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Review article

Tracing Forty Years of Research on the Bhopal Gas Tragedy: Trends, Themes, and Future Directions

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ABSTRACT

The Bhopal Gas Tragedy stands as a defining moment in the history of industrial disasters, prompting ongoing global discourse on public health, environmental safety, and corporate accountability. This study aims to systematically map and evaluate the scholarly landscape of the Bhopal Gas Tragedy over 40 years (1984–2024), offering a longitudinal perspective on the evolution, diffusion, and thematic transformation of research in this critical area. A total of 301 documents were analyzed, revealing fluctuating yet enduring scholarly engagement, with notable publication peaks corresponding to key anniversaries of the Bhopal Gas Tragedy. The findings show a clear thematic evolution from early technical and toxicological investigations focused on chemical causes and health effects to more holistic perspectives encompassing industrial safety, environmental sustainability, and disaster governance. In recent years, research has increasingly integrated themes of public health, psychosocial resilience, and environmental justice, reflecting a shift from reactive crisis response to preventive and adaptive frameworks. Factorial analysis further identified three dominant thematic clusters: institutional and technical management of the disaster, long-term health and environmental outcomes, and occupational or exposure-related risks. The bibliometric insights derived from this study advance understanding of industrial disasters by illustrating how Bhopal-related research has transitioned from immediate impact analyses to broader explorations of systemic governance and resilience. The significant implication of this work is the highlighting of the growing incorporation of environmental regulation, community preparedness, and psychosocial recovery into disaster management frameworks. This evidence-based synthesis clarifies the field's intellectual structure. It provides actionable guidance for policymakers and safety professionals, emphasizing the need for stronger preventive strategies, inter-agency collaboration, and resilience-building initiatives in industrial risk governance.

KEYWORDS

Bhopal gas tragedy, bibliometric analysis, industrial disaster, public health, research trends.

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1. Introduction

The Bhopal Gas Tragedy, which occurred during the night of December 2-3, 1984, represents a pivotal point in environmental health and industrial safety regulations, making it one of the worst industrial disasters globally. The release of approximately 40 tons of methyl isocyanate (MIC) from the Union Carbide India Limited (UCIL) pesticide plant directly resulted in immediate fatalities, with estimates ranging from 3,800 to 15,000 deaths on the night of the disaster and significant long-term health impacts affecting over 600,000 individuals (Broughton, 2005). The people of Bhopal were not only poisoned by gas, but have since been poisoned by neglect, highlighting the long-term institutional and systemic failures that compounded the original tragedy (Mathur & Morehouse, 2002). The toxic leak caused acute health crises and unleashed chronic psychological, immunological, and genetic issues that are still being observed decades later (Mishra et al., 2015).

The immediate health consequences highlighted various acute medical phenomena, predominantly respiratory, ocular, and neurological disorders. Victims experienced severe pulmonary edema, contributing to the fatalities that occurred during the disaster (Broughton, 2005). Follow-up studies conducted over the years have revealed persistent genomic instability among the exposed population, indicating that the health ramifications extend far beyond the initial chemical exposure (Samarth et al., 2021; Senthilkumar et al., 2015). The tragedy has been linked to severe reproductive health issues, including significantly elevated rates of stillbirths and infant mortality in the exposed population, which were reported to be three to four times higher than usual (Varma, 1987; Sarangi et al., 2010).

The long-term health and psychological consequences of industrial disasters, as observed in Bhopal, underscore the importance of understanding research trends in areas such as mental health, disaster response, and psychosocial preparedness, justifying a bibliometric analysis to map thematic developments and identify knowledge gaps (Marceta & Jurišic, 2024). The Bhopal Gas Tragedy also cast a long shadow on mental health within the survivor community. Evidence shows a lasting psychological impact characterized by elevated rates of PTSD, anxiety, and depression (Rao, 2006; Murthy, 2014). The study of disaster resilience in vulnerable communities, such as the low socio-economic and institutional resilience observed in coastal Bangladesh, highlights the critical need to examine how research addresses both immediate and long-term adaptive capacities, reinforcing the value of a bibliometric analysis of Bhopal-related literature to inform disaster governance, public health strategies, and community resilience (Kabir, Hossain, & Haque, 2022)

Bhopal is frequently cited in global debates on industrial accountability, risk communication, and sustainable development, making it a landmark case for researchers and policymakers alike (Shrivastava, 1992). Over the past four decades, this tragedy has generated widespread academic attention across disciplines, reflecting the complex interplay of industrial risk, environmental justice, and human rights (Dhara & Dhara, 2002; Sriramachari, 2004). Despite the vast academic output, there remains a significant research gap, a lack of comprehensive meta-analytical or bibliometric synthesis that systematically maps the evolution, collaboration patterns, and thematic trends in Bhopal-related scholarship. The research problem of this study is to identify trends, key contributors, and the evolution of the study over time through bibliometric analysis.

Industrial disasters, including chemical accidents such as Bhopal, result from the interaction of technical failures, human errors, and insufficient safety procedures, highlighting the need for a systematic analysis of research trends to inform disaster governance, corporate accountability, and public health resilience (Cvetković, Renner, & Jakovljević, 2024; Cvetković, 2025).

In the context of disaster governance, bibliometric synthesis allows researchers to trace how academic focus has shifted from immediate crisis response to long-term policy frameworks, community preparedness, and institutional resilience (Liu et al., 2022; Mănescu et al., 2022). Effective management of chemical industrial disasters requires coordinated emergency response and business continuity planning to minimize operational, human, and environmental risks, highlighting the importance of synthesizing research trends to inform disaster governance and policy development (Kumar, 2024). It identifies how insights derived from Bhopal have contributed to broader discussions on environmental management, risk communication, and disaster policy formation.

Regarding corporate accountability, this analysis maps the progression of research addressing ethical responsibility, regulatory mechanisms, and industrial safety governance. By visualizing citation networks and thematic linkages, the study highlights how Bhopal-related research has influenced the global discourse on corporate ethics, sustainability, and environmental, social, and governance (ESG) management (Siao et al., 2022; Hallinger, 2021). In relation to public health resilience, bibliometric mapping reveals the evolution of interdisciplinary research addressing the long-term health, psychological, and social effects of industrial disasters. It emphasizes the need to integrate community-based recovery models, mental health interventions, and epidemiological surveillance into broader resilience frameworks (Liu et al., 2022).

This bibliometric approach adds significant value by transforming fragmented literature into a structured knowledge map. It enables the identification of research gaps, interdisciplinary connections, and policy-relevant insights that can strengthen future academic inquiry and inform evidence-based decision-making in environmental governance and industrial risk management (Hallinger, 2021; Siao et al., 2022).

1.1. Need and Significance

This study is the comprehensive bibliometric analysis of research on the Bhopal Gas Tragedy, offering a systematic mapping of four decades of scholarly output. It identifies major thematic trends, influential authors, and collaboration networks, while uncovering underexplored areas such as interdisciplinary integration, mental health research, and policy-oriented studies. The findings provide valuable insights to guide future research directions and inform evidence-based policy formulation in industrial safety and environmental governance.

1.2. Objectives

- To map the growth and development of scholarly publications related to the Bhopal Gas Tragedy
- To identify the most influential journals, authors, and institutions contributing to the literature on the Bhopal Gas Tragedy
- To explore thematic evolution and research trends through keyword analysis
- To evaluate the interdisciplinary nature of research on the Bhopal Gas Tragedy

2. Method

The bibliometric analysis of literature related to the Bhopal Gas Tragedy reveals a focused yet steadily expanding body of scholarly work addressing one of the most consequential industrial disasters in history. Bibliometric analysis is a robust quantitative method for assessing the structure, performance, and thematic evolution of a scientific field by applying statistical and network-based tools (Adarsh & Sulthana, 2025). A total of 301 documents were retrieved from distinct sources, including peer-reviewed journal articles, book chapters, conference proceedings, and reviews, reflecting the interdisciplinary and evolving nature of research on this critical topic (Figure 1).

Publications were retrieved from two major bibliographic databases: Scopus and Web of Science (WoS). The search strategy included keywords related to "Bhopal Gas Tragedy," "industrial disaster," "environmental health," and "chemical exposure."

The time frame from 1984 to 2024 was selected to cover the entire scholarly response to the Bhopal Gas Tragedy, spanning four decades from the immediate aftermath to the present. Publications from 2025 were excluded because the year is ongoing, and indexing of articles in databases such as Scopus and Web of Science is incomplete, which could introduce inconsistencies and bias in the dataset.

Publications were included if they focused directly on the Bhopal Gas Tragedy or its health, environmental, social, or policy impacts. Studies not relevant to the disaster or lacking complete bibliographic information were excluded. Only publications in English were included, potentially introducing a language bias by excluding non-English literature.

Bibliometrix was chosen over tools such as VOSviewer and CiteSpace because it offers greater flexibility and reproducibility through its integration with R programming. Unlike VOSviewer, which primarily focuses on visualization, and CiteSpace, which emphasizes citation burst detection, Bibliometrix provides a comprehensive set of quantitative metrics, advanced statistical functions, and customizable analyses. Its integration allows for scripting, automation, and reproducible workflows, making it particularly suitable for rigorous, transparent bibliometric studies.

While bibliometric analysis offers a powerful tool for mapping research landscapes, it has inherent limitations. These include database bias, as some journals may not be indexed in Scopus or WoS, author name variations that may fragment collaboration networks, and the exclusion of non-English publications, which can limit the comprehensiveness of the study.

