

# Navigating the Data Labyrinth: A Bibliometrix of Data Governance Challenges in Implementing Digital Twins for Disaster Management in Developing Countries

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## ABSTRACT

Indonesia faces significant disaster risks due to its location in the Ring of Fire, necessitating advanced mitigation technologies like Digital Twins (DT). However, the effectiveness of DT relies heavily on real-time data integration, which is often hindered by governance issues rather than technological capability. This study aims to identify specific data governance challenges in adopting DT for the public sector specifically in disaster management and proposes a conceptual framework suitable for developing countries, using Indonesia as the primary representative case. A Bibliometric analysis was conducted using the PRISMA protocol. Data was collected from Scopus (n=107) and Google Scholar/PoP, covering the period 2018–2026, focusing on the intersection of Digital Twin, Disaster Management, and Data Governance. Additionally, a qualitative case study approach was employed, utilizing Indonesia as the primary representation of developing countries to validate the proposed framework. The study identifies three key challenge dimensions: (1) Organizational (data silos and ownership ambiguity), (2) Technical (semantic interoperability and legacy systems), and (3) Legal-Ethical (data privacy and sovereignty). The paper proposes the "Integrated Disaster Data Governance for Digital Twin (IDDG-DT)" framework, which aligns with the Satu Data Indonesia policy, emphasizing that robust data governance is a prerequisite for successful Digital Twin implementation.

## 1. Introduction

The rapid advancement of Industry 4.0 technologies has introduced the concept of the Digital Twin (DT) a virtual representation that serves as the real-time digital counterpart of a physical object or process [1]. In the context of disaster management, DT offers revolutionary potential for countries like Indonesia, which sits on the Pacific Ring of Fire. According to the National Agency for Disaster Countermeasure (BNPB), Indonesia records thousands of natural disasters annually, placing it consistently among the most vulnerable nations in the World Risk Index. This extreme risk underscores the critical need for advanced early warning systems. By simulating floods, earthquakes, or volcanic eruptions in a virtual environment, decision-makers can predict impacts and optimize evacuation routes before a disaster occurs[4]. However, while the technological vision is compelling, the practical implementation in the public sector faces a fundamental hurdle: data governance.

Current literature on Digital Twins is predominantly focused on technical creation, such as 3D modeling, sensor deployment, and IoT connectivity [3]. A significant gap exists in understanding the "fuel" of the Digital Twin: Data. Without high-quality, integrated, and real-time data, a Digital Twin is merely a static 3D model [1]. In developing countries, this issue is exacerbated by fragmented data management practices, limited fiscal

capacities, and unequal ICT infrastructure. Government agencies often operate in silos for instance, rainfall data from the Meteorology Agency (BMKG) may not be automatically integrated with the hydrological data from the Public Works Department (PU) or population data from the Civil Registry (Dukcapil).

Compared to traditional Geographic Information Systems (GIS) which offer static and descriptive mapping, Digital Twins provide a dynamic, real-time predictive capability. The primary advantage of DT lies in its ability to autonomously simulate "what-if" scenarios for emergency evacuation and resource allocation. However, this advanced capability comes with significant disadvantages: it is highly complex, requires immense computational cost, and is extremely vulnerable to data corruption or latency. If the underlying real-time data pipeline is flawed, the entire system can fail, making robust data governance a non-negotiable prerequisite.

In Indonesia, the Satu Data Indonesia (One Data Indonesia) policy (Perpres No. 39/2019) was established to address these interoperability issues [19]. However, its implementation in advanced use cases like Digital Twins remains untested. The complexity of DT requires not just data sharing, but real-time data synchronization, strict quality control, and privacy protection, which traditional e-government frameworks may not cover [6]. Specifically, governing real-time data flows introduces critical hurdles, such as transmission latency that can render disaster warnings obsolete and the necessity for automated validation of IoT sensors prone to data corruption. This complexity is further compounded by unresolved legal liabilities and accountability issues if erroneous sensor data misdirects critical disaster response efforts

