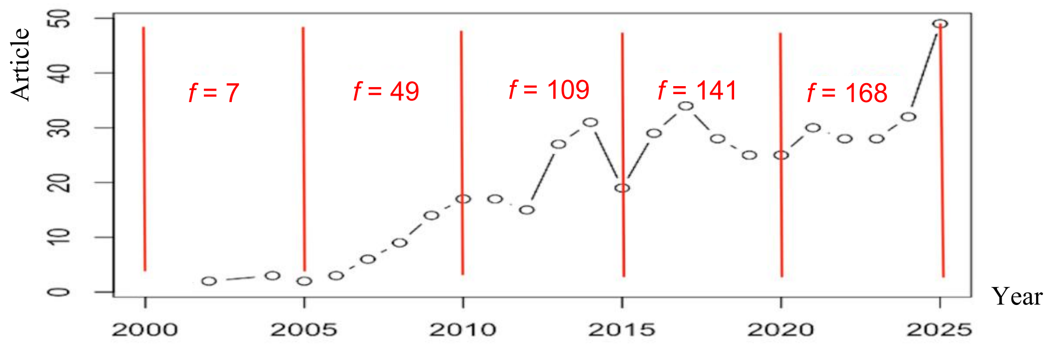

Figure 3. Annual scientific production of argumentation studies

RQ2. Which Journals, Authors, Countries, and Institutions Stand Out in Science Education Argumentation Studies?

The journals that stand out in terms of publication output in science education argumentation research are listed in Table 2 in descending order of article count. A substantial proportion of the analyzed articles (353 articles, 74.4%) were published in these 10 journals, with the *International Journal of Science Education* leading the field with 91 publications. This journal is followed by *Science & Education* (54), *Science Education* (52), and the *Journal of Research in Science Teaching* (45). Journals such as *Research in Science Education* and *Research in Science & Technological Education* also contribute a notable number of publications to the field.

Table 2. Journals with the highest number of publications in argumentation studies

Rank	Journal	Number of Articles
1	International Journal of Science Education	91
2	Science & Education	54
3	Science Education	52
4	Journal of Research in Science Teaching	45
5	Research in Science Education	38
6	Research in Science & Technological Education	19
7	International Journal of Science and Mathematics Education	18
8	Journal of Science Education and Technology	16
9	Chemistry Education Research and Practice	10
10	Instructional Science	10

Table 3 presents the authors with the highest number of publications in science education argumentation research. The analysis revealed that some authors appear under different name formats in WoS records. For example, articles by Archila were recorded as “Archila, P. A.” and “Antonio Archila, P.”. After consolidating these variants, Archila was identified as having contributed to 15 of the 474 articles published between 2001 and 2025, making this author the most prolific in the field. Archila is followed by Erduran (14 articles) and McNeill (14 articles). Other prominent authors include Sadler (10), Gonzalez-Howard (7), Hand (7), Molina (7), Restrepo (6), and Zeidler (6). The distribution in Table 3 represents the quantitative contribution of the most prolific authors, accounting for 86 articles in total.

Table 3. Most prolific authors in argumentation research

Rank	Author	Number of articles
1	Archila, P. A.	15
2	Erduran, S.	14
3	McNeill, K. L.	14
4	Sadler, T. D.	10
5	Gonzalez-Howard, M.	7
6	Hand, B.	7
7	Molina, J.	7
8	Restrepo, S.	6
9	Zeidler, D. L.	6
10	Kuhn, D.	5

Table 4 presents the country-level distribution of publications in science education argumentation research between 2001 and 2025. The United States of America (USA) leads the field with 159 articles (33.5%), followed by China (40 articles, 8.4%) and Turkey (33 articles, 7.0%). These are followed by Germany and Sweden (25 articles each, 5.3%) and the United Kingdom (23 articles, 4.9%). The top ten countries listed in Table 4 account for a large proportion (363 articles, 76.6%) of the articles examined, indicating a high quantitative contribution to the argumentation literature in science education.

Table 4. Countries producing the most articles in argumentation research

Rank	Country	Number of Articles	Percentage (%)
1	USA	159	33,5
2	China	40	8,4
3	Turkey	33	7,0
4	Germany	25	5,3
5	Sweden	25	5,3
6	United Kingdom	23	4,9
7	Spain	19	4,0
8	Colombia	15	3,2
9	Australia	13	2,7
10	Israel	11	2,3

Figure 4 illustrates the cumulative publication trends from 2001 to 2025 for the three most productive countries (USA, China, and Turkey). The publication curve for the USA shows a steady and uninterrupted increase throughout the period, reaching 159 articles by the end of 2025. In contrast, the publication trajectories of China and Turkey exhibit a later onset, with growth becoming particularly evident from the mid-2010s onward. By 2025, China reached 40 publications, while Turkey reached 33. Compared to the USA, both countries display lower growth slopes, with noticeable variations in growth rates across different periods.

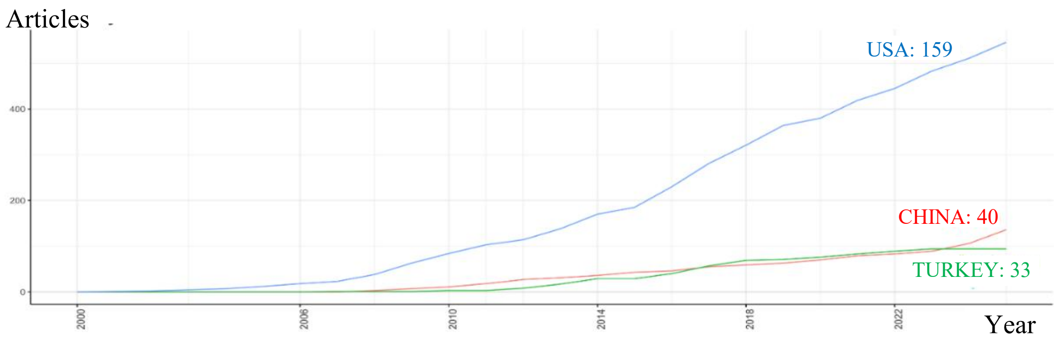

Figure 4. Countries with the highest publication output in argumentation research

Table 5 presents the institutions with the highest publication output in science education argumentation research between 2001 and 2025. According to the results, the University of Los Andes ranks first with 47 articles, followed by Boston College (26 articles). Among institutions based in Taiwan, National Taiwan Normal University and National Taiwan University of Science and Technology appear prominently. From Europe, the University of Oxford ranks among the leading institutions with 17 articles, while Recep Tayyip Erdoğan University from Turkey is also included in the top ten with 16 articles. The institutions listed in Table 5 collectively account for 201 articles (42.3%), highlighting their substantial contribution to the field.

Table 5. Most productive institutions in argumentation research

Rank	Institution	Number of Articles
1	Universidad de los Andes / University of Los Andes	47
2	Boston College	26
3	National Taiwan Normal University	19
4	National Taiwan University of Science and Technology	17
5	University of Oxford	17
6	Recep Tayyip Erdoğan University	16
7	Seoul National University	15
8	University of Iowa	15
9	University of Maryland	15
10	Florida State University	14

RQ3. How are the Citation Structures and Intellectual Foundations of Argumentation Studies in Science Education Shaped?

Figure 5 presents the most frequently cited studies in science education argumentation research. The results indicate that Zohar and Nemet (2002) is the most cited study, with over 700 citations, followed by Erduran et al. (2004) and Duschl (2008). Other highly cited works include those by Sandoval (2005), Sandoval and Reiser (2004), Sadler et al. (2007), and Sadler (2009). Most of the studies shown in Figure 5 were published between 2002 and 2009 and represent foundational contributions that shaped the early development of the field.