2.1. Data Collection

The data collection stage involves extracting relevant research articles from selected databases using well-defined search queries. After extraction, duplicate records between the Scopus and Web of Science databases were identified and removed using the R script >combined<-mergeDbsources (file name, remove.duplicated=TRUE), ensuring an accurate, non-redundant dataset for analysis.

The search query has been used for extracting documents from Web of Science (WOS), and Scopus are listed below;

("Bhopal gas tragedy*" OR "Bhopal disaster*" OR "Bhopal gas leak*" OR "Bhopal chemical disaster*" OR "Union Carbide Bhopal*" OR "Bhopal industrial disaster*" OR "Bhopal accident*" OR "Bhopal 1984" OR "Bhopal MIC leak*" OR "Bhopal aftermath" OR "Bhopal survivors" OR "Bhopal compensation")

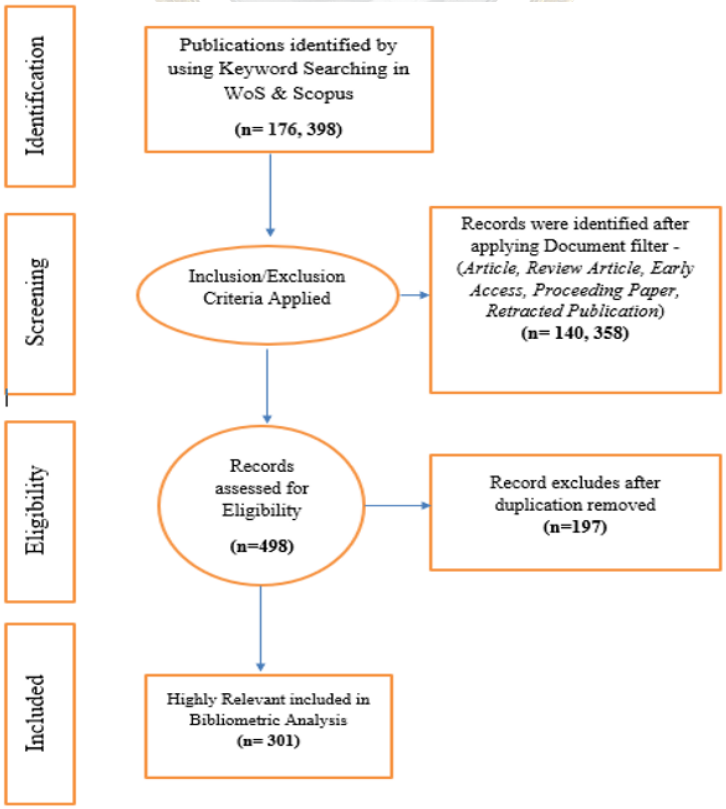

Figure 1. Methodology flow chart.

2.2. Data Analysis

The analysis was conducted using specialized bibliometric tools, Biblioshiny (an R-based bibliometric package) (Aria & Cuccurullo, 2017). The following techniques were applied:

- **Descriptive Analysis:** This involved the identification of publication trends, prominent journals, influential authors, and citation metrics.
- **Co-occurrence Analysis:** Keywords were analysed to visualize the thematic structure of the research field using network maps.
- **Thematic Mapping:** Themes were classified based on relevance and development degree using a two-dimensional analysis, categorizing topics into Basic Themes, Motor Themes, Niche Themes, and Emerging or Declining Themes.
- **Collaboration Network Analysis:** Country-level collaboration networks were assessed to identify leading research hubs and international partnerships
- **Thematic Evolution:** Temporal changes in research focus were mapped using Sankey diagrams to trace the progression of topics over different time periods.
- Factorial Analysis; Applied to identify underlying structures within the data by performing multiple correspondence analyses, thereby revealing thematic clusters

3. Result and Discussion

3.1. Annual Scientific Production

The annual publication output on the Bhopal Gas Tragedy from 1984 to 2024 totals 301 documents, reflecting steady but moderate scholarly engagement over four decades. The initial period (1984–1990) saw 43 publications, with a notable peak in 1985 (11 articles), indicating strong immediate academic interest following the disaster (Figure 2). From 1991 to 2004, output remained relatively low and stable, with annual publications ranging from 1 to 7, and a complete absence in 2001. A significant spike occurred in 2005 (18 articles), likely influenced by the 20th anniversary of the tragedy.

Between 2005 and 2015, the field experienced a more consistent output, averaging 9–14 publications annually, with visible peaks in 2010 (12), 2012 (15), and 2015 (14). This reflects growing academic engagement and thematic diversification. In the final phase (2016–2024), annual output remained strong, exceeding 10 publications per year. The highest productivity was observed in 2024 (19 articles), indicating renewed interest, possibly linked to the 40th anniversary. This trend suggests the sustained relevance of the Bhopal Gas Tragedy in contemporary scholarly discourse.

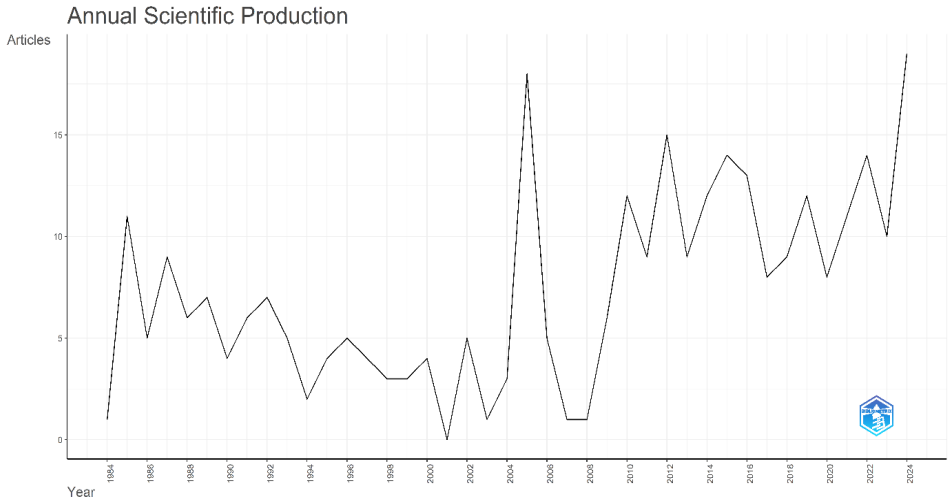

Figure 2. Annual scientific production (all figures in this paper, except Figure 6, have been prepared using Biblioshiny (Aria & Cuccurullo, 2017).

3.2. Citation Impact Over Time

The citation impact of scholarly output on the Bhopal Gas Tragedy varies significantly over the 40 years, reflecting shifts in both academic attention and long-term relevance. Early publications, particularly between 1985 and 1991, show relatively high average citation counts, with years such as 1987 (19.22), 1988 (14.83), and 1991 (17.67) indicating strong academic engagement and influence.1999 recorded the highest average with 31 citations per article, although based on a small number of documents ($n = 3$), suggesting the influence of a few highly cited works.

Subsequent peaks include 2003 (61.00) and 2005 (38.17), both likely driven by landmark publications and anniversary-related retrospectives. The years 2009 (21.83) and 2010 (27.92) also demonstrate substantial citation impact, suggesting a phase of heightened academic relevance. Post-2015, the average number of citations per article has declined. From 2019 onwards, the average falls below 5 citations per article, with 2023 (0.60) and 2024 (0.37) recording the lowest figures. This decline is expected due to the *recency effect*, as newer publications typically have had less time to accumulate citations. Citation impact has been concentrated in specific timeframes, particularly following anniversaries or significant policy developments, while recent years remain under-cited due to temporal proximity.

3.3. Most Relevant Sources

An examination of the publication sources reveals a *broad interdisciplinary distribution* of research on the Bhopal Gas Tragedy, with articles appearing across journals in chemical safety, environmental science, occupational health, public policy, and oral history. The most prolific source is the *Journal of Loss Prevention in the Process Industries*, contributing 20 articles, reflecting a strong emphasis on industrial safety, process risk management, and accident prevention. This is followed by *Process Safety and Environmental Protection* with 10 articles, reinforcing the technical and regulatory focus within the chemical process industries. The *Economic and Political Weekly* features 7 articles that highlight the integration of socio-political analysis and public discourse into the academic treatment of the tragedy. Health-related research is represented through the *Indian Journal of Medical Research* (5 articles) and *Toxicology and Industrial Health* (4 articles), emphasizing medical, toxicological, and long-term epidemiological concerns.

Environmental dimensions are captured through journals such as *Atmospheric Environment* (4 articles) and *Journal of Hazardous Materials* (4 articles), indicating sustained interest in air quality, pollution dispersion, and hazardous material management. Additionally, the presence of *Palgrave Studies in Oral History* (4 articles) underscores the importance of survivor testimonies, memory studies, and narrative documentation as a growing area of scholarship. The diversity of sources demonstrates the *multidimensional nature* of Bhopal-related research and its relevance across both scientific and humanistic disciplines.

3.4. Core Sources by Bradford's Law

Bradford's Law, introduced by Bradford (1934), describes the dispersion of articles across scientific journals. To identify the most influential sources in the literature on the Bhopal Gas Tragedy, Bradford's Law was applied. This law categorizes journals into zones based on the concentration of articles, helping to distinguish core sources that contribute the most to a given research field.

As illustrated, the core zone comprises a small number of journals that account for a disproportionately high number of articles. Specifically, the *Journal of Loss Prevention in the Process Industries* (20 articles) and Process Safety and Environmental Protection (10 articles) are the most prominent sources (Figure 3). These two journals together form the nucleus of scholarly output and are primarily focused on industrial risk management, process safety, and accident prevention, key themes in Bhopal-related research.

