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Review article

Developments in Pediatric Cardiac Intervention and Surgery Research: A Global Bibliometric Analysis (2002-2026)

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Abstract

Advances in pediatric cardiac interventions and surgery have substantially improved the management of congenital and acquired heart diseases in children. However, the global research landscape, including its evolving themes and patterns of scientific collaboration, remains insufficiently characterized. This study aimed to examine global research trends, thematic developments, and collaborative networks in pediatric cardiac interventions and surgery from 2002 to 2026 through bibliometric analysis. Bibliographic records were retrieved from Scopus using a predefined search strategy encompassing pediatric cardiology, pediatric cardiac interventions, pediatric cardiac surgery, and congenital heart disease. Bibliometric analyses were conducted using Bibliometrix and VOSviewer to assess publication trends, citation patterns, leading authors, institutions, countries, journals, international collaborations, and keyword co-occurrence networks. A total of 1,326 publications from 390 sources were identified, involving 6,372 authors, with an average of 21.22 citations and 6.72 authors per document. Annual publication output increased markedly after 2012, reaching its highest level around 2025. Keyword co-occurrence analysis identified congenital heart disease as the central research theme, with strong connections to cardiac surgery, cardiac catheterization, cardiopulmonary bypass, postoperative care, and acute kidney injury. The United States accounted for the largest share of publications (449; 33.86%), whereas the United Kingdom and Canada exhibited higher proportions of international collaboration. Boston Children's Hospital emerged as the most productive institution, while Pediatric Critical Care Medicine was identified as a leading publication outlet. Overall, the findings reveal an evolving research landscape in which procedural interventions are closely interconnected with perioperative management and postoperative complications. Differences in national research productivity and international collaboration patterns highlight opportunities to strengthen cross-border research partnerships and promote more integrated investigations across the continuum of pediatric cardiac care.

Keywords: Bibliometric analysis, congenital heart disease, pediatric cardiac intervention, pediatric cardiac surgery

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Introduction

Congenital heart disease (CHD) is the most common congenital anomaly in children and is one of the leading causes of morbidity and mortality in the pediatric population worldwide [1–4]. Rapid advances in pediatric cardiac intervention and surgery have significantly contributed to improved survival rates and quality of life for patients. These advances have been driven by innovations in diagnostic technology, catheter-based interventional techniques, cardiac surgical procedures, and increasingly comprehensive and integrated perioperative and postoperative care [5,6].

Since the beginning of the 21st century, the fields of pediatric cardiology and cardiac surgery have undergone major transformations, particularly with the increasing use of minimally invasive procedures and transcatheter

interventions [7–9]. Procedures such as device-based septal defect closure, balloon valvuloplasty, stent placement, and hybrid approaches have become alternatives or complementary options to open-heart surgery in certain cases [10,11]. On the other hand, advances in neonatal and infant surgical techniques, cardiopulmonary bypass technology, and postoperative intensive care have enabled the management of complex heart defects with increasingly high success rates [12]. These developments have led to a significant increase in the number of scientific publications discussing clinical, technological, and innovative aspects of pediatric cardiology.

Previous bibliometric studies have examined the broader research landscape of congenital heart disease from several perspectives. Farhat et al. (2013) compared congenital heart disease research between developing and developed countries, while subsequent analyses identified influential publications, patterns of scientific production, citation impact, international collaboration, and major research themes [13,14] . More recently, bibliometric research by Zhou et al (2025) has addressed specific areas, including cardiac rehabilitation in patients with congenital heart disease [15]. These studies have contributed to understanding the development and distribution of scientific activity in this field. However, their differing scopes indicate the importance of examining research specifically related to pediatric cardiac intervention and surgery, where procedural approaches, perioperative management, postoperative complications, and clinical outcomes represent interconnected dimensions of care.

Despite these contributions, a focused assessment of the global research landscape in pediatric cardiac intervention and surgery remains important to clarify how scientific output, research influence, international collaboration, and thematic relationships are distributed within this particular field. An integrated assessment of these dimensions can help distinguish the most established research themes from areas that may warrant further investigation. Such mapping is particularly relevant for understanding whether research activity is concentrated in a limited number of countries and institutions and how procedural research relates to broader aspects of pediatric cardiovascular care. Therefore, this study aimed to map global research on pediatric cardiac intervention and surgery from 2002 to 2026 using bibliometric analysis of publications indexed in Scopus. Specifically, it examined publication and citation trends, contributions from authors, institutions, countries, and journals, patterns of international collaboration, and keyword co-occurrence. By integrating these dimensions, the study provides an overview of the thematic structure and collaborative landscape of the field, offering a basis for identifying research priorities and opportunities for broader international engagement.

Materials and Methods

Materials

Data source

The primary data source for this study was the Scopus database (Elsevier), which provides comprehensive bibliographic records and citation information across a wide range of scientific disciplines. The dataset consisted of publications related to pediatric cardiology, pediatric cardiac interventions, pediatric cardiac surgery, and congenital heart disease published between 2002 and 2026. Bibliographic information retrieved from Scopus included publication titles, author names, institutional affiliations, abstracts, author keywords, publication years, source titles, document types, citation counts, and other relevant metadata. The retrieved records were exported in BibTeX and CSV formats for subsequent bibliometric analysis.

Bibliometric analysis tools

Bibliometric data were processed and analyzed using the Bibliometrix package in R software (version 4.5.2). VOSviewer (version 1.6.2.1) was employed to construct and visualize bibliometric networks, including keyword co-occurrence patterns, research clusters, and scientific collaboration networks.

Methods

Study design

This study employs bibliometric analysis, a quantitative approach used to evaluate the development of scientific publications, research productivity, citation patterns, scientific collaboration, and trends in research topics in the field of pediatric cardiac intervention and surgery during the period 2002–2026 [16,17].

Search strategy and data retrieval

A systematic bibliographic search was performed in the Scopus database using the TITLE-ABS-KEY field, which searches publication titles, abstracts, and keywords. The search strategy combined terms related to pediatric cardiology, pediatric cardiac interventions, pediatric cardiac surgery, and congenital heart disease using Boolean operators. The following search query was applied: TITLE-ABS-KEY("pediatric cardiology" OR "pediatric cardiac intervention" OR "pediatric cardiac surgery" OR "congenital heart disease") AND PUBYEAR > 2001 AND

PUBYEAR < 2027 AND LIMIT-TO(LANGUAGE, "English"). The search was conducted on February 7, 2026. All records meeting the search criteria were retrieved and exported in BibTeX and CSV formats for further processing and analysis.