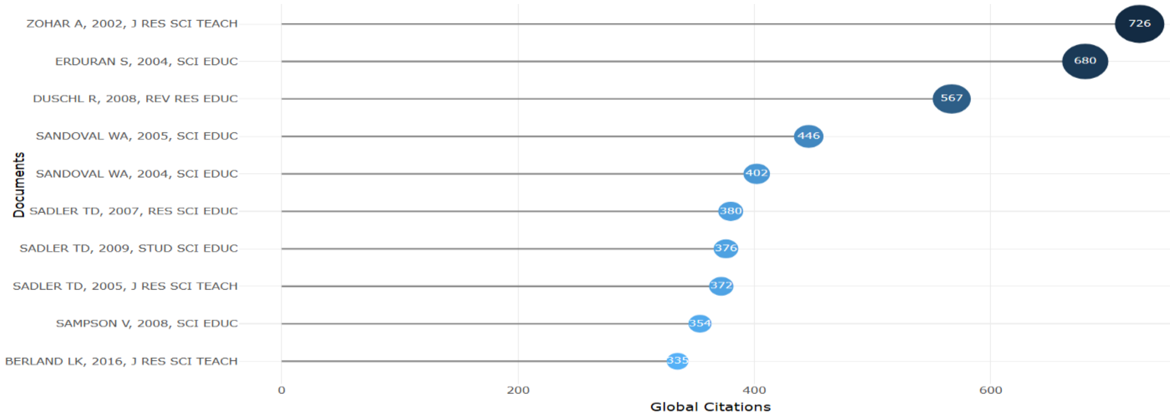

Figure 5. Most cited studies in argumentation research

The reference co-citation network for argumentation research in science education is shown in Figure 6.

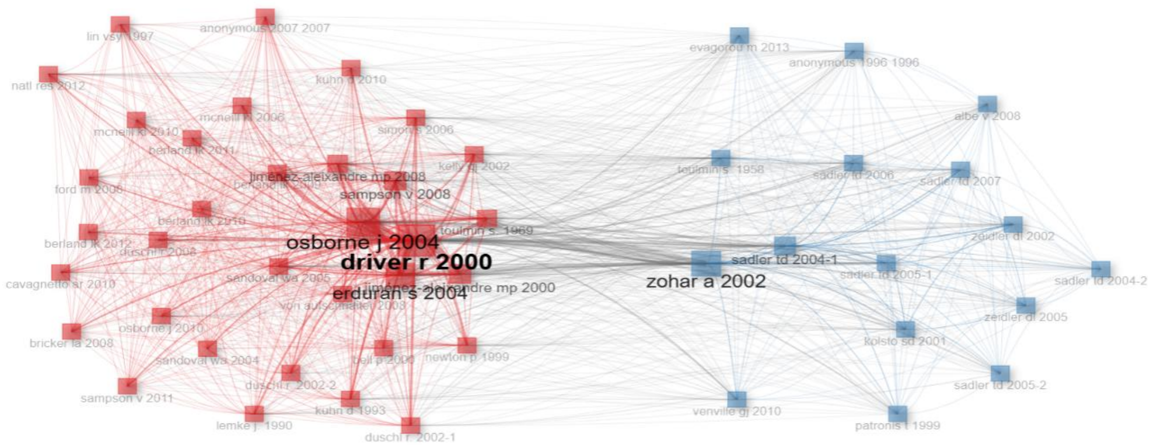

Figure 6. Co-citation network for argumentation studies in science education

The structural analysis of the co-citation network in Figure 6 reveals clear patterns in node size, link thickness, and inter-node distance. The network structure is organized around two distinct clusters. In Cluster 1, studies by Driver et al. (2000), Erduran et al. (2004), Osborne et al. (2004), and Sampson and Clark (2008) occupy central positions, characterized by large node sizes and dense interconnections. The gradual reduction in link thickness from central to peripheral nodes indicates a core–periphery structure within the network.

Cluster 2, positioned on the right side of the figure, includes studies such as Zohar and Nemet (2002), Sadler (2004), Sadler and Zeidler (2005), and Toulmin (1958). Within this cluster, Zohar and Nemet (2002) emerges as a focal node, as reflected by its node size and multidirectional connections. The distinctiveness of the distance between the clusters reveals that the two clusters in the network are spatially separated. The fact that Driver et al. (2000) establishes connections with both clusters indicates that this study is one of the bridge nodes connecting the clusters. Toulmin (1958), positioned in Cluster 2, serves as a fundamental theoretical reference, related to studies in different areas of the network. Within this distribution, the figure shows that argumentation studies are grouped under two main clusters: studies focusing on cognitive-epistemic processes and studies addressing socioscientific issues and discourse-based approaches. However, connections between these clusters are observed through some fundamental sources.

The three-field plot shown in Figure 7 illustrates the intellectual structure of science education argumentation research by depicting relationships among cited sources, authors, and keywords. Generated using Keywords Plus data, the visualization reflects conceptual consistency and clarity, with box sizes representing frequency and flow thickness indicating relational strength. In the cited sources column, Jiménez-Aleixandre and Erduran (2008) and Osborne et al. (2004) appear as dominant references. Classical works such as Toulmin (1958) and Kuhn (1993) are represented with lower frequencies but maintain multiple connections across authors and conceptual domains.

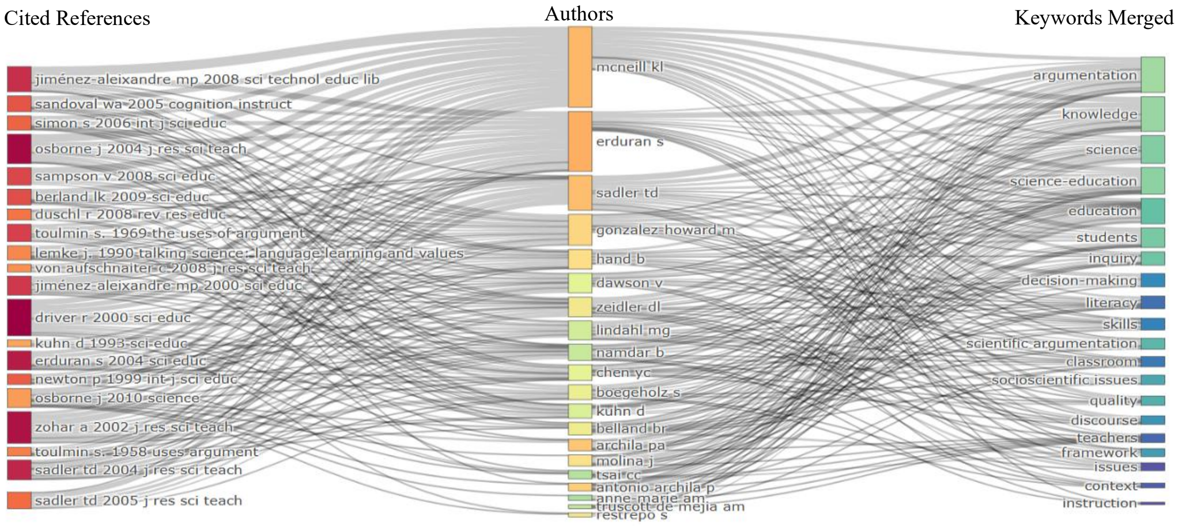

Figure 7. Reference–author–keyword relationships in argumentation studies

In the authors' field in Figure 7, McNeill occupies a central position with the highest frequency and largest box size; Erduran, Sadler, and Zeidler stand out with their multifaceted connections. In the keywords field, *argumentation*, *knowledge*, *science*, and *science education* emerge as the most prominent conceptual focal points. Examination of author–concept flows shows that McNeill and Erduran are strongly associated with *argumentation* and *knowledge*, whereas Sadler and Zeidler show stronger connections with *decision-making* and *socioscientific issues*. Authors such as Jiménez-Aleixandre, Osborne, and Sampson appear in both the cited sources and authors' fields, reflecting their role in connecting classical foundations with contemporary conceptual developments.