Other journals within the core zone include Economic and Political Weekly, Indian Journal of Medical Research, Atmospheric Environment, and Journal of Hazardous Materials, each contributing 4-7 articles. These sources reflect the multidisciplinary nature of Bhopal scholarship, spanning political economy, medical science, environmental studies, and toxicology.

The steep drop in the curve beyond the core zone indicates a high dispersion of articles across numerous peripheral sources, many of which contain only a single publication related to the topic. This confirms that while the core journals are central to the discourse, the broader literature is spread across a diverse range of journals, reflecting the topic's interdisciplinary appeal.

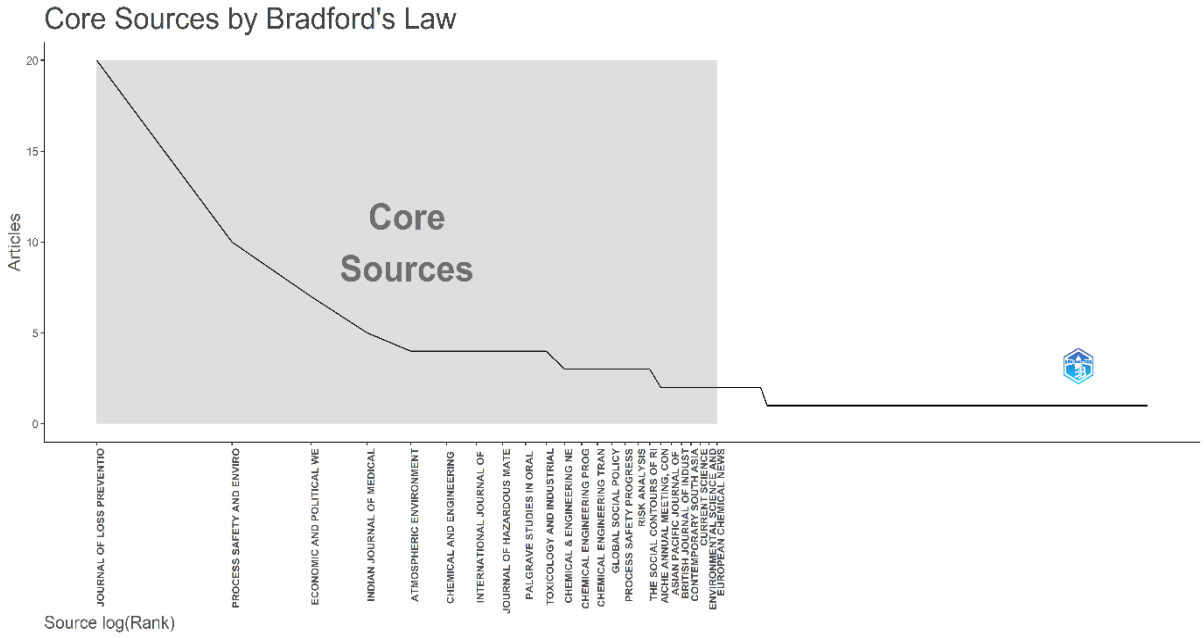

Figure 3. Core Sources Identified by Bradford's Law for Publications. The shaded region highlights the "core zone" of journals contributing the majority of publications in the dataset.

3.5. Sources' Local Impact

The local impact of publication sources was assessed using standard bibliometric indicators, including the h-index, total citations (TC), and number of publications (NP) related to the Bhopal Gas Tragedy. The *Journal of Loss Prevention in the Process Industries* emerged as the most influential source, with an h-index of 10, 344 total citations, and 20 publications since 2002. Similarly, *Process Safety and Environmental Protection* holds a strong position, with an h-index of 9, 282 citations, and 10 articles, and began its contributions in 2002.

Among health- and environment-focused journals, the Indian Journal of Medical Research shows a notable impact, with 5 articles, 79 citations, and an h-index of 5, dating back to 1987. Environmental science contributions are represented by *Atmospheric Environment* (h-index 4, 65 citations), with consistent outputs since 1995. The *Economic and Political Weekly*, though contributing 7 articles, has a comparatively low citation count (15) and h-index (3), indicating broader public discourse rather than citation-driven academic engagement.

Journals such as *Risk Analysis*, *Journal of Hazardous Materials*, and the *International Journal of Occupational Medicine and Environmental Health* also demonstrate mid-level impact with h-indices of 3 and total citations ranging from 84 to 107. These sources reflect interest in occupational risk, hazard mitigation, and long-term exposure studies. Finally, journals like the *British Journal of Industrial Medicine* and *Asian Pacific Journal of Cancer Prevention* contribute fewer articles, but with citation counts that reflect the relevance of specific studies within their domains.

The local impact analysis confirms that while a few core journals dominate in volume, citation impact is distributed among both high-output and lower-frequency sources, highlighting the interdisciplinary and fragmented nature of research on the Bhopal Gas Tragedy.

3.6. Most Relevant Authors

An analysis of the most prolific contributors to Bhopal Gas Tragedy research reveals a core group of authors with sustained engagement in the field, measured by both total publications and fractionalized authorship, which accounts for co-authorship weight.

P. Mishra leads in terms of total output, with 9 articles and a fractionalized contribution of 2.47, suggesting involvement primarily as a co-author across multiple collaborative works. While Mishra has the highest number of publications, the comparatively lower fractional score indicates shared authorship. *B. Bowonder* and *J. Gupta* follow closely, each with 8 and 7 publications, and high fractionalized scores of 5.42 and 5.46, respectively. These values suggest that both scholars have played significant roles in their publications, likely as first or corresponding authors, highlighting their central intellectual contributions to the field.

V. Dhara also stands out with 7 publications and a fractional score of 3.06, indicating both frequency and depth of involvement. Dhara's work has been influential, particularly in documenting the long-term health and epidemiological effects of the disaster. *W. Lepkowski* is unique in having a perfect one-to-one ratio, with 6 articles and a full fractional contribution of 6.00, implying single authorship or lead authorship in all publications. This suggests a strong independent contribution to the literature.

Other frequent contributors include *K. Maudar* and *N. Pathak* with 6 articles each, though their lower fractional scores (0.97 and 0.77, respectively) indicate more limited roles within co-authored papers. Notably, *S. Acquilla*, *J. Kasperson*, and *R. Kasperson* each authored 5 publications, with similar fractional contributions of 1.46-1.62, suggesting occasional but substantial involvement, possibly in interdisciplinary or collaborative studies. This distribution reflects a mix of deeply engaged lead authors and collaborative contributors, pointing to both individual and institutional commitment to long-term research on the Bhopal Gas Tragedy.

3.7. Author Productivity through Lotka's Law

Lotka (1926) proposed a law that explains the distribution of author productivity in the dataset: an inverse relationship between the number of authors and their publication count. As depicted in the graph, over 80% of contributors have authored only a single document. This reflects a *long-tail distribution* typical of most scientific fields, where a small number of authors produce a disproportionate share of the literature (Figure 4).

The solid line in the plot represents the observed data, while the dashed line indicates the expected theoretical distribution according to Lotka's Law. The close alignment between the two suggests that author productivity in the Bhopal Gas Tragedy research domain aligns well with bibliometric norms. This pattern implies a research field with a broad base of occasional contributors and a smaller core of highly productive authors. The limited number of authors with three or more publications suggests that *sustained engagement* with this topic is relatively rare, potentially reflecting the field's niche nature or challenges with sustained funding and interest.

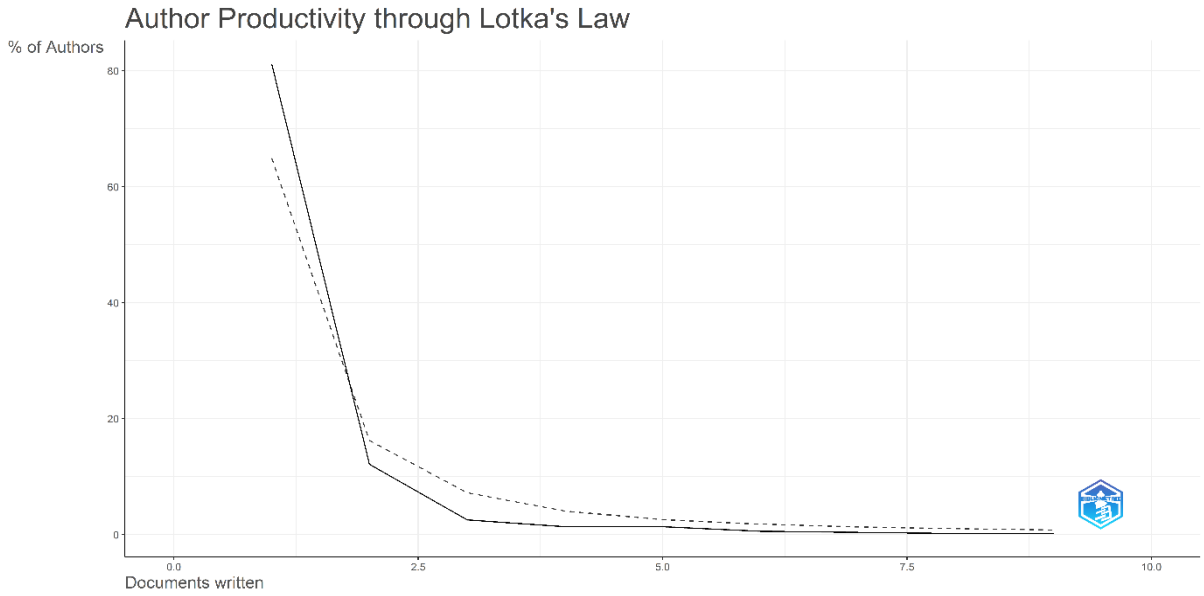

Figure 4. Author Productivity through Lotka's Law.