The scientific novelty of this research lies in shifting the Digital Twin discourse from technical engineering to public sector data governance, specifically tailoring a framework for the resource-constrained environments of developing countries. This study aims to bridge this gap by employing a two-phased methodological approach to address three interconnected research questions. First, through a bibliometric analysis, the research investigates the critical data governance dimensions required to successfully implement Digital Twins in disaster management. A bibliometric approach was primarily chosen because it provides a macro-level quantitative mapping of scattered global literature, which is essential to identify the exact governance gaps and thematic evolution within the field. Second, it identifies the specific barriers and challenges hindering the adoption of Digital Twin technologies within the public sector of developing countries. Finally, by synthesizing the bibliometric findings with a qualitative case study of flood management in Jakarta, the study seeks to determine how a robust data governance framework can be specifically designed and validated to support Digital Twin-based disaster mitigation efforts in Indonesia

## **2. Method**

### **2.1. Object and Scope of Research**

The object of this research is the data governance framework required for the successful implementation of Digital Twins in disaster management. The scope of the study is deliberately focused on the public sector within developing countries. Temporally, the literature review scope encompasses academic publications from 2018 to 2026 to capture the most recent advancements in Industry 4.0. Geographically and contextually, the scope is anchored by a specific qualitative case study of Flood Management in Jakarta, Indonesia. This specific setting was chosen to serve as the primary representative case for resource-constrained developing nations facing complex, real-world data governance barriers [6].

### **2.2. Tools and Materials Used**

The materials used in this study comprise bibliographic metadata extracted from reputable academic databases, primarily Scopus, which is recognized for its high-quality indexing of technical and social science literature. Publish or Perish was used as a supplementary tool to capture recent "grey literature" via Google Scholar. The final analytical material consisted of exactly 107 peer-reviewed documents. For the analytical tools, this study utilized the Biblioshiny app (part of the Bibliometrix R-package). This software tool was specifically selected over alternatives like VOSviewer due to its advanced capability to generate strategic diagrams and visualize the thematic evolution of the field.

### 2.3. Research Procedures or Stages

The research was conducted through a two-phased methodological approach, structured into three sequential stages:

1. **Stage 1: Data Collection (PRISMA Protocol).** The initial stage utilized the PRISMA protocol to ensure a transparent selection process. The search applied Boolean operators intersecting ("Digital Twin") AND ("Disaster" OR "Emergency" OR "Flood" OR "Mitigation") AND ("Data Governance" OR "Data Management" OR "Interoperability"). The PRISMA flow quantified the process: starting from Identification (400 initial documents from Scopus and Google Scholar), proceeding to Screening (removing duplicates and irrelevant titles/abstracts, leaving 170 documents), Eligibility assessment, and culminating in an Included final dataset of 107 relevant documents.
2. **Stage 2: Bibliometric Analysis.** The second stage involved importing the 107 documents into the Biblioshiny tool to map the conceptual structure. This stage analyzed keyword networks and classified the literature into Motor, Basic, Niche, and Emerging themes to answer RQ1 and RQ2 regarding critical dimensions and barriers.
3. **Stage 3: Thematic Synthesis and Case Study Validation.** In the final stage, a thematic analysis was performed to categorize the bibliometric findings into the "Technology-Organization-Environment" (TOE) framework. To directly address RQ3, these findings were synthesized with a qualitative case study approach. The proposed framework was conceptually applied and validated against the organizational silos and interoperability challenges present in the Jakarta Flood Management system.

## 3. Results and Discussion

### 3.1. Presentation of Research Results

The research results are derived from a bibliometric mapping of 107 documents and categorized based on the research questions. Network visualization indicates that "Digital Twin" serves as the central node, exhibiting strong links with "Interoperability" and "Information Management". This connectivity suggests a paradigm shift from purely technical 3D visualization towards the managerial challenges of data integration. Specifically for the dimensions of data governance (RQ1), the results identify three mandatory attributes for Digital Twins in disaster management: *Velocity* (near real-time data ingestion to prevent transmission delays), *Veracity* (automated quality checks to prevent AI model hallucinations), and *Variety* (ingestion of both structured databases and unstructured sensor/CCTV feeds) [1][3][4]. Furthermore, regarding implementation barriers (RQ2), the results highlight three major challenges:

1. *Organizational Challenges:* "Data Silos" and ego-sectoral tendencies prevent the free flow of data, complicating ownership and accountability across government agencies.
2. *Technical Challenges:* A lack of semantic interoperability and the presence of outdated legacy systems make integrating diverse sensor metadata highly difficult and costly.
3. *Legal and Ethical Challenges:* Utilizing citizen data for evacuation simulations raises significant privacy and data sovereignty concerns, particularly regarding compliance with national laws like Indonesia's Personal Data Protection Law (UU PDP).