Eligibility criteria and data screening

Publications were eligible for inclusion if they were indexed in Scopus, published in English between 2002 and 2026, and addressed at least one of the following topics: pediatric cardiac interventions, pediatric cardiac surgery, pediatric cardiology, or congenital heart disease. To provide a comprehensive overview of the research landscape, no restrictions were imposed on document type. Accordingly, research articles, review articles, conference papers, book chapters, books, editorials, letters, notes, and other Scopus-indexed document types were eligible for inclusion. Bibliographic records were screened for duplicate entries during data processing. Duplicate records, where identified, were removed before the bibliometric analysis.

Bibliometric indicators and citation analysis

Descriptive bibliometric analysis was performed using Bibliometrix to characterize research productivity and scientific impact. The indicators examined included annual publication output, publication growth rates, average citations per document, authorship characteristics, and the productivity of authors, journals, institutions, and countries. Citation analysis was conducted to assess the scholarly influence of publications and research contributors based on citation-related indicators. The analysis also examined the distribution of research output across countries and institutions to identify major contributors to pediatric cardiac intervention and surgery research.

International collaboration analysis

International research collaboration was assessed using country-level publication indicators generated through Bibliometrix. Single Country Publications (SCP) represented publications involving authors affiliated with institutions within a single country, whereas Multiple Country Publications (MCP) represented publications involving authors affiliated with institutions in more than one country. These indicators were used to examine differences between national research productivity and international collaboration patterns. Country collaboration networks were also analyzed to identify major collaborative relationships within the global research landscape.

Keyword co-occurrence and network visualization

Keyword co-occurrence analysis was performed to identify prominent research themes and relationships among topics in pediatric cardiac interventions and surgery. Bibliometric network maps were generated using VOSviewer to visualize keyword associations, thematic clusters, and patterns of scientific collaboration. Bibliometrix was additionally used to summarize thematic characteristics and publication trends. Together, these analyses provided an overview of the major research areas and their interconnections within the field.

Results and Discussion

General Characteristics of the Bibliometric Dataset

Table 1 presents the general characteristics of the bibliometric dataset on pediatric cardiac intervention and surgery research published between 2002 and 2026. A total of 1,326 publications were retrieved from the Scopus database, representing 390 publication sources, including scientific journals, books, and other scholarly outlets. The distribution of publications across these sources reflects the multidisciplinary nature of pediatric cardiac research, which encompasses clinical cardiology, cardiovascular surgery, perioperative management, critical care, and related medical disciplines.

The bibliometric analysis revealed an annual publication growth rate of 5.27%, indicating an overall expansion of scientific output in this field during the study period. This positive growth rate suggests sustained scholarly interest in pediatric cardiac intervention and surgery, although the magnitude and consistency of annual changes require further examination through publication trend analysis. The average document age was 8.65 years, reflecting a dataset comprising both relatively recent publications and earlier contributions that have shaped the development of the research field. Collectively, these findings provide an overview of the temporal characteristics and continuing development of the scientific literature on pediatric cardiac care.

In terms of scholarly impact, the publications received an average of 21.22 citations per document, while the dataset contained 46,926 cited references. These indicators demonstrate the extent of citation activity and the breadth of literature referenced within the analyzed publications. However, citation counts should be interpreted cautiously because they may be influenced by publication age, document type, journal visibility, and disciplinary citation

practices. Consequently, the average citation rate provides a descriptive measure of scholarly attention rather than a direct indication of the scientific quality or clinical relevance of individual studies.

Regarding publication types, original research articles constituted the largest proportion of the dataset, accounting for 1,048 publications (79.03%), followed by review articles with 207 publications (15.61%). Together, these two document types represented approximately 94.65% of all publications, indicating that the research landscape was predominantly characterized by original scientific investigations and evidence-synthesis studies. Other publication types included book chapters (37; 2.79%), conference papers (18; 1.36%), books (7; 0.53%), notes (3; 0.23%), short surveys (2; 0.15%), and a small number of editorials, letters, errata, and retracted publications. The predominance of original research articles suggests that the field is largely driven by primary investigations, while the substantial contribution of review articles reflects ongoing efforts to synthesize existing evidence and consolidate knowledge across different aspects of pediatric cardiac care.

Table 1. Main bibliometric characteristics of pediatric cardiac intervention and surgery research (2002–2026)

Bibliometric indicator	Results
Main information about the dataset	
Timespan	2002-2026
Publication sources	390
Documents	1,326
Annual growth rate (%)	5.27
Average document age (years)	8.65
Average citations per document	21.22
Cited references	46,926
Document contents	
Keywords Plus (ID)	6,962
Author's Keywords (DE)	2,565
Authorships	
Authors	6,372
Authors of single-authored documents	52
Single-authored documents	58
Co-authors per documents	6.72
International co-authorships (%)	16.29
Document types	
Article	1,048
Review	207
Book chapter	37
Conference papers	18
Books	7
Note	3
Short survey	2
Editorials	1
Errata	1
Letters	1
Retracted publications	1

Authorship analysis identified 6,372 contributing authors, highlighting the broad participation of researchers in this field. The dataset included 58 single-authored publications involving 52 distinct authors, whereas most publications were produced through collaborative authorship. The average number of co-authors per document was 6.72, suggesting that research in pediatric cardiac intervention and surgery commonly involves multidisciplinary teams. Such collaborative authorship is consistent with the complex nature of pediatric cardiac care, which often requires expertise spanning interventional cardiology, cardiac surgery, anesthesiology, intensive care, and other clinical specialties. Nevertheless, the bibliometric indicator alone does not establish the specific professional disciplines represented within individual research teams.

At the international level, 16.29% of publications involved co-authorship across national boundaries. This finding indicates that international collaboration contributed to the global research output, although most publications did not involve cross-country co-authorship. The observed collaboration pattern provides a basis for further examining differences in research partnerships among countries and identifying opportunities to strengthen international scientific networks. More detailed country-level collaboration analyses are therefore necessary to determine which countries play central roles in cross-border research and how these partnerships are distributed geographically.