RQ4. What are the Dominant Thematic Orientations, Thematic Transformations, and Research Trends in Science Education Argumentation Studies?

Within the scope of this research question, the conceptual structure of science education argumentation studies (Figure 8), their thematic positioning within the field (Figure 9), and the transformation patterns related to the temporal visibility of themes (Figure 10) are examined through bibliometric indicators that complement one another while representing distinct analytical dimensions.

The co-occurrence network of keywords presented in Figure 8 visualizes the conceptual structure and thematic relationships of argumentation studies in science education. An examination of the network reveals that the keywords cluster around four main clusters with different densities and connection patterns. At the center of the network, the *argumentation* and *science education* nodes occupy a prominent position in terms of node size and multiple connection lines. The distinct thickness of the connection between these two nodes indicates that these concepts are used together with a high frequency of co-occurrence in the dataset. In the central cluster positioned around the *argumentation* node, concepts such as *discourse*, *dialogue*, *evidence*, *epistemic practice*, *methods*, and *modeling* are represented by their proximity to the center and dense interconnections. In contrast, concepts such as *translanguaging*, *elementary science education*, *earth science education*, and *Toulmin* are located within the same cluster but in more peripheral areas of the network and are associated with weaker connections.

In other sections of the network shown in Figure 8, thematic clusters diverge around distinct focal points. In the cluster centered around the *science education* node, concepts related to teaching and learning – such as *collaboration*, *inquiry*, *learning*, *teachers*, *professional development*, *critical thinking*, *argumentative practices*, and *middle school* – are positioned together. In another cluster focused on *socioscientific issues*, concepts such as *decision-making*, *reasoning*, *scientific literacy*, *epistemology*, *nature of science*, and *curriculum* converge with relatively strong internal connections, while elements such as *climate change* and *preservice teachers* are incorporated into this structure with comparatively weaker links. Concepts such as *pedagogy* and *teaching*, located in more peripheral and sparsely connected areas of the network, are represented by lower-intensity connections in a separate cluster. These concepts are linked to the dominant clusters through thinner relational ties.

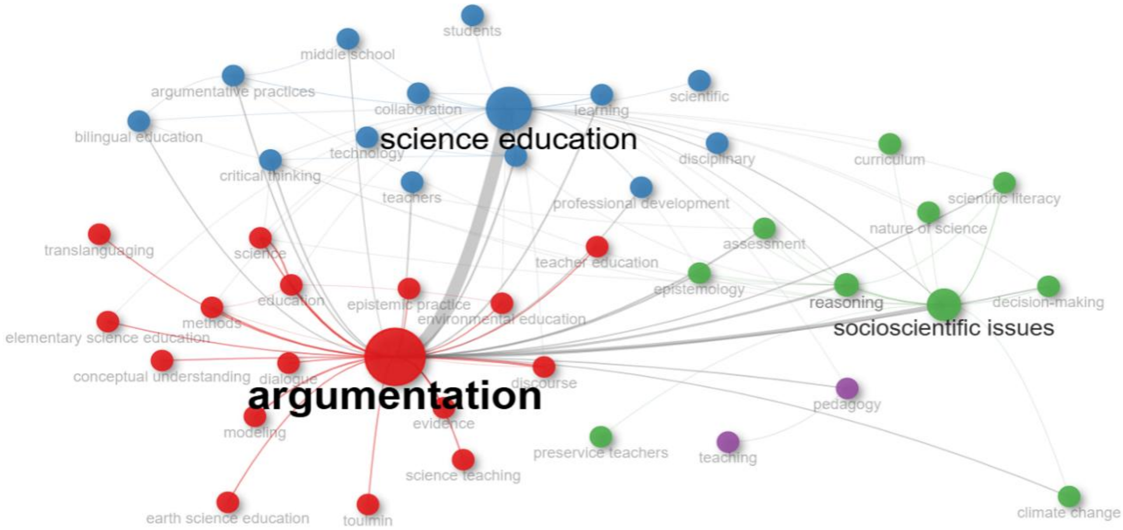

Figure 8. Keyword co-occurrence network for argumentation studies

The thematic map classifying the conceptual structure of argumentation studies in science education into four quadrants based on centrality and density criteria is presented in Figure 9. The results are presented according to their positions based on centrality and density (basic, motor, niche, and emerging/declining), rather than according to the numerical ordering of clusters. The analysis reveals that the field is structured around five principal thematic clusters. These themes are positioned as motor and basic themes representing the epistemic and theoretical backbone of the field, emerging or developing themes indicating the direction of thematic evolution, and niche themes reflecting specialized and application-oriented foci.

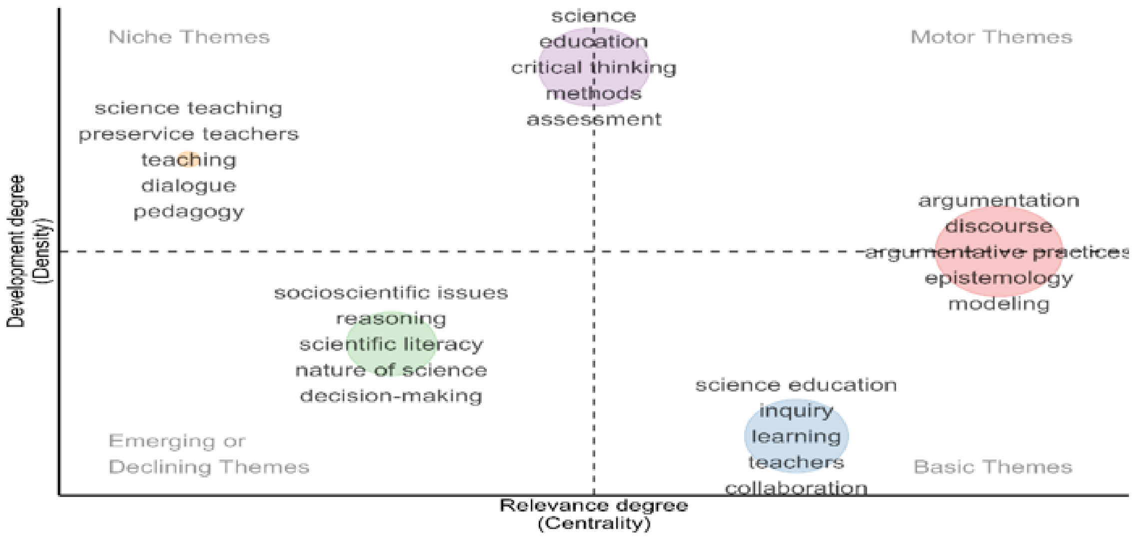

Figure 9. Thematic map of argumentation studies

Two dominant clusters emerge in the basic and motor themes region (lower right quadrant and upper right–middle transition). Cluster 1 consists of the concepts of *argumentation*, *discourse*, *argumentative practices*, *epistemology*, and *modeling* and occupies a position corresponding to the theoretical-epistemic core of the field. Cluster 2 encompasses the concepts of *science education*, *inquiry*, *learning*, *teachers*, and *collaboration* and exhibits a structure highly integrated with the broader literature. Cluster 4 (science, education, critical thinking, methods, and assessment), positioned in a transition zone between motor and niche themes, represents a methodological axis within the thematic map. Focusing on specialized applications, Cluster 5 (science teaching, preservice teachers, teaching, dialogue, and pedagogy) is located in the niche themes region and reflects a sub-area where classroom-oriented practices and pedagogical concerns are concentrated. Cluster 3, which includes *socioscientific* *issues*, *reasoning*, *scientific literacy*, *nature of science*, and *decision-making*, is positioned in the emerging themes region and indicates growing thematic orientations in terms of both centrality and density.