### 3.2. Dimensions of Data Governance (RQ1)

To analyze the conceptual structure of the field, a Thematic Map (Figure 1) was generated. The map classifies topics into four quadrants based on their centrality (relevance) and density (development degree). Analyzing the position of these themes reveals critical implications for data governance:

1. **Motor Themes (Upper-Right Quadrant):** Themes like "Interoperability," "Decision Making," and "Digital Twins" reside here [11]. Implication for data governance: Because these are the driving themes, it implies that governance frameworks must aggressively mandate interoperability standards (e.g., Satu Data Indonesia). Effective decision-making in disaster scenarios relies entirely on a connected data ecosystem; isolated data renders the Digital Twin obsolete.
2. **Basic Themes (Lower-Right Quadrant):** "Information Management" and "Data Integration" fall into this quadrant [11]. Implication for data governance: These represent foundational, established knowledge. The implication is that advanced predictive simulations cannot function without strict, standardized baseline protocols for fundamental data integration.

3. Niche Themes (Upper-Left Quadrant): Topics such as "Artificial Intelligence" and "IoT" are highly developed technically but isolated from the core governance discourse [11]. Implication for data governance: This highlights a regulatory lag. Public sector data governance policies need to rapidly evolve to regulate the deployment of IoT sensors and establish accountability for AI-driven decisions.
4. Emerging/Declining Themes (Lower-Left Quadrant): "Machine Learning" appears here with lower density [11]. Implication for data governance: As an emerging topic in this specific intersection, it indicates a pressing need for future regulatory frameworks to address automated ML decision-making and algorithmic biases in critical disaster response efforts.