The analysis of document contents identified 6,962 Keywords Plus entries and 2,565 author-provided keyword entries. These keyword indicators demonstrate the breadth of terminology represented in the dataset and provide a foundation for examining the conceptual structure of pediatric cardiac intervention and surgery research. Keywords Plus, which are generated through bibliographic indexing, complement author-provided keywords by capturing additional terms associated with the indexed literature. Together, these keyword datasets support subsequent co-occurrence and thematic analyses aimed at identifying prominent research topics, relationships among research themes, and potential areas of emerging scientific interest.

Overall, the descriptive bibliometric indicators presented in Table 1 characterize pediatric cardiac intervention and surgery as an expanding and collaborative research field, with a publication landscape dominated by original research articles and supported by substantial citation activity. The diversity of publication sources, contributing authors, and indexed keywords provides a foundation for more detailed analyses of annual publication trends, leading research contributors, international collaboration networks, and thematic developments within the field.

Author Keyword Co-occurrence Analysis

The author keyword co-occurrence network presented in Figure 1 identifies congenital heart disease as a prominent theme in pediatric cardiac intervention and surgery research, with notable connections to cardiac catheterization, cardiac surgery, cardiopulmonary bypass, postoperative care, and clinical outcomes. These associations suggest that the research landscape extends beyond the treatment of congenital cardiac defects to encompass interventional and surgical procedures, perioperative management, and postoperative outcomes. The presence of keywords such as “acute kidney injury,” “morbidity,” “neonates,” and “infant” further highlights the attention given to procedure-related complications and specific pediatric patient populations. Collectively, these patterns illustrate the interconnected nature of clinical management and outcome-oriented research in pediatric cardiac care.

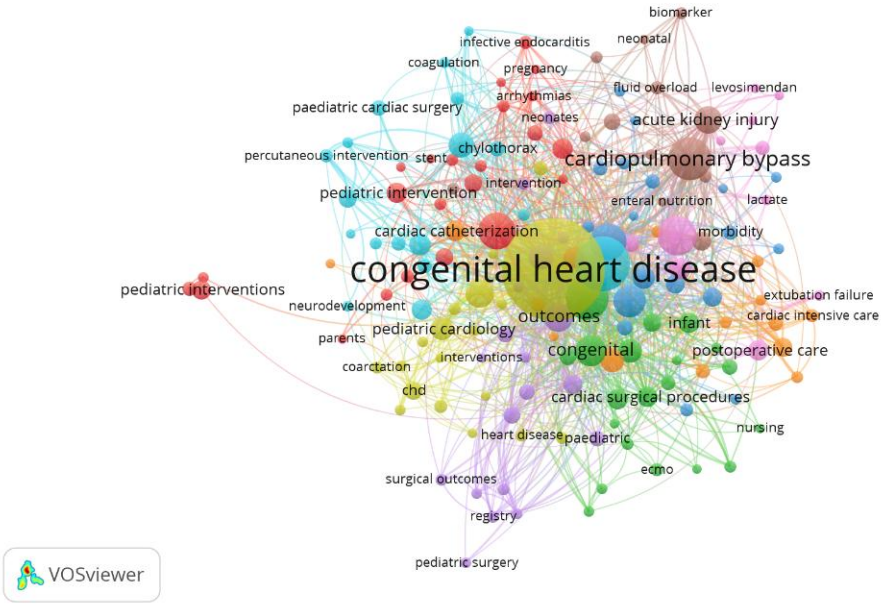


Figure 1. Visualization map of the co-occurrence network of global research keywords on congenital heart disease in the fields of pediatric cardiac intervention and surgery, created using VOSviewer (2002–2026)

The development of cardiac rehabilitation research in patients with congenital heart disease, providing a complementary perspective on recovery and long-term management. Although the scope of that bibliometric investigation differs from the present study, its findings underscore the broader relevance of care beyond the initial intervention. In contrast, the present analysis maps a wider range of interconnected research themes, encompassing procedural approaches, perioperative complications, and clinical outcomes. Of particular interest is the association between cardiopulmonary bypass, cardiac surgical procedures, postoperative care, and acute kidney injury. This thematic grouping suggests that pediatric cardiac research addresses not only procedural techniques but also the challenges of perioperative management and postoperative complications.

Importantly, keyword co-occurrence analysis identifies patterns of shared terminology across publications rather than direct causal relationships or measures of clinical importance. Accordingly, the strength of connections within the network should be interpreted as an indication of thematic association, not evidence that one clinical factor directly

influences another. Within this methodological context, the present study contributes an integrated overview of the relationships among cardiac interventions, surgical procedures, perioperative management, and postoperative complications in the global pediatric cardiac research literature from 2002 to 2026.

Temporal Trends in Research Topics

The temporal analysis of research topics presented in Figure 2 illustrates the evolving thematic landscape of pediatric cardiac intervention and surgery research between 2002 and 2026. During the earlier period, terms such as "anesthesia," "balloon catheter," and "diagnostic accuracy" were prominent, reflecting the representation of perioperative techniques, catheter-based interventions, and diagnostic evaluation in the literature. In the subsequent period, terms including "minimally invasive cardiac surgery," "cardiac surgical procedures," and "congenital heart malformation" became more prominent, indicating continued attention to surgical approaches and the management of congenital cardiac abnormalities. More recently, terms such as "clinical outcome," "diagnosis," "therapy," "epidemiology," and "neonatology" appeared in the temporal visualization, suggesting a broader distribution of research topics encompassing clinical assessment, therapeutic management, population-level characteristics, and neonatal cardiac care.