Figure 10 reflects the temporal distribution of themes in the argumentation literature in science education, their frequency of use, and changes in research trends. In the visualization, the size of the circles represents the total frequency of each theme across the entire study period, while their position on the horizontal axis represents the median year in which this usage was most concentrated. The horizontal lines indicate the temporal span between the year (Q_1) when cumulative usage first reached 25% and the year (Q_3) when it reached 75%. The circular markers denote the median year (Q_2), corresponding to the point at which 50% of cumulative usage was achieved.

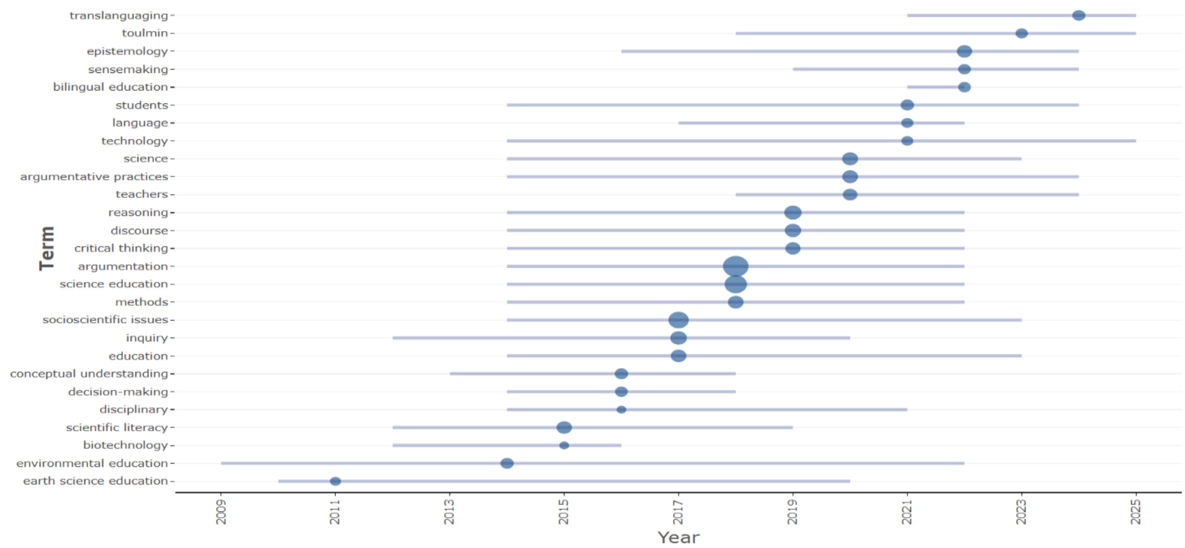

Figure 10. Research topics that have emerged over time in argumentation studies

Within the scope of the analysis, conducted using a minimum word frequency threshold of 5 and a word count of 3 per year, a total of 27 topics are visualized in Figure 10. Examination of the overall distribution shows that the topics with the highest total usage frequencies—*argumentation*, *science education*, *socioscientific issues*, *reasoning*, and *questioning*—are represented by larger circles and relatively balanced temporal distributions. In addition, the topics of *environmental education*, *technology*, *argumentative practices*, *students*, and *earth science education* exhibit the widest interquartile ranges (Q_3 - Q_1), indicating extended visibility across the literature.

With respect to the early period (2015 and earlier), the starting points (Q_1) of topics such as *environmental education*, *earth science education*, *scientific literacy*, *biotechnology*, and *inquiry* appear earlier than those of other topics. Among these, *inquiry* stands out as the topic with the highest usage frequency. Moreover, although *earth science education* and *environmental education* show early onsets, their relatively late third-quartile values (Q_3) indicate sustained prominence over an extended period. Notably, *earth science education* displays the most pronounced temporal asymmetry ($Q_3 - Q_2 > Q_2 - Q_1$), indicating a right-skewed distribution.

During the medium-term period (2015–2020), thematic diversity is represented by a relatively dense clustering of topics. The topics of *argumentation*, *science education*, *methods*, and *decision-making* exhibit symmetrical temporal distributions ($Q_3 - Q_2 = Q_2 - Q_1$). Although *decision-making* appears with a lower overall frequency, the remaining topics demonstrate both high frequency and temporal balance. During the same period, *socioscientific issues*, *reasoning*, *discourse*, *argumentative practices*, and *teachers* also show broad temporal spans and notable visibility.

In the most recent period (2020 and beyond), the median years (Q_2) of *translanguaging*, *Toulmin*, *epistemology*, *sensemaking*, and *bilingual science education* shift toward the later years of the timeline. Among these, the third-quartile values (Q_3) of *translanguaging*, *Toulmin*, and *technology* extend to the final year of analysis. The temporal distribution of *epistemology* indicates a relatively late onset and a left-skewed ($Q_3 - Q_2 < Q_2 - Q_1$) pattern. In particular, while the temporal visibility of *bilingual science education* concludes in 2022, *translanguaging* emerges in 2021 and continues through the end of the study period, highlighting its increasing relevance in recent research.

Discussion

This bibliometric study presents a comprehensive perspective on the development of argumentation research in science education over the last quarter century, highlighting its global trends and the thematic transformations it has undergone.

Temporal Development and Scientific Production Trends of Argumentation Studies in Science Education

The temporal distribution of argumentation studies in science education indicates that the field exhibits a dynamic structure that develops in distinct, though non-linear, phases. As shown in Figure 3, the number of publications gained significant momentum, particularly after 2010, reaching its highest value within the examined period in 2025. This quantitative increase is consistent with the logistic growth model estimates and the cumulative growth curve (Figure 2) and can be interpreted as an indication that the field is approaching maturity. Indeed, the high level of fit demonstrated by the model with empirical data ($R^2 = 0.776$) confirms that the identified growth trend reflects a statistically significant life-cycle pattern. This temporal pattern suggests that the field has followed a trajectory consistent with bibliometric life-cycle models. In this respect, the limited publication output between 2001 and 2010 corresponds to a theoretical formation phase, whereas the sharp rise observed during the 2011–2020 period reflects a phase of rapid expansion. The high and relatively stable trajectory after 2020 indicates that the field may be entering its maturation stage. Overall, the acceleration observed after 2010 suggests that argumentation has become one of the central research agendas within science education.

This marked increase appears to be driven by multiple interrelated factors. International large-scale student assessment programs (particularly PISA; OECD, 2006) and science curriculum reforms – such as the Next Generation Science Standards (NGSS; NGSS Lead States, 2013) – have explicitly emphasized scientific reasoning and argumentation, thereby increasing the institutional demand for related research. In addition, the adaptation of Toulmin's (1958) foundational theoretical framework to science education contexts (Driver et al., 2000; Osborne et al., 2004), together with the expansion of open-access publishing, has contributed to the acceleration of scientific output. The high publication volume observed in recent years suggests that scholarly activity in the field remains sustained and that research has begun to demonstrate qualitative diversification beyond mere quantitative growth. This pattern is consistent with contemporary perspectives in the literature, which increasingly conceptualize argumentation not only as a skill to be examined, but also as a core pedagogical approach shaping science teaching and learning processes (Osborne et al., 2019).

Leading Journals, Authors, Countries, and Institutions in Science Education Argumentation Research

The publication and impact patterns of argumentation studies in science education reveal that the field is concentrated around specific journals, leading authors, influential countries, and prominent institutions. This structure suggests that the literature has evolved through sustained research traditions and institutional collaborations rather than isolated individual efforts. At the same time, this structure remains dynamic, as the network continues to expand with the participation of new research communities from diverse geographical contexts.