3.8. Most Relevant Affiliations

The analysis of institutional affiliations reveals that Indian institutions have predominantly driven research on the Bhopal Gas Tragedy. The *Indian Council of Medical Research (ICMR)* is the most prolific contributor, with 22 publications. This highlights the central role of ICMR in advancing medical and epidemiological research related to the disaster. Closely following is the *ICMR – Bhopal Memorial Hospital and Research Centre (BMHRC)*, with 19 articles. As a specialized institution located in the region directly affected by the tragedy, BMHRC has played a crucial role in long-term health monitoring and clinical studies on survivors.

The *Indian Institute of Technology (IIT) System* contributed 9 publications, reflecting an important engagement with engineering, risk analysis, and industrial safety. International collaboration is evident as well, with *McGill University* and the *University of Pennsylvania* each publishing 7 articles, suggesting sustained academic interest in the Bhopal disaster among leading global institutions. Other key contributors include the *Advanced Centre for Treatment, Research and Education in Cancer (ACTREC)* and the *Tata Memorial Centre (TMC)*, each with six publications, indicating a strong oncology and toxicology research component. Regional engineering and technical institutions such as the *Maulana Azad National Institute of Technology (MANIT) Bhopal*, the *National Institute of Technology (NIT) System*, and *Memorial University of Newfoundland* also appear among the top affiliations, each contributing five articles.

This distribution reflects a collaborative research landscape with strong national leadership from Indian public health and engineering institutions, complemented by selective, yet meaningful, international academic participation.

3.9. Corresponding Authors' Countries

The analysis of the countries of corresponding authors provides insight into the geographic origins of research on the Bhopal Gas Tragedy and the extent of international collaboration. Countries are classified based on whether publications are authored solely by researchers from one country (Single Country Publications – SCP) or co-authored across national borders (Multiple Country Publications – MCP).

India emerges as the most prolific contributor, followed by the United States, together accounting for the majority of publications. However, both nations show a strong dominance of SCPs, with low

MCP rates (India: 4.9%, USA: 4.7%). This suggests a reliance on domestic research networks and infrastructure, potentially influenced by funding mechanisms, national research priorities, or the localized nature of the Bhopal case. It also highlights that, while international co-authorship may be present, the corresponding author role remains predominantly national (Figure 5).

In contrast, smaller or more developed nations such as the Netherlands and South Africa exhibit 100% MCP rates, indicating a clear preference or necessity for international collaboration to address this topic. Germany and Canada also display relatively high levels of cross-border cooperation (33.3% and 28.6%, respectively), which may reflect their strong global academic linkages and support for collaborative research frameworks. Several countries, including Australia, Italy, Mexico, Singapore, Brazil, Colombia, Greece, Jordan, Norway, the Philippines, Portugal, and Turkey, show no recorded MCPs. This absence of international collaboration may stem from limited engagement in this specific research area, regional research agendas, or resource constraints.

Countries such as the United Kingdom, China, and France exhibit mixed collaboration patterns, engaging in both domestic and international research. This balance suggests a dual strategy of building national expertise while remaining integrated within the global research ecosystem. The collaboration profile indicates a centralized research structure in dominant countries like India and the USA, alongside more outward-looking strategies among smaller or research-intensive nations.

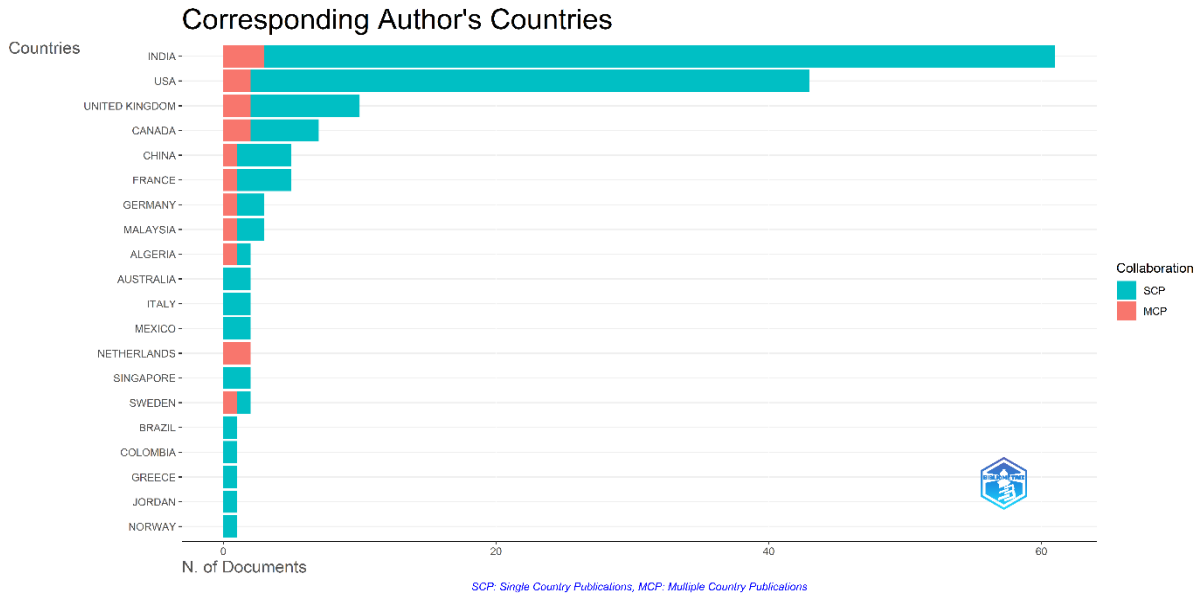

Figure 5. Corresponding Author Countries.

3.10. Most Cited Countries

Citation analysis by country reveals notable geographic trends in research impact. The *United States* leads with 1,033 citations and an average of 24 citations per article, underscoring its dominant role in shaping scholarly discourse on the Bhopal Gas Tragedy. India, despite being the most productive country in terms of publication count, ranks second in citations with 610 total citations and a comparatively lower average of 10 citations per article, suggesting a need for broader international engagement or visibility (Figure 6).

The United Kingdom (176 citations, 17.6 per article) and Canada (169 citations, 24.1 per article) also demonstrate strong academic influence. Notably, Mexico stands out with an exceptionally high average of 65 citations per article from 130 total citations, indicating fewer but highly impactful publications. Countries such as Norway (53 citations, 53.0 per article) and Brazil (39 citations, 39.0 per article) similarly reflect high-impact contributions from limited output. Meanwhile, China, France, and Italy each show moderate citation performance, reflecting steady but less central roles in the citation landscape. These findings suggest that while countries like India are central to the discourse

in terms of volume, others, particularly the USA, Mexico, and Canada, play a more influential role in shaping academic impact.

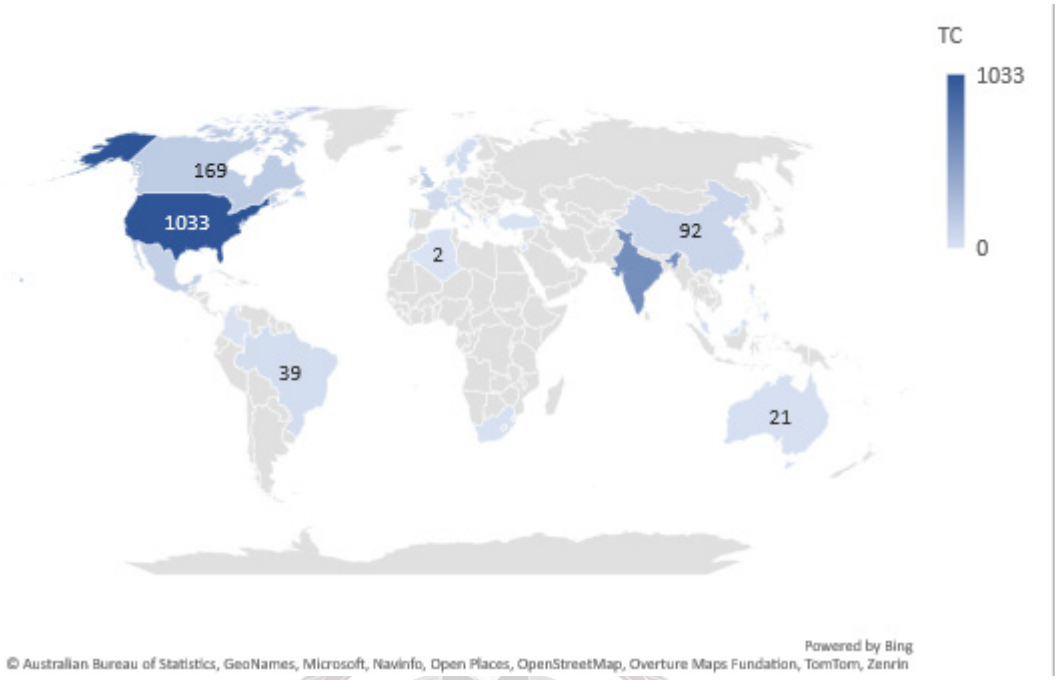

Figure 6. Most cited countries.