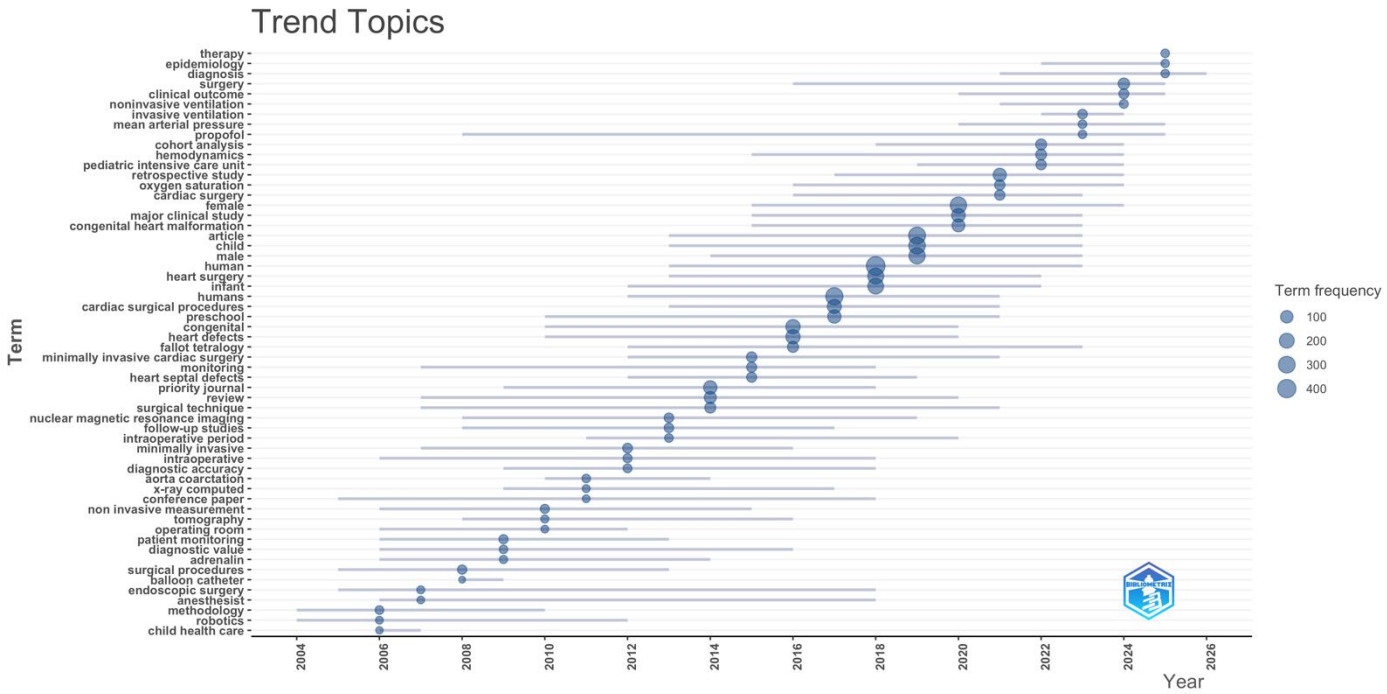


Figure 2. Temporal trends in pediatric cardiac intervention and surgery research, 2002–2026

These observations are broadly consistent with previous bibliometric research on congenital heart disease. Velasque et al. (2023) reported increasing global scientific output in this field, with substantial contributions from the United States, China, and the United Kingdom [18]. Although their analysis covered congenital heart disease more broadly, it provides context for the expansion and diversification of related research. Similarly, Gupta et al. (2024) reviewed developments in minimally invasive surgery for congenital heart disease, highlighting its growing application while emphasizing limitations in the available comparative evidence, which remains largely based on observational studies and retrospective analyses [19]. Together, these findings suggest that the temporal patterns observed in the present study are compatible with broader developments in pediatric cardiac research, although the appearance of particular keywords does not independently establish changes in clinical practice or research priorities.

The temporal distribution of research topics can also be interpreted alongside the keyword co-occurrence network shown in Figure 1. Whereas the co-occurrence analysis identifies thematic relationships among congenital heart disease, surgical procedures, cardiopulmonary bypass, and postoperative care, the temporal analysis provides an additional perspective on when particular terms were represented in the literature. This complementary interpretation suggests that procedural innovation and perioperative management remain interconnected components of the research landscape. Nevertheless, advances in surgical techniques must be considered alongside the strength of clinical evidence and the accessibility of specialized care. Gupta et al. (2024) emphasized the need for stronger comparative evidence on the outcomes of minimally invasive approaches [19], while Vervoort et al. (2024) highlighted persistent global disparities in access to cardiac surgical services and the limitations of surgical capacity [20].

Importantly, the appearance of terms such as “clinical outcome” and “therapy” in more recent periods should not be interpreted as definitive evidence of a shift toward outcome-oriented research or improvements in patient care. Temporal keyword visualizations describe the distribution and timing of terminology within the analyzed publications but do not directly measure research quality, clinical effectiveness, or the impact of procedural innovations. Overall, the combined temporal and co-occurrence analyses provide complementary insights into the thematic development and conceptual structure of pediatric cardiac intervention and surgery research. These findings underscore the importance of future investigations that critically evaluate clinical outcomes, strengthen comparative evidence, and address disparities in access to pediatric cardiac care.

Most Cited Countries and International Research Collaboration

The country-level citation analysis presented in Figure 3 provides an overview of the geographical distribution of scholarly influence in pediatric cardiac intervention and surgery research from 2002 to 2026. Unlike publication productivity, which reflects the volume of scientific output, citation-based indicators provide information on the extent to which research associated with particular countries has been cited in subsequent publications. Examining these indicators alongside international collaboration networks offers a broader perspective on national contributions to the development and dissemination of knowledge in pediatric cardiac care.



Figure 3. Country-level citation impact and international research collaboration networks in pediatric cardiac intervention and surgery research, 2002–2026.

Previous bibliometric studies have documented the substantial contribution of several countries to congenital heart disease research. Zila-Velasque et al. (2023), in an analysis of 8,934 publications published between 2011 and 2020, identified the United States, China, and the United Kingdom as major contributors to global research output, with 89,835 citations recorded across the analyzed literature [18]. Similarly, Sew and Drury (2020), who examined the 100 most-cited publications on pediatric congenital heart disease, reported that 74% originated from the United States [21]. These findings provide context for the prominent role of established research centers in the international pediatric cardiac literature. However, differences in publication periods, database coverage, search strategies, and methods of assigning publications to countries limit direct comparisons between these studies and the present analysis.

Beyond citation impact, international collaboration networks provide additional insight into how scientific contributions are connected across national boundaries. Cross-country research partnerships may facilitate the exchange of clinical expertise, methodological approaches, and research resources, particularly in a field that requires specialized facilities and multidisciplinary clinical teams. Nevertheless, the presence of collaboration links in a bibliometric network indicates co-authorship relationships rather than the effectiveness, quality, or clinical impact of those partnerships. Accordingly, country-level citation patterns and collaboration networks should be interpreted as complementary, rather than interchangeable, indicators of scientific activity.

The geographical distribution of research output and citation impact also warrants consideration in relation to disparities in research capacity. Farhat et al. (2013) reported differences in congenital heart disease research productivity between Arab countries and more established research settings, drawing attention to limitations in research infrastructure and the importance of strengthening international scientific cooperation [13]. Such findings provide a broader context for understanding geographical inequalities in scientific visibility. However, citation counts alone cannot establish differences in research funding, institutional capacity, quality of clinical care, or access to pediatric cardiac services.