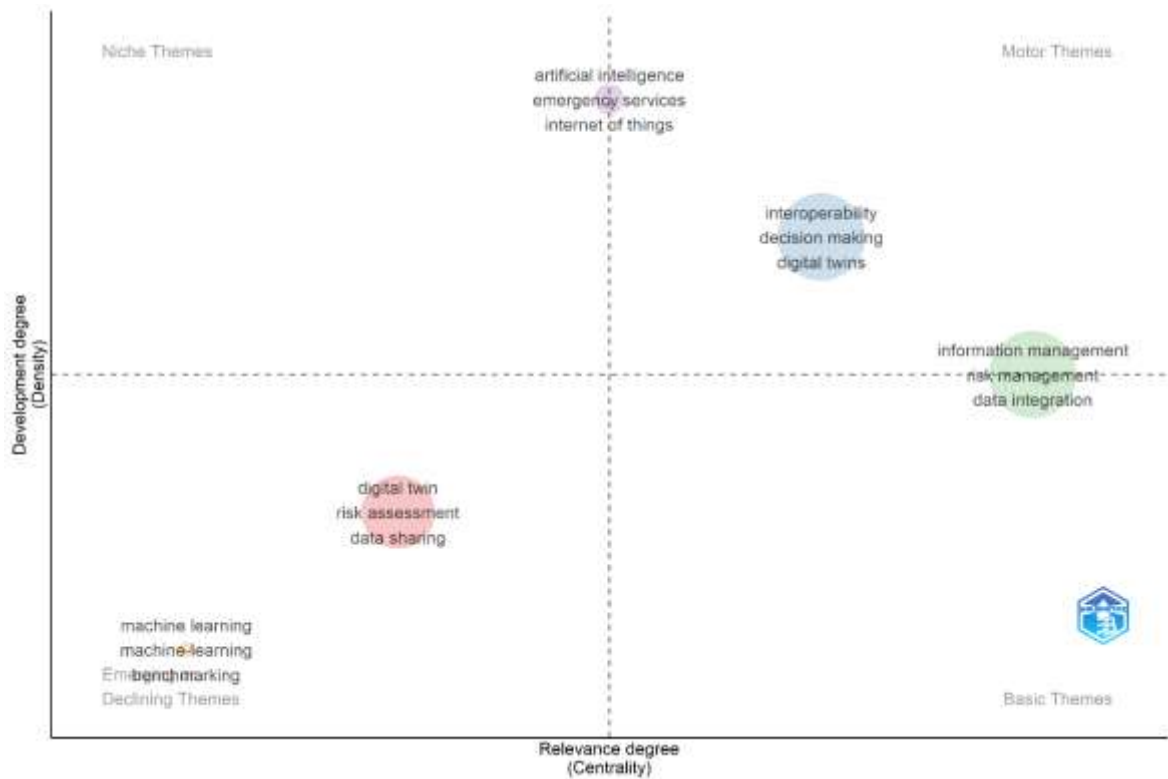


Figure 1 Thematic Map

Explanation of Figure 2 (Thematic Network Diagram) Figure 2 illustrates the Thematic Network Diagram generated via the Biblioshiny application, mapping the conceptual relationships and co-occurrence of key terms across the 107 analyzed documents. In this network visualization, "Digital Twin" emerges as the central node (n=164), demonstrating highly dense and robust connections with governance-centric terms, most notably "Interoperability" (n=204) and "Information Management" (n=203). The thickness of the links and the proximity of these nodes provide empirical evidence of a strategic paradigm shift in the literature. It indicates that current academic discourse has moved beyond purely technical discussions of 3D visualization and sensor deployment, directly prioritizing the managerial and governance challenges of data integration. Consequently, this network diagram visually reinforces the study's premise: establishing a highly interoperable information management system is the fundamental prerequisite for operationalizing Digital Twins.

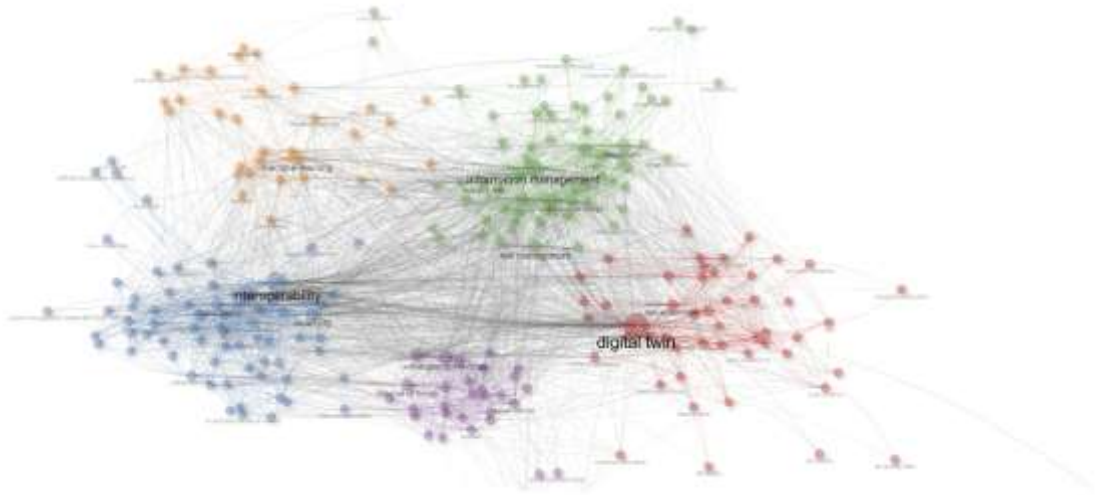


Figure 2 Thematic Network Diagram

### 3.3. Implications of the Results

The primary implication of synthesizing these findings is the necessity for a structured solution to overcome the identified barriers. Consequently, this study proposes the Integrated Disaster Data Governance for Digital Twin (IDDG-DT) framework [10]. The core innovation of this framework is the "Governance Gateway" (Layer 2), a mandatory filtering layer that ensures all heterogeneous data inputs comply with national interoperability standards and privacy regulations (UU PDP) before entering the Digital Twin simulation engine [13]. The practical implication of this framework was validated through a qualitative case study on Jakarta Flood Management [13][14]. By conceptually applying the Governance Gateway, the framework demonstrates how to break down organizational silos between the Meteorology Agency (BMKG), Public Works (PUPR), and the Provincial Government [14][15]. It ensures that only verified, privacy-preserving data enters the simulation, transforming the Digital Twin from a static 3D model into a reliable predictive decision-support system for early warnings and safe evacuations.