3.11. Most Global Cited Documents

The most influential publications within the corpus are identified through total citations and citation rates per year. *Broughton (2005), published in Environmental Health, is the most cited work,* with *375 total citations* and an impressive *17.86 citations per year*, indicating enduring relevance and scholarly impact (Table 1). *Weick (2010)* also demonstrates substantial influence, with *194 citations* and a citation rate of *12.13 per year*, underscoring the ongoing importance of organizational learning and disaster interpretation. *Bessac (2010) and Ice (1991) follow with 119 and 104 citations,* respectively, reflecting the continued interest in toxicological and communication perspectives. *Varma (2005) and Khan (1999) have received 97 and 90 citations, respectively, with Varma's work contributing to science and technology discourse and Khan's spanning safety processes* and technological forecasting.

Among Indian contributors, *Mishra (2009)* stands out with *77 citations* and *4.53 per year*, reflecting regional expertise in occupational and environmental medicine. Earlier foundational works, such as *Varma (1993), Kleindorfer (2003), and Cullinan (1997), also continue to attract* academic attention, each exceeding *50 citations* over time. These publications constitute the intellectual high points of Bhopal-related research, bridging the domains of health, management, communication, and risk assessment.

Table 1. Most Global Cited Documents.

Paper	DOI	Total Citations	TC per Year
BROUGHTON E, (2005). ENVIRON HEALTH GLOBAL ACCESS SCI SOUR	10.1186/1476-069X-4-6	375	17.86
WEICK, K. (2010). J MANAGE STUD	10.1111/j.1467-6486.2010.00900.x	194	12.13
BESSAC B, 2010, PROC AM THORAC SOC	10.1513/pats.201001-004SM	119	7.44
ICE R (1991). MANAGE COMMUN Q	10.1177/0893318991004003004	104	2.97
VARMA R, (2005). BULL SCI TECHNOL SOC	10.1177/0270467604273822	97	4.62

KHAN F, (1999). PROCESS SAF PROG TECHNOL FORECAST SOC CHANGE	10.1002/prs.680180304 10.1016/0040-1625(87)90039-4	90	3.33
MISHRA P (2009). INT J OCCUP MED ENV	10.2478/v10001-009-0028-1	77	4.53
VARMA D, (1993). J TOXICOL ENV HEALTH	10.1080/15287399309531816	64	1.94
KLEINDORFER P, 2003, RISK ANAL	10.1111/1539-6924.00365	61	2.65
CULLINAN P, (1997). BMJ-BRIT MED J	10.1136/bmj.314.7077.338	54	1.86

3.12. Most Frequent Words

An analysis of the most frequently occurring words in the dataset reveals key thematic concentrations within the literature on the Bhopal Gas Tragedy. The term *methyl isocyanate* appears most frequently, with a total of 54 occurrences (Figure 7). This reflects the centrality of the chemical compound responsible for the disaster and highlights its sustained relevance in scholarly discussions.

The word *India*, with 47 mentions, underscores the research's geographical focus, while human, with 39 mentions, points to the emphasis on human health impacts and exposure outcomes. Closely following are the terms *Bhopal* (37 occurrences), *Bhopal disaster* (36), and *Bhopal gas tragedy* (34), all of which demonstrate the continued scholarly attention to the specific case and its enduring legacy.

Figure 7. Most Frequent Keywords.

The broader terms, such as disasters (31) and disaster (26), indicate an expansion of focus to include general industrial and environmental catastrophes. The terms *chemical industry* (24) and *accidents* (20) suggest a consistent interest in systemic industrial safety, operational risks, and accident prevention. These high-frequency words collectively reflect the field's dominant concerns: the chemical and industrial origins of the tragedy, its location-specific context, and the significant human and environmental consequences that followed.

3.13. Trend Topics

The analysis of trend topics over time reveals a dynamic shift in the research focus on the *Bhopal Gas Tragedy*. In the early years following the incident, particularly from the late 1980s through 2000, the literature was dominated by terms directly referencing the event itself. Keywords such as

"Bhopal," "Bhopal Gas Leak," "Bhopal Accident," "Methyl Isocyanate," "Cyanates," and *"Chemical Plants"* were among the most frequently occurring. These early terms reflect the immediate academic concern with understanding the technical, chemical, and operational causes of the disaster, as well as the toxicological effects of the gas release. The continued presence of these keywords across subsequent years, indicated by their extended horizontal trajectories in the trend plot, suggests their sustained relevance in the scholarly discourse.

During the 2000s and early 2010s, a noticeable shift in terminology emerged. Keywords expanded to include more general disaster-related terms such as *"Disaster," "Disasters," "Explosions," "Industrial Disasters," "Exposure," "Hazardous Materials," "Risk Assessment,"* and *"Management."* This period appears to reflect a broadening of research interests, moving from a sole focus on Bhopal to encompassing broader concerns about industrial safety and disaster risk reduction. The term *"Review"* also becomes prominent during this phase, particularly between 2006 and 2016, indicating an increase in integrative studies and retrospective analyses aimed at consolidating existing findings on industrial accidents.

In the most recent period, from 2016 onward, there is a discernible increase in the use of demographic and health-related terms. Keywords such as *"Adult," "Aged," "Middle Aged," "Humans,"* and *"Male"* suggest a growing interest in understanding how industrial disasters affect human health across different population groups. At the same time, the appearance of *"COVID-19"* as a keyword marks a significant contemporary shift, reflecting the integration of pandemic-related themes into broader disaster and health impact research. Environmental concerns also appear to be gaining traction, as evidenced by the rising use of the term *"Environment."* This may indicate a renewed emphasis on ecological consequences and long-term sustainability considerations in the context of industrial incidents.

The trend topic analysis highlights how scholarly attention has evolved in response to both the enduring legacy of the *Bhopal disaster* and the emergence of new global health and environmental challenges. The shifts in keyword frequency and timing underscore the academic community's responsiveness to evolving societal concerns while maintaining a foundational focus on the core issues related to the original industrial tragedy.

This temporal evolution illustrates how the Bhopal Gas Tragedy has transformed from a localized industrial accident into a global reference point for understanding systemic risk, human vulnerability, and environmental governance. The transition from chemical and technical keywords to those related to health, demography, and sustainability signals a maturing research paradigm that increasingly integrates social and ecological dimensions of industrial disasters. The recent convergence of pandemic-related and environmental terms further indicates that scholars are framing Bhopal within broader discourses of planetary health and resilience. This interpretative trajectory underscores the continuing relevance of Bhopal not only as a historical case but as a conceptual anchor in global disaster and public health scholarship.

3.14. Co-occurrence Network Analysis

The keyword co-occurrence network reveals a moderately dense structure, suggesting a notable degree of interconnectedness among concepts within the literature on the Bhopal Gas Tragedy. The network's density indicates that many keywords co-occur frequently, suggesting the development of shared vocabularies and interlinked research themes. The *Walktrap clustering algorithm* has effectively identified multiple communities, each representing a distinct thematic area within the broader research domain. The varying node sizes reflect keyword frequency, with larger nodes such as *"human," "India," "methyl isocyanate,"* and *"disaster"* denoting central terms that are both frequent and well-connected across clusters (Figure 8).

Each color-coded cluster offers insight into specific sub-domains. The purple cluster appears to focus on *health impacts and affected populations*, particularly the survivors of the disaster. Terms such as *"Bhopal accidental release," "middle-aged female," "male," "humans," "adults," "survivors,"* and *"public health"* dominate this area, indicating an epidemiological and medical lens. The inclusion of *"oxi-*

dative stress" points to investigations into biological responses and toxicological effects. The green cluster centers on chemical exposure and environmental health, with key terms such as *"cyanates," "gas poisoning," "nonhuman," "review," "disaster,"* and *"pollution."* This suggests studies concerned with chemical toxicity, occupational exposure, and broader environmental risks.

The blue cluster reflects themes related to *accident prevention and safety management*, with keywords such as *"accidents," "accident prevention," "risk assessment," "safety," "Bhopal,"* and *"Madhya Pradesh."* These highlight a strong emphasis on risk mitigation, policy response, and regional specificity. The orange cluster connects to the *industrial and temporal dimensions* of the event, containing terms like *"hazards," "chemical plants," "industrial accidents," "management,"* and *"risk."* This points to systemic concerns about industrial safety and governance over time. Smaller clusters also emerge: the pink cluster is centered around *"exposure,"* likely focusing on dose-response studies and environmental health monitoring, while the gray cluster, consisting solely of *"model,"* may represent attempts to develop conceptual or predictive models of the disaster or its consequences.

The most central terms *"human," "India," "methyl isocyanate,"* and *"disaster"* capture the essential focus of the field. *"Human"* reflects the persistent concern with public health and direct human impact. *"India"* anchors the research geographically and contextually. *"Methyl isocyanate"* highlights the toxic agent at the center of the tragedy, and *"disaster"* encapsulates the overarching framework through which the event is studied. Together, these elements illustrate a multifaceted scholarly discourse that spans technical, medical, environmental, and socio-political domains.

The structure of the co-occurrence network demonstrates how research on the Bhopal Gas Tragedy has matured into an interconnected and interdisciplinary knowledge system. The coexistence of biomedical, environmental, and governance-oriented clusters indicates a transition from isolated disciplinary studies toward a more integrated understanding of industrial disasters as complex socio-environmental phenomena. The strong centrality of human- and India-related terms underscores both the national embeddedness of the discourse and its human-centric ethical dimension. At the same time, the limited presence of globally oriented or comparative keywords suggests that the field remains primarily domesticated within the Indian research ecosystem, offering opportunities for broader international engagement. The network portrays a research landscape that is thematically rich yet geographically bounded, highlighting the need to globalize industrial disaster scholarship through cross-regional collaboration and comparative inquiry.