Overall, the combined assessment of country-level citation impact and international collaboration provides a multidimensional perspective on the global pediatric cardiac research landscape. These findings highlight the importance of distinguishing scientific productivity, citation visibility, and collaborative connectivity when evaluating national research contributions. Further investigations incorporating normalized citation indicators, institutional resources, and measures of healthcare access would be valuable for understanding whether geographical differences in research activity are associated with broader inequalities in pediatric cardiac care.

Annual Scientific Production

Figure 4 illustrates the annual scientific production in pediatric cardiac intervention and surgery research between 2002 and 2026. Overall, the number of publications demonstrated an upward trend, although fluctuations were observed across individual years. Annual publication output increased from approximately 10 documents in the early years of the study period to more than 100 documents in 2025, which represented the highest annual publication count within the analyzed dataset. This pattern indicates a substantial expansion of scientific activity in pediatric cardiac intervention and surgery over the past two decades.

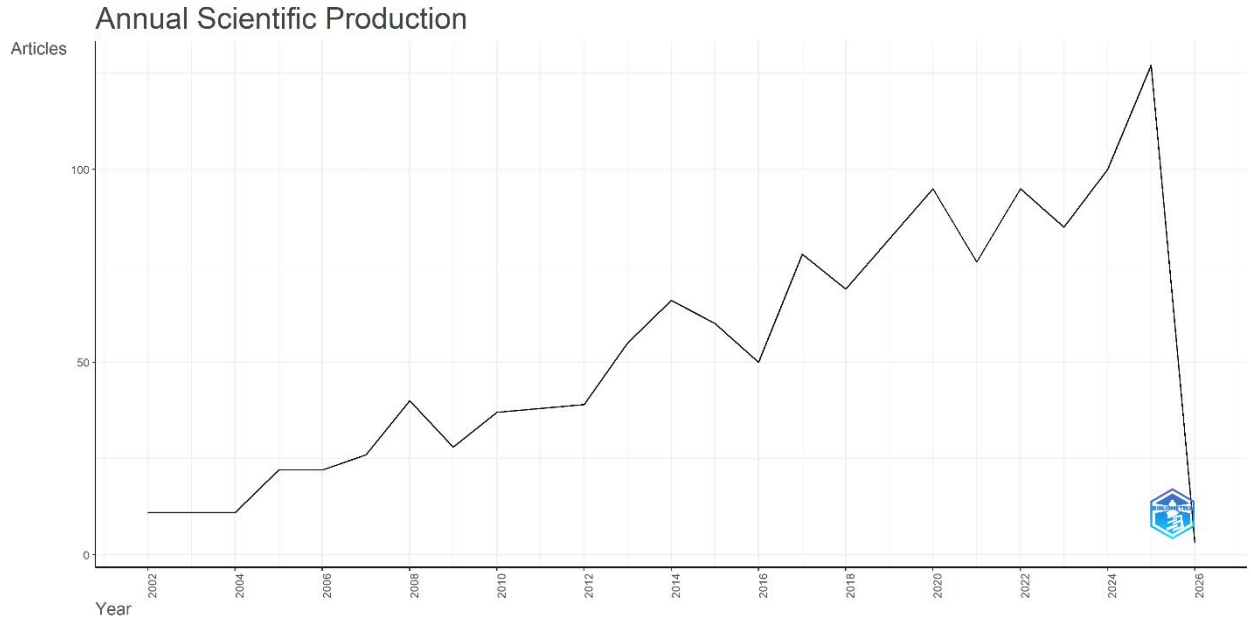


Figure 4. Trends in annual scientific output from research on pediatric cardiac interventions and surgery, 2002–2026.

The observed increase is broadly consistent with the bibliometric findings of Zila-Velasque et al. (2023), who reported growing scientific output in congenital heart disease research based on 8,934 Scopus-indexed publications from 2011 to 2020 [18]. Although their study encompassed a broader range of congenital heart disease research, the similarity in publication trends provides contextual support for the expansion observed in the present analysis. Nevertheless, the annual fluctuations suggest that publication growth has not followed a strictly linear trajectory, potentially reflecting variations in research activity, publication patterns, and database coverage over time.

A notable reduction in the number of publications was observed in 2026. However, this decrease should not be interpreted as evidence of declining scientific interest because the bibliographic search was conducted on February 7, 2026, before the completion of the calendar year. Consequently, the publication count for 2026 represents only a partial observation period and is not directly comparable with the counts for preceding full years. This limitation is particularly important when interpreting the most recent segment of the publication trend. The findings may also be considered alongside the bibliometric analysis by Van den Eynde et al. (2021), which examined influential publications in congenital heart disease research. However, studies focusing on highly cited articles assess scholarly influence rather than overall annual publication productivity. Therefore, comparisons between these approaches should be interpreted as complementary perspectives on research development rather than equivalent measures of scientific growth.

Taken together, the annual publication trends indicate sustained growth in the volume of research related to pediatric cardiac intervention and surgery, particularly during the later years of the observation period. This expansion provides a foundation for examining the journals, institutions, and countries contributing to the development of the field. he country-level citation analysis presented in Figure 3 provides

Leading Source Journals and Bibliometric Impact

Table 2 presents the leading publication sources in pediatric cardiac intervention and surgery research based on bibliometric indicators of productivity and citation impact. Among the analyzed journals, Pediatric Critical Care Medicine emerged as the leading source, with an h-index of 40, a g-index of 72, 6,022 total citations, and 152 publications. These findings indicate that the journal has made a substantial contribution to the indexed literature, both in terms of publication volume and accumulated citation impact. Its prominent position also highlights the representation of critical care and perioperative management within the broader pediatric cardiac research landscape.

Other prominent journals included Cardiology in the Young, Catheterization and Cardiovascular Interventions, and Pediatric Cardiology. The presence of these journals among the leading publication sources reflects the diverse disciplinary scope of the field, encompassing congenital heart disease, pediatric cardiology, catheter-based interventions, surgical management, and postoperative care. This distribution suggests that research on pediatric cardiac interventions and surgery is disseminated across multiple clinical specialties rather than being concentrated exclusively within cardiovascular surgery journals.