An examination of journal distribution indicates that outlets such as *International Journal of Science Education, Science & Education,* and *Science Education* function as core publication platforms within the field (Table 2). With their long-standing traditions in science education research, these journals continue to provide central venues for scholarly discussions on foundational topics such as argumentation. At the same time, the notable presence of publications in journals such as *Research in Science & Technological Education*, *International Journal of Science and Mathematics Education*, and *Journal of Science Education and Technology* suggests that argumentation research has increasingly extended toward STEM integration, technology-enhanced learning, and interdisciplinary pedagogical contexts. This diversification indicates that argumentation has evolved into a broader research domain encompassing not only the core dimensions of science education but also contexts related to linguistic diversity and inclusive education (Lee, 2005).

In terms of author productivity, the sustained contributions of researchers such as Archila, Erduran, and McNeill have played a key role in shaping the development of the field (Table 3). In particular, the studies of Erduran and Simon (2004) and McNeill and Krajcik (2008) have become foundational references for understanding classroom-based argumentation and its assessment. Archila's publication profile, in turn, reflects the growing emphasis on linking argumentation with sociological dimensions and citizenship education. Moreover, the work of scholars such as Sadler, Gonzalez-Howard, Hand, Molina, and Zeidler indicates that the field is not confined to a single core group, but rather continues to expand through diverse theoretical perspectives and research questions. This pattern suggests that argumentation research in science education is characterized by a vibrant and evolving academic structure shaped by center–periphery interactions.

The country-based distribution of publications highlights the dominant role of the USA in terms of research output (Table 4; Figure 4). This prominence can be attributed to the country's well-established research infrastructure in science education and its early engagement with systematic argumentation research. However, the strong representation of China and Turkey indicates that argumentation has emerged as a globally relevant research focus. The fact that Turkey ranks third worldwide with 33 publications (7.0%) is particularly noteworthy. This trend may be associated with revisions to the Turkish science curriculum in 2013 and 2018, which explicitly emphasized competencies related to argumentation—such as evidence-based explanation, discussion, and reasoning—alongside scientific process skills (MEB, 2013, 2018). The relatively balanced contribution of European countries further suggests that argumentation constitutes a shared research agenda across different educational contexts.

At the institutional level, the prominence of the University of Los Andes, Boston College, and several Taiwanese universities (Table 5) indicates that argumentation research tends to be concentrated in institutions with strong graduate programs and established research groups. The inclusion of institutions such as Recep Tayyip Erdoğan University alongside the University of Oxford underscores the presence of influential academic hubs at both global and local levels. Overall, institutional visibility suggests that research productivity in this field is shaped not only by individual scholarly efforts but also by institutional support structures and sustained research networks.

Citation Structures and Intellectual Foundations of Argumentation Studies in Science Education

The citation analyses conducted in this study indicate that argumentation research in science education is characterized by a strong degree of theoretical continuity and is structured around a relatively limited set of highly influential references. The development of the field appears to have been guided by a foundational body of early, high-impact studies that provided a shared intellectual framework for subsequent research. This pattern suggests that the literature has evolved through cumulative articulation around common references rather than through fragmented or random knowledge accumulation.

As shown in Figure 5, studies such as Zohar and Nemet (2002), Erduran et al. (2004), and Duschl (2008) have received particularly high citation counts. These works have played a central role in establishing the theoretical, pedagogical, and discursive dimensions of argumentation in science education. Their sustained citation impact indicates that they continue to function as key reference points in contemporary research rather than serving solely as historical foundations. Similarly, the prominence of studies by Sandoval and Reiser (2004) and Sadler (2004) reflects the early emergence of research linking argumentation to epistemological inquiry and socioscientific contexts.

The reference co-citation network analysis (Figure 6) makes the relational structure between studies forming the theoretical core of argumentation research in science education more visible. Studies such as Driver et al. (2000), Erduran et al. (2004), and Osborne et al. (2004), which occupy a central position in Cluster 1 of the network, are concentrated around core references representing the fundamental orientations of argumentation research in the field based on cognitive and epistemic processes. This core reflects a distinct line of research focusing particularly on the nature of arguments, forms of justification, and students' scientific reasoning processes. In contrast, sources such as Zohar and Nemet (2002), Sadler (2004), Sadler and Zeidler (2005), and Toulmin (1958), which are prominent in Cluster 2 of the network, point to a different research orientation organized around sociological issues, decision-making processes, and discourse-based approaches. The spatial separation between the clusters suggests that these two main trends form relatively independent sub-lines in the literature. However, the connections established by Driver et al. (2000) bridging both clusters and Toulmin's (1958) fundamental position within Cluster 2 through multiple relationships reflect the existence of common theoretical ground and conceptual continuity underlying this apparent divergence. This situation demonstrates that, despite thematic diversification, the field exhibits a tendency toward relational coherence through shared references.

The three-field plot presented in Figure 7 offers a holistic perspective on the intellectual structure of argumentation research in science education, illustrating the relational flows between theoretical roots, the researchers who engage with these roots, and the conceptual foci that emerge from them. The high frequency with which studies such as Jiménez-Aleixandre and Erduran (2008) and Osborne et al. (2004) appear in the cited sources area of the diagram suggests that the current intellectual dynamism of the field is concentrated in research focused on the restructuring of the theoretical heritage in pedagogical and methodological contexts. In contrast, classic references such as Toulmin (1958) and Kuhn (1993), although with more limited absolute frequencies, continue to nourish the field's enduring epistemic ground through their multiple connections extending to different authors and concept clusters.

The relational patterns observed in the fields of authors and keywords reveal how this theoretical groundwork has been addressed in the literature through a specific focus. The strong connections established by McNeill and Erduran with the concepts of *argumentation* and *knowledge* represent the field's line of research focused on cognitive and epistemic processes, while the relationships established by Sadler and Zeidler with *socioscientific issues* and the concept of *decision-making* point to a different orientation that centers on the contextual and social dimensions of argumentation. The fact that authors such as Erduran, Sadler, and Kuhn are represented both as referenced sources and as authors, and that they occupy an important mediating position in the flow from classical references to contemporary concepts, demonstrates the establishment of a relational continuity between theoretical heritage and application-oriented research. This situation suggests that these authors, occupying both reference and producer positions in the three-field plot, serve as a bridge in transferring theoretical frameworks to current pedagogical and methodological developments. When considered alongside the citation patterns in Figures 5 and 6, this structure indicates that argumentation studies in science education have developed within an intellectual order that varies across thematic emphases yet progresses through shared theoretical foundations. Taken together, these findings address the third research question by revealing a stable yet evolving intellectual structure shaped by enduring theoretical traditions and expanding methodological orientations.

Dominant Thematic Orientations, Thematic Transformations, and Research Trends in Science Education Argumentation Studies

The results of the thematic analysis reveal that argumentation in science education is not a one-dimensional field of research, but rather a multi-layered and dynamic domain in which pedagogical, epistemic, and contextual dimensions are intertwined. This structure has expanded and deepened cumulatively over time, gaining complexity through successive layers. Indeed, argumentation research has shifted from early approaches focused primarily on cognitive processes to a more holistic orientation in which knowledge is constructed through social interaction and contextualized practices. This transformation reflects the increasing visibility of argumentation in science education as a practice that encompasses not only individual reasoning skills but also the social and dialogical construction of scientific knowledge.

The co-occurrence network of keywords presented in Figure 8 illustrates the conceptual structure of the field and the strength of relationships among key terms. The high co-occurrence density between *argumentation* and *science education* at the center of the network suggests that these concepts are not treated independently in the literature; rather, *argumentation* is positioned as a foundational component of *science education*. Concepts such as *discourse*, *dialogue*, *evidence*, and *epistemic practice*, which are concentrated in the central cluster, indicate that the field's focus has shifted from merely producing correct answers to the epistemic processes of how scientific knowledge is produced and justified. This conceptual orientation aligns with the perspective of Driver et al. (2000), who frame science learning within the social construction of scientific knowledge and its epistemic underpinnings.