Beyond mapping conceptual relationships, the co-occurrence network indirectly reflects patterns of scholarly collaboration and knowledge transfer. The clustering of public health, safety engineering, and environmental governance themes suggests emerging intersections between scientific and policy-oriented communities. However, the overall structure reveals limited integration of international safety networks. Strengthening connections with global platforms such as ProSafeNet (https://prosafenet.com/), the Global Hub for Safety, Security, Risk & Emergency Professionals, could substantially enhance research capacity and international equity in industrial disaster scholarship. ProSafeNet exemplifies how collaborative infrastructures can turn expertise into action through shared training, real-time communication, and transnational learning, helping build a safer, more resilient world. Integrating such collaborative mechanisms would not only expand India's leadership in industrial risk research but also promote reciprocal knowledge exchange and co-development of standards, ensuring that lessons from Bhopal inform global safety governance.

From a policy perspective, the network clusters point to practical imperatives for disaster management and industrial resilience. The dominance of health- and environment-related clusters underscores the ongoing need for robust environmental monitoring and long-term epidemiological surveillance. Meanwhile, clusters emphasizing "risk management," "accident prevention," and "safety" translate directly into frameworks for industrial hazard regulation, on-site emergency planning, and institutional accountability. The integration of these themes signals a maturing research field that increasingly aligns with the objectives of the Sendai Framework for Disaster Risk Reduction (2015–2030)—particularly its priorities on understanding risk, strengthening governance, and enhancing preparedness. Thus, the co-occurrence network not only maps academic interconnections but also highlights pathways for translating knowledge into capacity building, regulatory innovation, and community resilience.

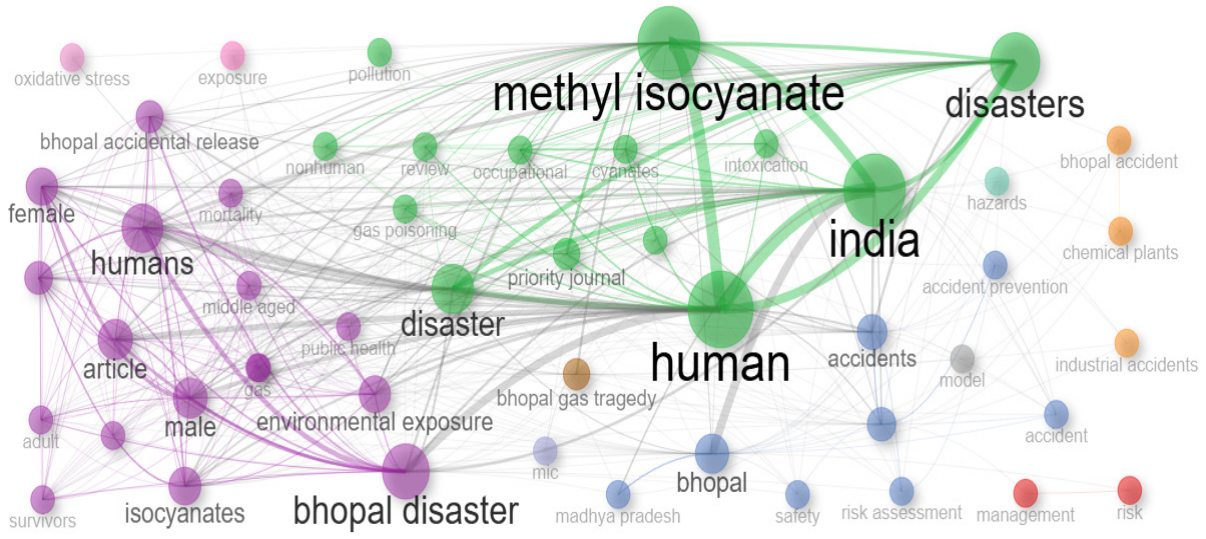

Figure 8. Co-occurrence Network Analysis of Keywords.

3.15. Thematic Map

The thematic map, constructed using the *Walktrap* community detection algorithm and visualized through a strategic diagram, provides a structured representation of the conceptual landscape in Bhopal Gas Tragedy research. Themes are plotted according to two key parameters: *centrality*, indicating their importance within the overall field, and *density*, reflecting their internal development or cohesion (Figure 9). The map is divided into four quadrants: motor themes, basic themes, niche themes, and emerging or declining themes, each offering insights into the evolution and positioning of various research focuses.

Positioned in the upper-right quadrant, the motor themes represent the most central and well-developed areas of research. Dominated by topics related to the *Bhopal disaster* and *methyl isocyanate*, this cluster reflects the core scholarly interest in the direct health, genetic, and environmental consequences of the gas leak. High-impact articles such as Ganguly (2018) in *Mutation Research* and *Environmental Science and Pollution Research*, and De (2020) in *Public Health*, underscore a robust body of work examining mutagenic effects, public health outcomes, and pollution-related consequences. A related sub-theme, identified as *priority journals*, includes foundational articles such as Ramana (1992) in Archives of Environmental Health, which further emphasize the integration of environmental health into disaster studies.

In the lower-right quadrant, basic themes are characterized by high relevance but lower density. These themes revolve around *hazard management, explosions, accident prevention,* and *safety engineering*. Although central to the discourse, they remain less theoretically consolidated. Contributions such as Okoh (2013) in *Chemical Engineering Transactions* and Gupta (2005) in the *AIChE conference proceedings* illustrate the engineering and procedural focus of this domain. The relatively underdeveloped density suggests a potential area for future growth, especially in translating post-disaster learnings into actionable prevention strategies.

The upper-left quadrant is occupied by specialized, well-developed niche themes that are less central to the broader field. This includes clusters exploring *chemical processing, safety boards, Dow Chemical Company,* and human-centered interpretations of the Bhopal incident. These themes may support more focused investigations into regulatory responsibilities and corporate accountability, or into the human factors involved in industrial safety lapses. Despite their specialization, these clusters contribute valuable depth and diversity to the field's knowledge base.

In the lower-left quadrant, the map identifies themes that are either *emerging or declining*. These include topics such as *errors, environmental law, chemical disasters, gas dispersion, emergency planning,* and *oral history*. Their position suggests that while not yet central or well-developed, these areas

may be gaining scholarly traction or represent nascent lines of inquiry. Notably, the inclusion of *oral history* indicates a growing qualitative interest in personal narratives and lived experiences of the disaster, contrasting the otherwise data- or systems-driven nature of much of the literature.

The thematic map reveals that research in this domain is heavily oriented toward analysing the immediate consequences of the Bhopal tragedy, particularly in terms of health and environmental damage. However, the positioning of themes such as *accident prevention* and *risk management* in the map's basic and peripheral areas suggests that more emphasis on proactive, preventive frameworks may still be required. Furthermore, the presence of emerging themes related to legal, environmental, and human factors points to a gradually shifting focus towards more systemic and policy-oriented perspectives in industrial disaster scholarship.

The structure of the thematic map underscores both the maturity and the limitations of the existing research landscape. The dominance of post-disaster biomedical and environmental themes suggests that scholarly attention has largely remained reactive—centered on the consequences rather than the governance of industrial risk. The relative marginality of prevention and legal frameworks reveals an imbalance between response-oriented inquiry and proactive resilience-building approaches. At the same time, the gradual emergence of themes like environmental law and oral history signals an epistemological broadening—from technoscientific analyses toward human-centered and justice-oriented perspectives. This shift marks an important step toward integrating industrial disaster studies within the wider paradigms of sustainability, human rights, and disaster governance. To advance the field, future research should bridge these thematic divides by linking environmental science, legal accountability, and community memory into cohesive frameworks of industrial risk reduction and resilience.

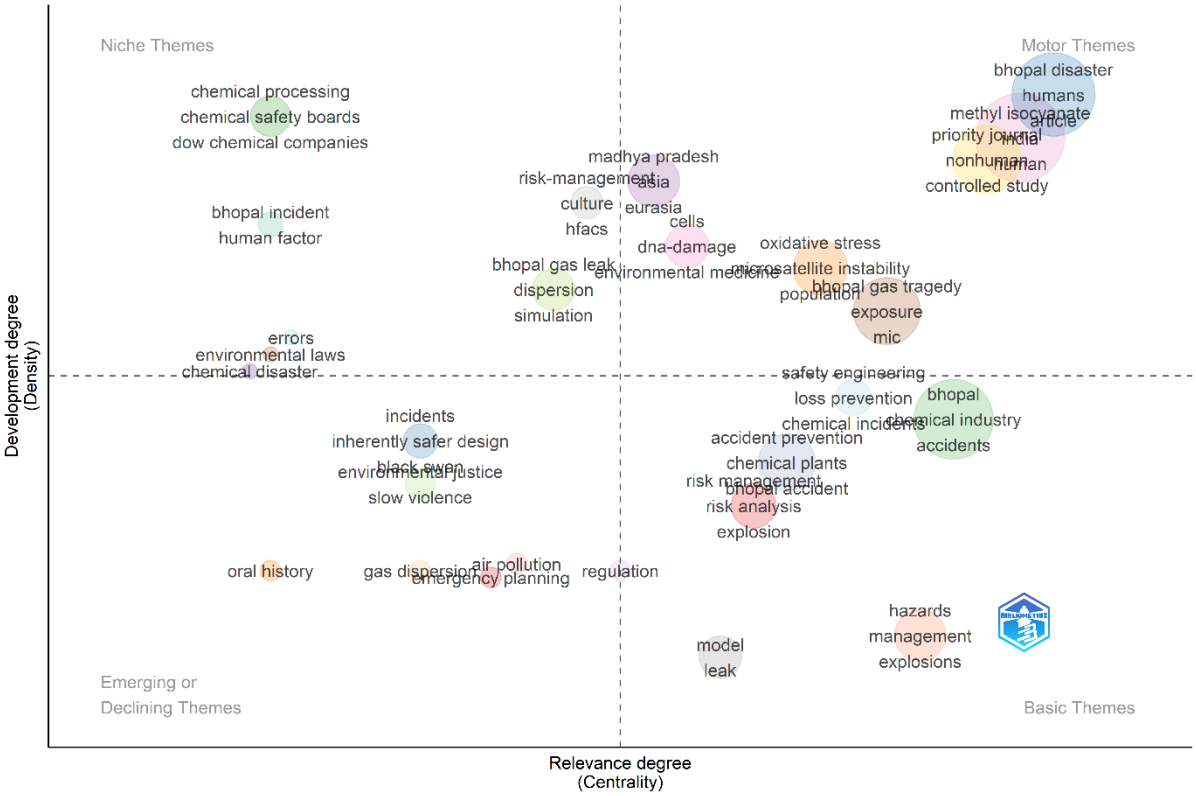

Figure 9. Strategic visualisation of the intellectual structure of research by plotting the main themes based on two key metrics: centrality and density.