Table 2. Leading source journals in pediatric cardiac intervention and surgery research based on bibliometric indicators (2002–2026)

Source journal	h-index	g-index	m-index	TC	NP	PY start
Pediatric critical care medicine	40	72	1.74	6,022	152	2004
Cardiology in the young	19	28	0.83	1,085	73	2004
Catheterization and cardiovascular interventions	19	31	1	1,038	48	2008
Pediatric cardiology	19	30	0.76	1,055	63	2002
Journal of cardiothoracic and vascular anesthesia	18	32	0.72	1,246	81	2002
Congenital heart disease	13	20	0.68	488	20	2008
Critical care medicine	12	14	0.48	959	14	2002
Journal of thoracic and cardiovascular surgery	12	20	0.57	537	20	2006
Journal of the american college of cardiology	10	11	0.5	1,267	11	2007

Abbreviations: TC, total citations; NP, number of publications; PY start, first publication year represented in the analyzed dataset. The h-index represents the number of publications (h) that have each received at least h citations, while the g-index emphasizes highly cited publications. The m-index is calculated by dividing the h-index by the number of years since the first publication represented in the dataset. All bibliometric indicators were calculated within the study dataset.

The interpretation of journal performance requires consideration of several complementary bibliometric indicators. Publication counts represent the volume of research output, whereas total citations reflect accumulated scholarly attention. The h-index combines publication productivity and citation performance by identifying the number of publications that have each received at least the corresponding number of citations. The g-index places greater emphasis on highly cited publications, thereby providing an additional perspective on citation concentration within a journal's contributions to the dataset.

The importance of evaluating journals using multiple indicators is consistent with the findings of Loomba et al. (2021), who compared bibliometric characteristics of journals publishing research related to pediatric cardiology and congenital heart disease [22]. Their findings highlighted differences between specialty-focused and broader cardiology journals in terms of citation-based performance, emphasizing that journal influence cannot be adequately characterized by a single metric. In the present study, the combined assessment of publication volume, h-index, g-index, and total citations therefore provides a more comprehensive description of the leading sources within the analyzed literature.

Importantly, these indicators are influenced by the number and age of publications, citation practices, and the scope of the bibliographic dataset. Accordingly, the leading position of Pediatric Critical Care Medicine should be interpreted within the context of the present Scopus search rather than as evidence of its overall superiority across all pediatric cardiology and cardiovascular surgery research. Overall, the distribution of leading journals demonstrates the multidisciplinary publication structure of pediatric cardiac intervention and surgery research and underscores the close relationship between procedural care, perioperative management, and clinical outcomes.

Top 10 Most Productive Affiliations

Figure 5 presents the ten most productive institutional affiliations in pediatric cardiac intervention and surgery research from 2002 to 2026. Boston Children's Hospital emerged as the leading institution, contributing 113 publications, followed by The Children's Hospital of Philadelphia (58 publications) and Harvard Medical School (53 publications). Other prominent affiliations included The Hospital for Sick Children, Baylor College of Medicine, and UPMC Children's Hospital of Pittsburgh. The predominance of specialized pediatric hospitals and academic medical centers among the leading institutions suggests that research productivity in this field is strongly associated with institutions actively engaged in specialized pediatric cardiac care and academic research.

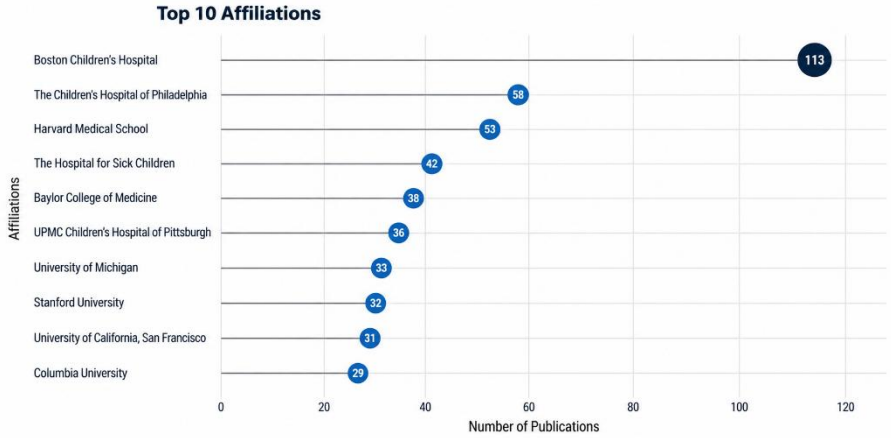


Figure 5. Top 10 most productive institutional affiliations in pediatric cardiac intervention and surgery research

This institutional distribution is consistent with previous bibliometric findings. Sew and Drury (2021), in their analysis of the 100 most-cited publications on pediatric congenital heart disease, identified Boston Children's Hospital, Harvard University, The Children's Hospital of Philadelphia, and the University of Pennsylvania among the prominent institutions contributing to highly cited research. Similarly, Zila-Velasque et al. (2023) identified the United States as a major contributor to global congenital heart disease research, providing broader context for the substantial representation of US-based institutions in the present analysis. Although these studies differed in their research scope and bibliometric approaches, their findings collectively highlight the sustained visibility of established pediatric cardiac research centers in the international scientific literature.

The representation of both specialized pediatric hospitals and academic medical schools among the leading affiliations further illustrates the close relationship between clinical practice and academic research in pediatric cardiac care. The leading position of Boston Children's Hospital is particularly noteworthy, as its prominence in both publication productivity and previous analyses of highly cited literature suggests a consistent contribution across different bibliometric indicators. Nevertheless, institutional publication counts should not be interpreted as direct measures of research quality, clinical effectiveness, or the strength of interinstitutional collaboration. Furthermore, differences in institutional naming conventions, affiliation standardization, and the assignment of multiple institutional affiliations to individual publications may influence the reported rankings.

Overall, these findings indicate that research productivity in pediatric cardiac intervention and surgery is concentrated among established pediatric hospitals and academic medical centers, particularly those based in the United States. The observed distribution provides a foundation for further investigations into institutional research networks, collaborative partnerships, and the geographical distribution of scientific contributions in this field.

Authors' Production Over Time

Figure 5 illustrates the temporal distribution of publication activity among the most productive authors in pediatric cardiac intervention and surgery research from 2002 to 2026. The visualization reveals distinct patterns of scientific productivity, with several authors, including Gauvreau K, Ghanayem N, Jacobs JP, and Gaynor JW, contributing publications across multiple years, whereas others exhibited more concentrated periods of research output. These differences suggest that the development of the field has been supported by both sustained contributions from established researchers and periods of increased publication activity among other investigators.