### 3.4 Proposed Framework: Integrated Disaster Data Governance for Digital Twin (IDDG-DT)

To answer RQ3, it is necessary to systematically transform the bibliometric results and the positions of the Thematic Map (answering RQ1 and RQ2) into the structural components of the proposed framework. This transformation is achieved by categorizing the findings through the Technology-Organization-Environment (TOE) analysis framework:

1. Technology (T): The Thematic Map highlighted "Interoperability" and "Information Management" as critical Motor and Basic themes. The need for near real-time data ingestion (Velocity) and automated quality checks (Veracity) directly translates to the technical infrastructure of the proposed framework. These technological requirements form the basis of Layer 1 (Heterogeneous Data Sources) and Layer 3 (Digital Twin Engine).
2. Organization (O): The bibliometric findings identified "Data Silos" and "Ownership Ambiguity" as primary barriers hindering the free flow of data among government agencies. To address this organizational challenge, the framework introduces the Governance Gateway (Layer 2) as a mandatory control process. This layer strictly enforces the *Satu Data Indonesia* standard to compel inter-agency data sharing and break down sectoral egos.
3. Environment (E): The literature review also uncovered legal and ethical barriers, specifically concerning citizen privacy and data sovereignty during disaster tracking. These environmental pressures dictate the regulatory compliance mechanism of the framework. Consequently, the Governance Gateway (Layer 2) is equipped with strict privacy filters to ensure all data ingestion adheres to Indonesia's Personal Data Protection Law (UU PDP).

By synthesizing these TOE dimensions, the Integrated Disaster Data Governance for Digital Twin (IDDG-DT) framework is proposed as a structured pipeline. As illustrated in Figure 3, the framework operates by transforming heterogeneous raw data into actionable decision support, with a strict governance filter acting as the central "gatekeeper."

The framework consists of four hierarchical layers:

1. Layer 1: Heterogeneous Data Sources (Input). Aggregates diverse streams including real-time IoT sensors, static legacy government data, and unstructured social media reports [14][15].
2. Layer 2: The Governance Gateway (Process Control). The core contribution addressing the 'O' and 'E' of the TOE framework. It enforces Standards (*Satu Data Indonesia*), Quality (automated validation), and Privacy (UU PDP compliance)[12][19][21].
3. Layer 3: Digital Twin Engine (Processing). Processing only the "Trusted Data" that clears the gateway through 3D modeling and AI predictive algorithms.
4. Layer 4: User Action (Output). Delivering Early Warning Systems and executive dashboards for emergency response[5][8].

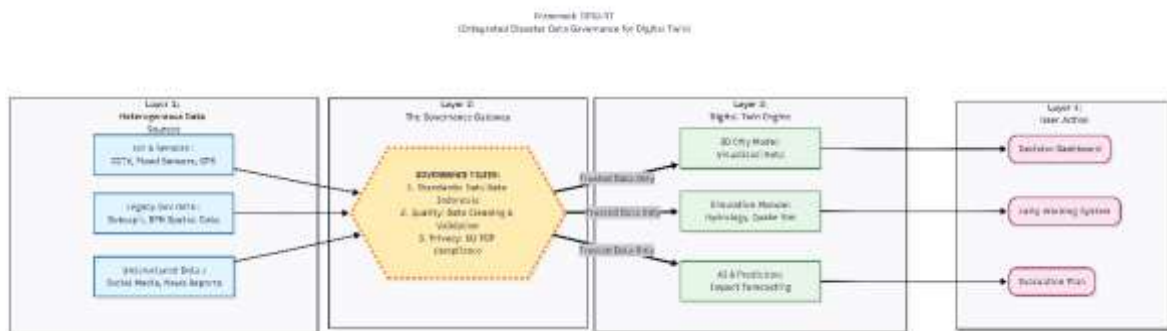


Figure 3 The proposed IDDG-DT Framework. The central "Governance Gateway" ensures data compliance with national standards (*Satu Data Indonesia*) and privacy laws (UU PDP) prior to simulation processing.

### 3.5. Conceptual Application: An Illustrative Scenario in Jakarta Flood Management

It is crucial to clarify that this section serves as a conceptual application and an illustrative scenario rather than an empirical validation. Given the early stage of Digital Twin adoption in the Indonesian public sector, conducting empirical validation such as expert interviews, Focus Group Discussions (FGDs), or assessing actual technical implementations falls outside the scope of this bibliometric study. Instead, this scenario theoretically demonstrates how the proposed IDDG-DT framework could resolve the identified structural barriers within a real-world context.