3.16. Thematic Evolution

Thematic evolution analysis reveals a clear trajectory in the development of scholarly interest surrounding industrial disasters, with the *Bhopal Gas Tragedy* remaining a dominant and enduring point

of reference. The longitudinal mapping, visualized through Sankey diagrams and strategic maps, demonstrates how research themes have shifted from immediate responses and localized concerns to broader questions of risk management, regulatory frameworks, and environmental sustainability (Figure 10).

In the earliest phase (1984–1989), the thematic structure was primarily driven by foundational terms such as *"India"* and *"Methyl Isocyanate"*, which emerged as motor themes. This reflects the initial scholarly effort to ground the disaster geographically and chemically, focusing on the causative agent and its immediate context. Interestingly, terms like *"Bhopal Disaster"* and *"Emergency Planning"* appeared during this period but remained underdeveloped and peripheral, possibly due to the nascent stage of academic engagement or limited data availability at the time.

By the 1990s, the thematic landscape began to expand. *"Methyl Isocyanate"* retained its central position, while *"Disasters"* emerged as a key motor theme, indicating a gradual generalization of the discourse beyond Bhopal itself. Simultaneously, terms such as *"Exposure"* and *"Gas Leak"* entered the thematic space as emerging concepts, suggesting a growing concern with the physiological and environmental consequences of chemical accidents. These themes remained in flux, reflecting a diversification in focus as the field matured.

The period from 2000 to 2009 marked a conceptual shift toward *industrial safety and risk mitigation*. Themes such as *"Loss Prevention"* and *"Chemical Safety"* emerged as dominant, highlighting an increased attention to pre-emptive measures and regulatory strategies. This evolution likely stemmed from an accumulation of knowledge about the Bhopal disaster and the need to translate those lessons into forward-looking frameworks. Notably, *"Union Carbide"*, the company at the center of the Bhopal tragedy, began to appear as a specific thematic term, suggesting growing academic scrutiny of corporate accountability.

In the following decade (2010–2019), the *"Bhopal Disaster"* re-emerged as a central motor theme, indicating renewed scholarly interest possibly spurred by milestone anniversaries or the availability of new long-term impact data. This period also saw a more sustained focus on *"Human Health"*, which denotes a transition from technical and procedural issues toward the broader societal and epidemiological consequences of the disaster. Although the number of emerging themes increased, many remained marginal, pointing to a proliferation of research areas that lacked integration with the field's core discourses.

The most recent phase (2020–2024) continues to exhibit the enduring relevance of *"Bhopal Disaster"* as a motor theme, but now within a context that includes broader concerns like *"Disasters"* and *"Risk Management"*. The inclusion of *"COVID-19"* as an emerging theme signals the intersection of pandemic research with disaster studies, particularly in environmental toxicology, public health infrastructure, and systemic vulnerability. Furthermore, themes such as *"Rehabilitation"* and *"Environmental Management"* appear as developing or peripheral concepts, indicating a potential shift toward *post-disaster recovery* and *long-term environmental governance*.

Across all five time periods, specific thematic patterns remain consistent. The centrality of *"India"* as a basic theme throughout underscores the enduring geographical specificity of the discourse. At the same time, the fluctuating prominence of *"Methyl Isocyanate"* reflects its continued relevance as a focal point of chemical concern. Over time, the terminology becomes more refined, as seen in the shift from broad geopolitical identifiers like *"India"* to more localized terms such as *"Madhya Pradesh."* This lexical refinement suggests a deepening granularity in research approaches and contextual analyses.

The thematic evolution highlights a research field that has progressively broadened from immediate chemical and health concerns to more systemic investigations into disaster prevention, legal accountability, and environmental justice. The persistent visibility of the *Bhopal Disaster* across decades not only reflects its catastrophic scale but also affirms its continued value as a *critical case study* for shaping both academic inquiry and public policy in the domain of industrial disaster research.

The thematic trajectory across four decades reveals three distinct phases in the evolution of Bhopal-related scholarship. During the 1980s and 1990s, research was primarily technical and toxicolog-

ical, reflecting immediate post-disaster inquiries into chemical properties, exposure mechanisms, and biomedical outcomes. The 2000s and 2010s marked a pronounced shift toward environmental and public health impacts, as scholars examined pollution dynamics, epidemiological consequences, and the social dimensions of recovery. In the 2010s through the 2020s, the literature began to integrate broader policy-oriented and governance frameworks, emphasizing disaster risk reduction, institutional accountability, and community resilience. This chronological transition from reactive, event-specific studies to preventive and systemic approaches underscores the field's intellectual maturation.

These temporal shifts hold significant implications for industrial safety and resilience. The early emphasis on toxicology and exposure provided critical scientific insights into the mechanisms of harm, forming the evidence base for subsequent safety protocols. The second phase, focused on environmental and health impacts, expanded the discourse to include socio-ecological systems, influencing environmental regulation and public health surveillance. The most recent turn toward policy, governance, and resilience reflects a paradigmatic reorientation from disaster response to disaster prevention—aligning with global frameworks such as the Sendai Framework for Disaster Risk Reduction and the Sustainable Development Goals. This evolution illustrates how the legacy of the Bhopal Gas Tragedy has progressively informed the architecture of industrial risk governance, transforming a singular catastrophe into a catalyst for systemic learning and institutional reform.

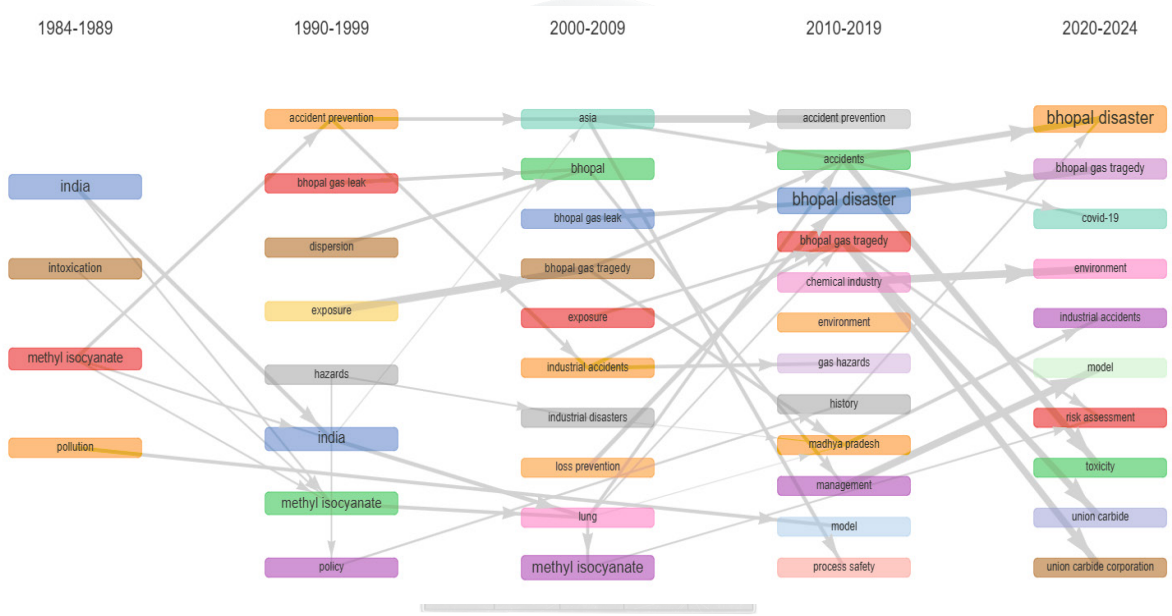

Figure 10. The thematic evolution analysis provides a longitudinal view of how research themes in the Bhopal Gas Tragedy have evolved.

3.17. Factorial Analysis

The factorial analysis, based on *Multiple Correspondence Analysis (MCA)* of the co-occurring keyword data, provides a dimensional interpretation of the conceptual space in Bhopal Gas Tragedy research. The two primary axes, Dimension 1 and Dimension 2, together account for over 90% of the variance in the data, indicating a well-structured thematic differentiation across the corpus. Specifically, Dimension 1, accounting for *80.19%* of the total variance, appears to reflect the dominant thematic polarity. In contrast, Dimension 2, explaining *10.04%*, introduces a secondary layer of differentiation that adds nuance to the conceptual layout (Figure 11).