The relationships established between the central core and concepts such as *socioscientific issues*, *reasoning*, *decision-making*, and *scientific literacy*, which emerge prominently in other thematic wings of the network, reflect how *argumentation* has expanded beyond its cognitive boundaries to encompass ethical, social, and citizenship-focused dimensions. This expansion is consistent with contemporary approaches that emphasize the consideration of *argumentation* in the context of socioscientific debates (e.g., Sadler, 2004; Sadler & Zeidler, 2005). In particular, the connections established between the set of socioscientific topics and epistemic concepts suggest that *argumentation* functions as a fundamental reasoning tool in making sense of current social issues. Similarly, the co-location of teaching-focused concepts such as *teachers*, *professional development*, *inquiry*, and *collaboration* indicates that the theoretical discussions in the literature are progressing towards integrating classroom practices and pedagogical transformation. This situation can be interpreted as argumentation research moving beyond being a niche pedagogical field to becoming one of the mainstream components of science education.

In contrast, the relatively low connectivity of concepts such as *translanguaging*, *climate change*, and *earth science education*, which are located in more peripheral areas of the network, indicates that these themes have not yet taken on a framing role in the argumentation literature. Similarly, the fact that the concepts of *pedagogy* and *teaching* establish more limited relationships with central clusters provides data suggesting that there is still room for development between theoretical argumentation studies and the general pedagogical literature. This view reflects that the intellectual depth of the field tends to concentrate around a specific conceptual core; however, its spread in interdisciplinary contexts and specific content areas shows signs of relative maturation. This situation can be interpreted as meaning that, while the field has a strong theoretical foundation, it has potential for development in terms of application and contextual expansion, and that the central role of critical discourse in this process remains important (Osborne, 2010).

The thematic map analysis presented in Figure 9 illustrates the strategic positions and maturity levels of the themes in the field. The positioning of the *argumentation* theme (Cluster 1) in a transitional zone between fundamental and motor themes indicates that this line of research has matured and is guiding the field. This supports the view that *argumentation* has become an established epistemic practice in science education research that guides the production, justification, and verification of knowledge, rather than merely serving as a teaching method. This positioning indicates that the view that argumentation plays a central role in the social construction of scientific knowledge (Driver et al., 2000) has become a prominent framework in the field. The inclusion of *science education*, *inquiry*, teacher-focused studies, and collaborative learning approaches within Cluster 2 reflects the field's strong pedagogical grounding. Its location among the basic themes highlights the potential for deeper integration between inquiry-based, teacher-centered approaches and argumentation research.

The positioning of Cluster 4 in a transitional space between motor and niche themes suggests that methodological and assessment-oriented studies have developed with consistent but relatively limited centrality in argumentation research. This finding aligns with prior observations that the development of robust tools for classroom-based assessment of argumentation remains an ongoing research need (Osborne et al., 2004). Cluster 5, situated in the niche themes quadrant, focuses on pre-service teacher education, pedagogical dialogue, and classroom practices, indicating that teacher education constitutes a specialized and context-sensitive area of expertise. This interpretation is consistent with studies emphasizing the importance of instructional support and professional preparation for teaching argumentation effectively (McNeill & Krajcik, 2008). Finally, the structure of Cluster 3, located in the emerging or declining themes area and centered on *socioscientific issues*, *reasoning*, *nature of science*, and *decision-making*, suggests that this thematic line is still in a developmental phase. This finding is consistent with approaches highlighted by researchers such as Sadler (2004) and Zeidler (2014) in the context of socioscientific issues, which position *argumentation* as a central component of social and ethical reasoning. Similarly, recent bibliometric results also confirm that socioscientific issues are emerging as a developing and strategically important theme in argumentation research (Noris et al., 2024).

The trend topics analysis shown in Figure 10 reveals the temporal development of argumentation research in science education and its patterns of thematic transformation. This analysis enables a combined interpretation of the conceptual continuity illustrated in Figure 8 and the historical maturation of thematic positions identified in Figure 9. In doing so, it not only identifies the themes structuring the field but also highlights the periods and intensities during which these themes gained prominence, thereby complementing the preceding analyses.

In particular, the symmetrical temporal distribution exhibited by themes with high frequency of use shows that topics such as *argumentation*, *science education*, and *methods*, which occupy a central position in Figure 8, have consistently maintained their foundational roles in the field over time. This view indicates that these concepts function as fundamental research axes that are continuous in the literature rather than being temporary areas of interest specific to certain periods (Osborne et al., 2004, Tosun, 2024).

The low first-quartile values observed for themes such as *environmental education*, *earth science education*, and *biotechnology*, more visible in the early period, suggest that these areas function as "heritage themes" that emerged during the formative phase of the field and laid the groundwork for later research. In this study, the term "heritage themes" refers to topics that were relatively prominent during the early developmental phase of the field and helped establish foundational research directions, even if their later visibility declined or diversified. In particular, the right-skewed temporal distribution of the earth science education theme indicates that this discipline-specific focus played a significant role in the early acceleration of the field but gradually yielded to more interdisciplinary and pedagogically oriented approaches. In contrast, the early emergence and sustained high frequency of use of the inquiry theme indicates that a framework focusing on the epistemic dimension of learning processes and scientific discourse practices remained dominant in the early stages of argumentation research (Duschl & Osborne, 2002).

The thematic diversification observed between 2015 and 2020 reveals that while the theoretical core of the field has been preserved, there has been a significant expansion in pedagogical and social dimensions. During this period, the high frequency and broad temporal distribution of *socioscientific issues*, *reasoning*, and *discourse* topics indicate that argumentation began to be approached as a social, ethical, and citizenship-based reasoning tool (Sadler, 2004). This trend is also mirrored in the placement of these themes within emerging and transitional clusters in Figure 9.

A particularly notable thematic transformation concerns the temporal restructuring of language-focused research. Although the *bilingual science education* theme exhibits a relatively limited temporal span up to 2022, the continued visibility of the *translanguaging* theme through the end of the analysis period suggests more than a terminological shift. Rather, it points to the growing influence of theoretical orientations that conceptualize language as a dynamic, contextual, and meaning-making resource in learning processes (Garcia & Wei, 2014). This transformation parallels the maturation of language-related themes located in emerging clusters in Figure 9 and aligns with recent synthesis studies that frame *argumentation* as an epistemic practice grounded in discourse, interaction, and multimodal representation (Tang, 2024). Similarly, the left-skewed temporal distribution of the *epistemology* topic indicates that, despite its relatively late emergence, it rapidly became a focal point of scholarly attention, underscoring the increasing centrality of epistemic concerns in argumentation research.

It is noteworthy, however, that several fundamental pedagogical concepts with high overall usage frequencies – such as *learning*, *assessment*, *modeling*, *collaboration*, and the *nature of science* – do not appear as distinct trend topics in Figure 10. This outcome is attributable to the methodological logic of trend topics analysis, which emphasizes temporal concentration rather than cumulative frequency. The widespread but temporally dispersed use of these concepts suggests that they function as pedagogical and methodological "fundamental constants" embedded throughout the field, rather than as time-bound focal topics. In this study, the term "fundamental constants" denotes core concepts that maintain a stable presence across all phases of the field's development instead of peaking within a specific period. Their stable cross-temporal presence indicates that they operate as structural anchors within the evolving thematic landscape.