Applying the IDDG-DT Framework to the chronic flood management issues in Jakarta reveals the following operational improvements:

1. Breaking Organizational Silos (Layer 1 & 2): Currently, disaster data is fragmented across the Meteorology Agency (BMKG), Public Works (PUPR), and Civil Registry (Dukcapil). Implementing the Governance Gateway enforces the *Satu Data Indonesia* standard, hypothetically allowing real-time ingestion of heterogeneous data without bureaucratic friction.
2. Ensuring Data Trust (Layer 2): Previous initiatives faced challenges with "noisy" social media data. The framework's Quality Control filter illustrates how verified crowdsourced reports (e.g., via the JAKI application) can be systematically separated from false alarms before entering the simulation engine.
3. Privacy-Preserving Evacuation (Layer 2 & 3): Simulating evacuation routes requires citizen location data. The framework demonstrates conceptual compliance with the UU PDP by masking individual identifiers at the Gateway level, balancing predictive accuracy with legal privacy rights.

By strictly outlining these governance rules, the conceptual scenario highlights how a Digital Twin can shift from a static visualization tool to a predictive decision-support system.

### 3.5. Limitations of the Study

Despite its contributions, this study has several limitations. First, the bibliometric mapping is inherently constrained by the selected database (primarily Scopus) and the specific search string utilized, which may exclude relevant local policy documents not indexed internationally. Second, the proposed IDDG-DT framework has currently only been evaluated conceptually and qualitatively through a single case study in

Jakarta. Because Jakarta possesses the highest fiscal capacity and most advanced ICT infrastructure in Indonesia, the direct transferability of this framework to other regional governments remains unproven. Broader applicability requires further empirical testing in other developing cities with varying levels of infrastructure, fiscal constraints, and data literacy.

#### 4. Conclusion

This study successfully navigated the data governance challenges of implementing Digital Twins in disaster management by directly addressing its three core research questions. Addressing the first research question (RQ1), the findings indicate that beyond mere 3D visualization, the critical data governance dimensions required for Digital Twins are velocity (near real-time ingestion), veracity (automated quality checks), and variety (handling heterogeneous data). Regarding the second research question (RQ2), the analysis confirms that the primary barriers hindering adoption in developing countries are organizational (persistent data silos and ownership ambiguity), technical (lack of semantic interoperability and legacy systems), and legal-ethical (privacy and data sovereignty concerns).

To answer the third research question (RQ3), this research proposes the Integrated Disaster Data Governance for Digital Twin (IDDG-DT) framework. The core conceptual contribution of this framework is the "Governance Gateway"—a mandatory filtering layer designed to enforce national interoperability standards (such as Satu Data Indonesia) and privacy regulations (such as UU PDP) before any data enters the simulation engine.

Furthermore, the Jakarta Flood Management case study presented in this paper serves strictly as an illustrative application rather than an empirical validation. While this conceptual scenario demonstrates the theoretical potential of the IDDG-DT framework in breaking down sectoral egos between government agencies to establish a trusted data pipeline, its actual practical utility and real-world effectiveness remain untested.

Consequently, policymakers are urged to prioritize "Governance before Construction" in smart city initiatives, establishing robust data sharing protocols as a prerequisite. Future research must focus on the technical prototyping of the Governance Gateway, expert evaluations, and empirical field tests across various developing cities to rigorously validate its latency performance and practical applicability in real-time disaster scenarios.

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#### Declarations

**Author contribution.** Andi Agus Salim developed the research concept, performed the bibliometric analysis, and wrote the original draft. Hasbu Naim Syaddad and Luki Ishwara contributed to the methodology and data validation. Irawan, Estiko, and Irfan assisted in the review process, visualization of the framework, and final editing. All authors have read and agreed to the published version of the manuscript.

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**Conflict of interest.** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Data and Software Availability Statements

**Data Availability:** The dataset analyzed in the current study consists of bibliographic data retrieved from the Scopus database. The raw data files (CSV format) used for the bibliometric analysis are available from the corresponding author upon reasonable request.

**Software Availability:** The bibliometric analysis was conducted using **Biblioshiny** (part of the *Bibliometrix* R-package, version 4.1). The conceptual diagrams were designed using standard visualization tools. No custom code or proprietary software was developed for this study.

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