Variations in bubble size and color intensity further illustrate differences between annual publication productivity and citation performance. While larger bubbles represent a greater number of publications in a given year, differences in color intensity reflect variations in citation counts. These patterns indicate that publication volume and citation impact do not necessarily follow parallel trajectories. Authors with sustained publication activity may not consistently achieve the highest citation counts, as citation performance can also be influenced by publication age, research topic, journal visibility, and the broader scientific relevance of individual studies. Accordingly, evaluating

author contributions requires consideration of both research productivity and citation-related indicators rather than relying exclusively on publication counts.

These observations are consistent with previous bibliometric research examining influential publications in pediatric surgery. Banerjee and Bendre (2022) demonstrated that highly cited pediatric surgical research encompasses different publication types and contributions from multiple geographical regions [23]. Although their analysis focused on highly cited publications rather than longitudinal author productivity, it provides a complementary perspective on the distinction between scientific output and citation impact. Similarly, recent bibliometric investigations of artificial intelligence applications in pediatric surgery have identified prominent authors and institutional collaboration networks, highlighting the value of integrating author-level productivity analyses with broader assessments of scientific collaboration [24].

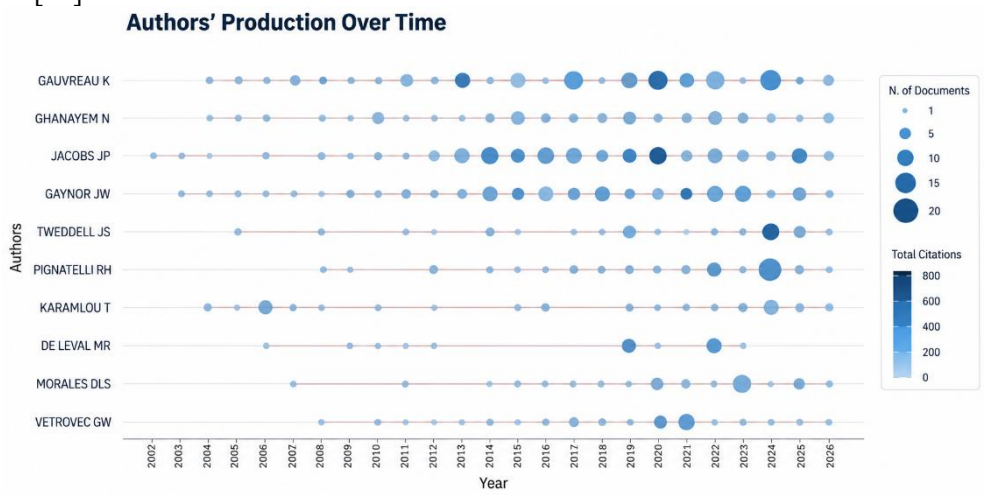


Figure 5. Temporal patterns of publication productivity and citation activity among leading authors in pediatric cardiac intervention and surgery research, 2002–2026.

The temporal distribution also indicates that research development in pediatric cardiac intervention and surgery has involved contributions from multiple investigators with differing publication trajectories. Nevertheless, the visualization should not be interpreted as definitive evidence of changes in individual scientific influence or research quality. Citation counts may vary according to the time available for publications to accumulate citations, while author-name ambiguity, indexing inconsistencies, and differences in institutional affiliations may affect the attribution of publications to individual researchers. Furthermore, the analysis does not establish the specific roles or contributions of authors within collaborative publications.

Overall, the authors' production-over-time analysis provides a longitudinal perspective on the distribution of scientific productivity and citation activity among prominent contributors to pediatric cardiac intervention and surgery research. When considered alongside institutional productivity and international collaboration analyses, these findings contribute to a more comprehensive understanding of the researchers and collaborative structures associated with the development of this field.

Country-Level Research Productivity and International Collaboration

Table 3 presents the geographical distribution of scientific publications and patterns of international collaboration in pediatric cardiac intervention and surgery research from 2002 to 2026. The United States emerged as the leading contributor, accounting for 449 publications (33.86% of the dataset), substantially exceeding China (66; 4.98%), the United Kingdom (62; 4.68%), India (57; 4.30%), and Germany (54; 4.07%). The substantial contribution of the United States reflects its prominent representation within the analyzed literature. This distribution is broadly consistent with the findings of Zila-Velasque et al. (2023), who identified the United States, China, and the United Kingdom as major contributors to global congenital heart disease research during 2011–2020 [18].

Table 3. Leading countries by publication output and international collaboration in pediatric cardiac intervention and surgery research (2002–2026)

Country	Publications, n	Share (%)	SCP	MCP	MCP %
USA	449	33,86	396	53	11,8040089
China	66	4,98	57	9	13,6363636
United Kingdom	62	4,68	45	17	27,4193548
India	57	4,30	55	2	3,50877193

Germany	54	4,07	43	11	20,3703704
Canada	42	3,18	31	11	26,1904762
Italy	33	2,49	25	8	24,2424242
Australia	26	1,96	17	9	34,6153846
Japan	26	1,96	25	1	3,84615385

SCP = Single Country Publications; MCP = Multiple Country Publications. MCP (%) = MCP divided by the total publications attributed to the country, multiplied by 100. Publication share (%) is calculated using the total dataset of 1,326 documents.

However, publication volume alone does not fully characterize international research engagement. Analysis of Single Country Publications (SCP) and Multiple Country Publications (MCP) revealed considerable variation in cross-country co-authorship patterns. The United States recorded the highest absolute number of internationally co-authored publications (53 MCPs), but these accounted for only 11.80% of its total output. In comparison, the United Kingdom produced 17 MCPs, representing 27.42% of its publications. Among the countries listed in Table 3, Australia demonstrated the highest proportion of internationally co-authored publications (34.62%), followed by the United Kingdom (27.42%), Canada (26.19%), and Italy (24.24%). These findings indicate that countries with comparatively smaller publication outputs may exhibit higher relative levels of international collaboration.