Recent temporal patterns indicate that, with the resurgence of topics such as the Toulmin model, interpretation, and technology, a more holistic relationship is beginning to emerge between theoretical frameworks and application-oriented approaches. The prominence of the Toulmin model in this context indicates that the model is being revisited in line with current research questions and inquiry-based needs, rather than a return to a classical framework (Kelly, 2014). Overall, when the results obtained from Figure 10 are evaluated together with the conceptual and strategic data in Figures 8 and 9, the findings suggest that the argumentation literature in science education is organized around a solid theoretical core and is moving towards a structure that integrates contextual, epistemic, and linguistic dimensions in a more visible way over time. This view presents a framework suggesting that argumentation in science education is beginning to be addressed not only as a pedagogical tool but also within a broader context that integrates the justification of scientific thinking, epistemic processes supported by the history and philosophy of science, and a participatory understanding of science (Archila, 2015; Jiménez-Aleixandre & Erduran, 2008).

Conclusion

The bibliometric analyses conducted in this study indicate that argumentation research in science education has experienced substantial development and has moved toward a relative level of maturation over the last quarter century. The field has not only expanded in terms of quantitative output but has also acquired a multi-layered structure that strengthens its theoretical foundations, broadens its research networks, and diversifies its thematic orientations. By addressing temporal, social, intellectual, and thematic dimensions through an integrated bibliometric approach, this study has revealed the structural and conceptual development of the field from a holistic perspective. Temporal patterns demonstrate that argumentation has assumed a central position in science education research, particularly since the 2010s. This trend suggests that the field has moved beyond being a temporary research focus and is increasingly consolidating into a more stable and enduring research domain, closely linked to curriculum reforms and international assessment frameworks.

Analyses of the social and intellectual structures reveal that research in this field is shaped by strong academic networks and shared theoretical references. Common citation patterns reflect that the field is built on deep theoretical foundations; cognitive, epistemic, and discourse-based approaches have developed within a complementary relational unity. However, the intellectual geography of the field is also seen to be expanding steadily. The prominence of countries such as Turkey and China alongside established research centers such as the United States reflects the global diffusion of interest in argumentation studies. This expansion appears to be associated with epistemic orientations embedded in local curriculum reforms and teacher education programs.

The thematic results provide a more detailed picture of the transformation experienced by the field. Rather than exhibiting a homogeneous pattern of development, argumentation research in science education demonstrates a dynamic structure in which multiple thematic strands evolve simultaneously but at different levels of maturity. Early studies focusing primarily on argument structures and individual cognitive processes have gradually become more integrated with socioscientific contexts, social decision-making processes, and classroom practices. The increasing prominence of application-oriented themes – particularly teacher education and formative assessment – has reinforced the tendency to translate the field's accumulated theoretical knowledge into pedagogical practice. This broader perspective suggests that the literature has moved beyond the question of how arguments are structured, progressing instead toward more dynamic theoretical frameworks. In particular, language-focused studies reveal a terminological and conceptual shift from a *bilingual education* orientation toward a *translanguaging* perspective. At the same time, classical argumentation models, such as Toulmin's framework, are not being displaced but rather re-contextualized and re-functionalized within digital and contemporary pedagogical environments.

Fundamental concepts such as *learning* and *assessment*, although not temporally prominent in thematic maps or represented within niche clusters, continue to function as infrastructural constants across all developmental phases of the field. This persistence can be interpreted as an important indicator of the methodological maturity and theoretical depth achieved in science education argumentation research. In this context, it can be said that the comprehensive keyword standardization and conceptual consolidation approach applied in the study strengthens the analytical consistency and validity of thematic mapping; in this respect, it provides a methodological reference framework for similar bibliometric studies. In conclusion, *argumentation* is positioned in the literature not only as a pedagogical tool in science education but also as a multi-layered and expanding epistemic ground that relates scientific reasoning to language, culture, technology, and democratic citizenship practices.

Recommendations

The bibliometric maps and thematic structure analyses presented in this study highlight current trends, structural gaps, and developmental opportunities in argumentation research in science education, suggesting several directions for future research:

- *Deepening niche areas and theoretical integration should be prioritized*. Thematic maps indicate that areas such as formative assessment, cross-linguistic transfer, teacher professional development, and curriculum integration remain niche or emerging. Future research should place greater emphasis on experimental and design-based studies that explicitly connect these themes to the core theoretical foundations of the field and to classroom practice. Systematically linking these areas to the mainstream research agenda may enhance not only thematic diversity but also theoretical coherence and pedagogical impact. Strengthening their connection with cross-temporal constants such as learning and assessment would further anchor these developments within the field's core structure.
- *Conceptual and methodological expansion should be encouraged*. Argumentation studies remain concentrated around specific theoretical frameworks. Future research may benefit from refunctionalizing classical models such as Toulmin's within contemporary digital learning environments and AI-supported meaning-making processes. Methodologically, integrating bibliometric mapping with longitudinal case studies and discourse analysis aimed at explaining how and why these trends emerge could provide a more explanatory account of the field's developmental dynamics.
- *Global and comparative perspectives should be made more visible in the research agenda*. Bibliometric production networks reveal a marked rise, particularly in countries such as China and Turkey, indicating that argumentation research is increasingly multi-centered. Comparative studies across educational systems and cultural contexts therefore represent a promising direction for future investigation.
- *Greater emphasis should be placed on impact-oriented research*. While the literature demonstrates strong connections between argumentation-based pedagogies and classroom practices, their long-term effects on student outcomes remain underexplored. Future studies should examine sustained impacts on domains such as scientific literacy, critical thinking, and citizenship education, positioning argumentation not only as a pedagogical strategy but also as an epistemic foundation.
- *Methodological transparency and standardization should be strengthened*. Future bibliometric research would benefit from more explicit reporting of data-cleaning procedures, keyword standardization

processes, and threshold selection criteria. Such transparency would contribute to greater comparability across studies and support the cumulative advancement of the field.

Limitations

Several limitations should be considered when interpreting the results of this study. First, the analyses are restricted to publications indexed in the WoS database. Although this choice ensures methodological rigor in terms of citation standards, data consistency, and bibliometric comparability, it necessarily excludes relevant studies indexed in other databases such as Scopus or Google Scholar. Consequently, the results primarily reflect high-impact publications with strong international visibility.

Second, the inclusion of only English-language publications may have limited the representation of studies produced in local languages (e.g., Turkish or Chinese) within the thematic and co-occurrence networks. Nevertheless, this decision facilitated clearer tracing of conceptual interactions and shared epistemic frameworks within the international literature. In addition, the inclusion of publications up to the end of 2025 means that some recent studies may not yet have reached full citation maturity, potentially limiting the interpretive depth of citation-based network analyses.

Finally, by their nature, bibliometric analyses do not aim to capture the qualitative depth of individual studies. The threshold values and algorithmic parameters used to enhance visual clarity and analytical focus may have led to the underrepresentation of concepts that are conceptually important but dispersed over time. Accordingly, the thematic structures identified in this study are not intended to replace in-depth pedagogical or theoretical analyses; rather, they provide a systematic and comparable analytical foundation that can inform future qualitative and mixed-method investigations.

These limitations define the scope of the macro-level perspective offered by bibliometric mapping rather than undermining the validity of the results. Future research that integrates multiple databases, includes multilingual publications, and complements bibliometric analyses with qualitative content analysis would contribute to a more comprehensive and nuanced understanding of argumentation research in science education.

Scientific Ethics Declaration

* The data used in this study were obtained from secondary bibliographic sources provided by WoS and did not involve any human participants or personal data. Therefore, this study does not require ethical committee approval. The principles of scientific research and publication ethics were strictly adhered to at every stage of the analysis process.

Conflict of Interest

* There is no conflict of interest among the authors regarding this study.

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Appendix 1. Consolidated Keyword List and Variant Mapping: 51 Superordinate Concepts; n = 396 Variants

The table below presents the complete mapping of 396 keyword variants consolidated under 51 superordinate conceptual terms. Consolidations were based primarily on lexical proximity and recurrent contextual usage within the dataset. The objective was to reduce terminological fragmentation while preserving thematic coherence in the analytical framework. Superordinate concepts are listed in alphabetical order.

Superordinate Concept	Included Variants
Argumentation	argumentation, scientific argumentation, socioscientific argumentation, socio-scientific argumentation, science argumentation, argument, arguments, argument structure
Argumentative Practices	argumentative practices, argumentation skills, argument skills, evidence-based arguments, argumentative writing, argumentation analysis, argumentation learning, dialectic argumentation, bilingual written scientific argumentation, individual argumentation, group argumentation, classroom argumentation, online argumentation, e-argumentation, engagement in argumentation, difficulties in writing arguments, argument evaluation, argument podcasting, argument generation skills, argument map, argument mapping, argument quality, argumentation activities, argumentation norms, argument-based instruction
Assessment	assessment, formative assessment, educational assessment, classroom assessment, self-assessment
Biotechnology	biotechnology, biotechnology education, biotechnology attitudes
Bilingual Education	bilingual education, bilingual science education, emergent bilinguals, emergent bilingual students, bilingual/bicultural, university bilingual science courses, university bilingual science education
Climate Change	climate change, climate change education
Collaboration	collaboration, collaborative argumentation, collaboration argumentation, collaboration scripts, collaborative, collaborative contexts, collaborative contributor, collaborative learning, collaborative talk, computer-supported collaborative learning, student collaboration, cognitive collaboration
Conceptual Understanding	conceptual understanding, conceptual change, conceptual development, conceptual learning, conceptual analysis
Critical Thinking	critical thinking, critical and analytical thinking, critical questioning, critical evaluation, critical evaluation skills, critique, scientific critical thinking, intellectual humility, perspective taking, higher order thinking, higher-order thinking, high-order learning skills, comparing and contrasting
Curriculum	curriculum, curriculum development, curricular tasks, curriculum enactment, educational design, educative curriculum
Decision-making	decision-making, decision making, decision-making competence, decision
Dialogue	dialogue, dialogism, dialogical argumentation, dialogic teaching, dialogic pedagogy, dialogic instruction, dialogic feeback, dialogic discourse, dialogic, dialogue theory
Disciplinary	disciplinary, disciplinary practices, disciplinary enculturation, discipline background
Discourse	discourse, discourse analysis, classroom discourse, argumentative discourse, argumentative discourse practices, classroom talk, classroom dialog, classroom discussion, classroom interaction, productive talk, interaction analysis, interactional patterns, temporal properties of teacher talk
Earth Science Education	earth science education, geology
Education	education, education for, educational policy, educational practice, educational innovation, educational questions
Elementary Science Education	elementary science education, elementary science, elementary school science, early education, elementary, elementary education
Environmental Education	environmental education, environmental, environments, environmental health, education for sustainable development, ecology, sustainability, sustainable development

Epistemic Practice	epistemic practice, epistemic practices, epistemologies in practice, epistemic discourse, epistemic tools, epistemic agency
Epistemology	epistemology, epistemological beliefs, epistemic beliefs, epistemological development, epistemological stance, epistemic cognition, epistemic criteria, epistemic goals, epistemic goal, epistemic insight, epistemic uncertainty, epistemic vigilance, scientific epistemological, personal epistemology, practical epistemology
Evidence	evidence, evidence use, evidence based, evidence evaluation, scientific evidence
Inquiry	inquiry, scientific inquiry, inquiry-based learning, inquiry learning, inquiry-based education, inquiry-based science, inquiry-based teaching, inquiry-type experiment, argument-based inquiry approach
Language	language, language use, language and literacy of science, language of classroom science, language of science, language of science and classrooms
Learning	learning, learning environment, learning preferences, learning progression, learning study, learning with social media, authentic learning, context-based learning, situated learning, cooperative learning, self-regulated learning, game-based learning, digital learning, mobile learning, flipped learning approach, intentional learning, student-centred learning
Methods	methods, methodology, mixed methods, methodologies, methodology of analysis, (dbr), design-based research, design study, case study, case studies, qualitative research, quantitative research, ethnography, content analysis, lag sequential analysis (lsa), multilevel modeling, linear mixed-effects, exploratory factor analysis (efa)
Middle School	middle school, middle school students, middle
Modeling	modeling, modelling, model, model-based learning, models, scientific modeling, modeling-based learning, modeling-based teaching, modelling-based teaching, scientific models, construct modeling
Nature of Science	nature of science, nature of science (nos), nature of scientific practice, (nos)
NGSS	NGSS, next generation science standards, (ngss)
Pedagogy	pedagogy, pedagogical issues, pedagogical content knowledge, pedagogical content knowledge (pck), technological pedagogical content knowledge, pedagogic reform, pedagogical approaches, pedagogical principles, pedagogical content
Preservice Teachers	preservice teachers, pre-service teachers, preservice science teachers, preservice elementary teachers, initial teacher education, in-service teachers, student teachers
Professional Development	professional development, teacher professional development, professional
Rasch Model	rasch model, rasch measurement, rasch analysis, rasch partial credit model
Reasoning	reasoning, socioscientific reasoning, informal reasoning, scientific reasoning, reasoning skills, evidence-based reasoning, reasoning abilities, reasoning levels, reasoning map, social scientific reasoning, flaws in reasoning, logical connectives, logical connectors, hypotheses, causal inference, induction, heuristics, bias, open-mindedness
Scaffolding	scaffolding, teacher scaffolding, argumentation scaffolding, computer-based scaffolding, hard scaffolding
Science	science, school science, sciences, science and culture, science capital, science identity, science professionals, science studies, science major
Science Education	science education, science learning, science interest, science investigation, science and technology literacy, university science education, reform-based science, community science
Science Practices	science practices, science-as-practice, scientific practices
Science Teaching	science teaching, science instruction, science classrooms, science classroom discourse, science teaching contexts, science teachers, science teachers' beliefs, science teacher education
Scientific	scientific, scientific knowledge, scientific uncertainty, scientific theory
Scientific Literacy	scientific literacy, literacy, science literacy, scientific and technological literacy (stl) teaching

Sensemaking	sensemaking, science sensemaking, meaning making, meaning-making, explanation construction, meaningful learning
Socioscientific Issues	socioscientific issues, socio-scientific issues, socioscientific, socio-scientific issue, socio-scientific, socioscientific issues-based instruction, (ssi), ssi, socioscientific issue (ssi), socioscientific issues (ssi), socioscientific issues (ssis), socio-scientific issues (ssis), local socioscientific issues
Students	students, student, student achievement, student attitudes, student beliefs, student culture, student diversity, student knowledge, student learning, student perceptions, student performance, student standpoint
Teachers	teachers, teacher, teacher beliefs, teacher perceptions, teachers' perceptions, teacher views, teachers' practices, teacher mastery, teacher's role, teachers in Saudi Arabia
Teacher Education	teacher education, teacher training, teacher development, teacher learning
Teaching	teaching, teaching practice, teaching practices, teaching strategies, teaching/learning strategies, teaching-learning sequence, teaching context, teaching materials in science education, teaching/distance education (cc)
Teacher Moves	teacher moves, teacher questions, teacher planning, teacher-student interactions, teacher collaboration
Technology	technology, technology-enhanced learning, technology-enhanced classroom, interactive technology
Toulmin	toulmin, rebuttal argument, toulmin argument pattern, toulmin argumentation pattern (tap), warrants, claims, abductive argument, sound argument, faulty argument, hypothetico-predictive argumentation, argument-critique-argument
Translanguaging	translanguaging, multilingualism, multilingual learners, multilingual students, English as a second language, English-learning, linguistically responsive teaching, content and language integration, academic language