Further differences were observed among other major contributing countries. Germany recorded an MCP proportion of 20.37%, followed by China (13.64%), Japan (3.85%), and India (3.51%). The relatively low MCP proportions observed in some countries indicate that most of their publications, as classified by this bibliometric indicator, involved authors affiliated with institutions within a single country. Nevertheless, a low MCP proportion does not necessarily imply limited scientific collaboration, as substantial research partnerships may occur within national boundaries. Furthermore, MCP proportions may be influenced by national research capacity, institutional structures, research funding, and the availability of established international partnerships, although these factors were not directly assessed in the present study.

The importance of international research collaboration has also been highlighted in previous bibliometric investigations. El Ayoubi et al. (2024), in their analysis of congenital heart disease research in the Arab world, reported that approximately 26% of publications involved international collaboration and identified an association between cross-country partnerships and research productivity [25]. Although these findings provide useful context for interpreting collaboration patterns, such associations should not be considered evidence that international collaboration directly increases publication output. Rather, international co-authorship represents one dimension of research connectivity that may complement national scientific productivity.

Taken together, the country-level findings demonstrate a marked difference between the geographical distribution of publication output and the relative prevalence of international co-authorship. The United States contributed the largest number of publications and internationally co-authored documents in absolute terms, whereas Australia, the United Kingdom, and Canada exhibited higher MCP proportions. These patterns highlight the importance of evaluating both research productivity and collaboration intensity when characterizing national contributions to pediatric cardiac intervention and surgery research. They also suggest opportunities to strengthen international research partnerships, particularly through collaborations involving established research centers and countries that remain underrepresented in the global publication landscape.

This study has several strengths. First, it examines a 25-year publication period from 2002 to 2026, providing a longitudinal overview of research development in pediatric cardiac intervention and surgery. The inclusion of 1,326 Scopus-indexed publications enables the characterization of publication trends, major research contributors, international collaboration patterns, and thematic relationships across a substantial body of literature. Second, the integration of multiple bibliometric indicators, including citation performance, author productivity, institutional contributions, country-level publication output, and keyword co-occurrence, provides a multidimensional perspective on the structure and development of the research field. Third, the combined use of Bibliometrix and VOSviewer facilitates quantitative analysis and network visualization, allowing complex patterns of scientific collaboration and thematic associations to be examined systematically.

Despite these strengths, several limitations should be acknowledged. First, the analysis relied exclusively on the Scopus database, excluding publications indexed only in other bibliographic databases, such as Web of Science, PubMed, or Dimensions. Consequently, the findings may not fully represent the global scientific literature on pediatric cardiac intervention and surgery. Second, restricting the search to English-language publications may have introduced language bias, potentially underrepresenting contributions from countries where research is commonly published in other languages.

Third, citation-based indicators are subject to temporal and disciplinary biases. Older publications have generally had more time to accumulate citations, while citation practices may vary across journals, research topics, and document types. Accordingly, citation counts should not be interpreted as direct measures of methodological

quality, clinical relevance, or scientific validity. Fourth, the accuracy of author- and institution-level analyses may be affected by variations in author names, institutional affiliations, and bibliographic indexing. Similarly, keyword co-occurrence and temporal analyses depend on the terminology used by authors and database indexers, potentially influencing the identification and interpretation of thematic clusters.

An additional limitation concerns the search strategy, which included the broad term "congenital heart disease" without an explicit pediatric age restriction. Although this approach increased the retrieval of potentially relevant publications, it may also have captured studies involving adult patients with congenital heart disease. Furthermore, the bibliographic search was conducted on February 7, 2026, meaning that publication data for 2026 represent only a partial calendar year. Consequently, trends involving the most recent year should be interpreted cautiously.

Finally, bibliometric analysis primarily characterizes publication patterns, citation relationships, and scientific networks rather than the methodological quality or clinical effectiveness of individual studies. Therefore, the observed research trends cannot independently establish improvements in patient outcomes or the implementation of evidence-based practices. Future research could integrate bibliometric mapping with systematic reviews, methodological quality assessments, and clinical evidence synthesis to provide a more comprehensive understanding of how scientific developments contribute to pediatric cardiac care.

Conclusion

This bibliometric study provides an overview of global research trends, scientific contributions, collaborative networks, and thematic developments in pediatric cardiac intervention and surgery from 2002 to 2026. The analysis of 1,326 Scopus-indexed publications revealed sustained growth in scientific output, particularly after 2012, reflecting increasing research activity in this field. Keyword analyses identified congenital heart disease as a central research theme, closely associated with cardiac surgery, cardiac catheterization, cardiopulmonary bypass, perioperative management, and postoperative complications. These thematic relationships highlight the multidisciplinary scope of pediatric cardiac research, encompassing procedural interventions, critical care, and clinical outcomes.

The United States emerged as the leading contributor in terms of publication output, while international collaboration patterns varied considerably across countries. Although the United States recorded the highest absolute number of internationally co-authored publications among the countries analyzed, Australia, the United Kingdom, and Canada demonstrated higher relative proportions of international collaboration. These findings emphasize the importance of distinguishing research productivity from international research connectivity when evaluating national scientific contributions.

Overall, this study provides a bibliometric perspective on the development and structure of pediatric cardiac intervention and surgery research. The findings highlight opportunities to strengthen international research partnerships, broaden geographical participation, and promote future investigations addressing clinical outcomes, perioperative complications, and disparities in access to specialized pediatric cardiac care. Further studies integrating bibliometric analysis with systematic evidence synthesis are warranted to assess the clinical relevance and practical implications of these research trends.

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Declarations

Author contribution : MRG, WS, AHM and AFH contributed to the conception and design of the study. RG, WS, LH and FAF contributed to data acquisition, analysis, and interpretation. RG drafted the manuscript, while WS, AHM, AFH, MM, MF and DPA critically reviewed and revised the manuscript for important intellectual content. All authors reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

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Ethics Declaration	:	Ethical approval was not required for this study because it used publicly available bibliographic data and did not involve human participants, animals, or identifiable personal data.
Additional information	:	The authors confirm that all statements and interpretations presented in this review are based on the available published literature and represent the authors' independent scholarly synthesis.

Informed Consent Statement

Not applicable. This study did not involve human participants or the collection of identifiable personal information.

Data Availability Statement

The bibliographic data used in this study were obtained from the Scopus database. The data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to the terms and conditions of the Scopus database.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors acknowledge the use of artificial intelligence-assisted tools solely for language editing and improvement of manuscript readability. All AI-assisted suggestions were critically reviewed, revised, and verified by the authors to ensure the accuracy, integrity, and scientific validity of the manuscript. The authors take full responsibility for the final content presented in this work.

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