Although no distinct clusters were extracted due to the absence or underperformance of the clustering parameter (clust:1), the spatial arrangement of terms on the factorial plane nonetheless allows for meaningful interpretative groupings based on proximity and density of terms. Terms located near each other are more likely to co-occur within the same documents, thus indicating thematic cohesion.

On the upper-left of the plane lies a clearly delineated *"Bhopal Disaster"* region. This includes terms such as *"Bhopal gas tragedy," "Madhya Pradesh," "chemical plants," "accident prevention," "exposure,"* and *"management."* The concentration of these terms suggests a strong focus on the institutional, technical, and geographic dimensions of the disaster, highlighting research related to its occurrence, location, and subsequent risk assessment strategies. Closely adjacent to this area, though slightly more centralized, is a thematically aligned *"Disaster and Accident"* cluster, where terms such as "disaster," "accident," "chemical industry," and "methyl isocyanate India" are located. This region consolidates broader industrial accident discourse and positions the Bhopal event within a comparative framework of similar industrial disasters.

In contrast, the upper-right quadrant reveals a thematically distinct *"Health Outcomes"* cluster. Terms such as *"adult," "middle-aged," "mortality," "controlled study," "survivors,"* and *"isocyanic acid derivative"* dominate this region, pointing to a strong orientation toward demographic and epidemiological research. These studies are typically concerned with the long-term medical and toxicological effects on populations affected by the disaster. The adjacency of this cluster to the central axis also suggests its integration with more general disaster and environmental health studies. Just below this lies the *"Chemical Exposure"* zone, populated by terms such as *"gas poisoning," "environmental exposure,"* and *"review."* This grouping reflects research that synthesizes toxicological pathways and the environmental spread of hazardous substances. Slightly further south and centered vertically on the plot, the *"Occupational Exposure"* grouping is represented by terms like *"intoxication," "cyanates,"* and *"occupational."* These terms point to a specialized subdomain focused on the risks faced by workers and first responders, as well as the specific occupational health consequences of the industrial gas leak. The distance of individual terms from the origin (0,0) of the factorial space indicates their relative contribution to the definition of each dimension. Along Dimension 1, terms such as *"Bhopal gas tragedy," "management"* (on the far left), and *"adult," "middle-aged," "isocyanic acid derivative"* (on the far right) exert the most influence. This suggests that Dimension 1 represents a thematic continuum ranging from *institutional and environmental management* to *population health and biomedical impacts*. Dimension 2, meanwhile, appears to stratify themes by their focus on either demographic variables, indicated by terms like "adult" and "middle-aged," at the top, or occupational and chemical risk factors, seen in terms like "occupational," "cyanates," and "intoxication," at the bottom. This axis may therefore be interpreted as a contrast between *population-level epidemiology* and *workplace-specific toxicological exposure.*

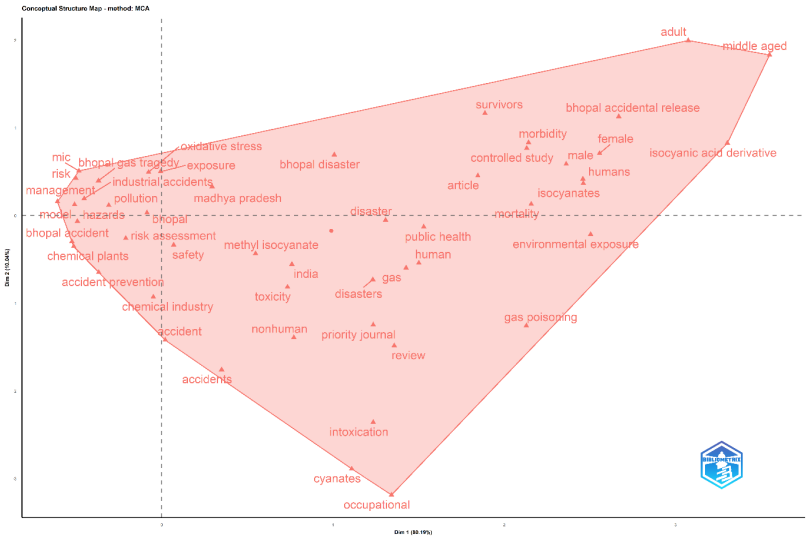

Figure 11. The factorial analysis, performed using Multiple Correspondence Analysis (MCA)

The factorial analysis reveals a bifurcated structure within the research field: one side oriented toward *technical, institutional, and chemical dimensions* of industrial disasters, and the other grounded in *biomedical, demographic, and public health responses*. This thematic polarity underscores the interdisciplinary nature of Bhopal-related scholarship, spanning environmental engineering, occupational health, toxicology, disaster management, and social medicine.

3.18. Collaboration Network

The collaboration network offers a structural representation of international research partnerships in the scholarly discourse surrounding the Bhopal Gas Tragedy. In this network visualization, the size of each node corresponds to the number of collaborative ties a country maintains, and its spatial position reflects the intensity of these relationships. Countries positioned closer to one another have more frequent co-authorship connections (Figure 12). The thickness of the edges denotes the strength of bilateral collaboration, with thicker edges indicating a higher volume of co-authored publications.

A review of the network reveals that the United States and India are the most dominant nodes, signifying their leading roles in international research collaborations within this field. Their central placement and relatively large node sizes underscore their substantial contributions to both publication output and partnership formation. Adjacent to this core, other countries such as the United Kingdom, France, Canada, and China also emerge as influential collaborators. Their positioning near the USA and India suggests sustained bilateral or multilateral collaborations, potentially driven by transnational research programs, international conferences, or institutional partnerships.

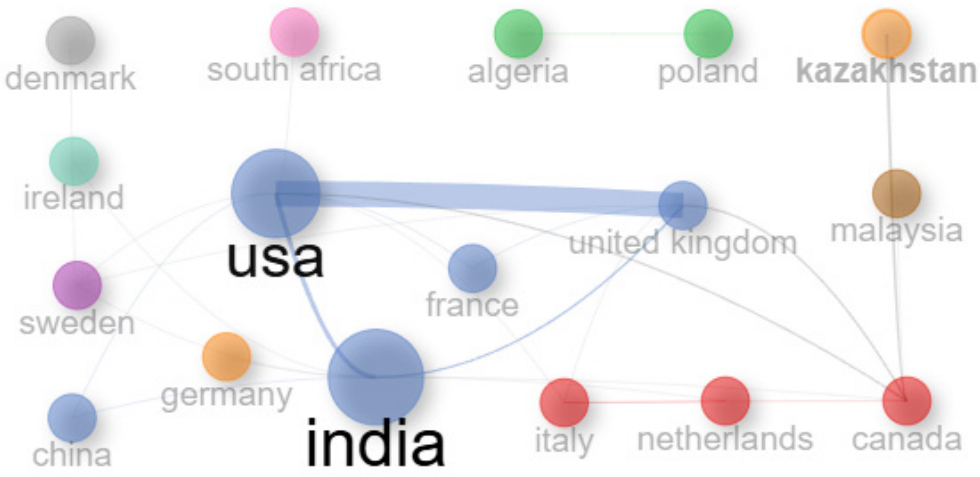

Figure 12. Collaboration Network of Countries.

The community structure, derived using the *Walktrap* community detection algorithm, reveals distinct clusters of collaboration. The most prominent of these is a *USA–India-centered cluster*, which includes close ties with China, France, Ireland, South Africa, Sweden, and the United Kingdom. A separate *European cluster*, anchored by Canada, Italy, and the Netherlands, reflects another cohesive research group. Beyond the dominant clusters, smaller bilateral collaborations are also visible. Notable among these are the links between Algeria and Poland, and between Kazakhstan and Malaysia. While these relationships are less pronounced in volume, they contribute to the network's diversity and point to localized or specialized research initiatives.

It is important to note that the analysis is limited to co-authorship data, as the absence of cited references restricts deeper insights into knowledge flow and intellectual influence. Despite this constraint, the collaboration network provides a valuable overview of the geopolitical distribution of scholarly engagement. It underscores the central role of a few countries in shaping the discourse on industrial disasters.

4. Major Discussion and Future Direction

The development of research on the Bhopal Gas Tragedy shows a steady shift from early chemical and medical investigations to a broader body of work that connects industrial safety, public

health, environmental governance, and institutional accountability. The co-occurrence network and thematic evolution indicate that while toxicology and health impacts remain central, newer studies have expanded into areas such as risk management, accident prevention, environmental regulation, and long-term community outcomes. This shift demonstrates a clear intellectual progression: Bhopal is now treated not only as a historical event but also as a model for understanding broader patterns of industrial risk and social-environmental vulnerability. At the same time, the factorial analysis suggests that several newer areas, such as occupational exposure, rehabilitation, and environmental assessment, remain loosely developed and require stronger conceptual integration. The continued dominance of India-centered themes also shows that the field would benefit from more comparative and cross-regional research that positions Bhopal within global discussions on disaster governance.

Future research should focus on long-term and intergenerational health studies, detailed environmental assessments, and community-centered resilience frameworks that capture the lived conditions of affected groups. Comparative research linking Bhopal to other major industrial disasters can strengthen theory-building and contribute to more unified global safety standards. There is also significant scope for policy-focused research evaluating regulatory reforms, safety governance structures, and the practical application of the Sendai Framework in industrial contexts. Stronger use of predictive models, satellite-based environmental monitoring, and decision-support tools can improve proactive risk reduction. Collaboration with international safety networks will further strengthen global knowledge exchange and help position insights from Bhopal within broader industrial safety practice. These directions will enable future scholarship to link better scientific evidence, governance improvements, and community resilience, contributing to safer and more just industrial systems.

5. Conclusion

This bibliometric analysis of research on the Bhopal Gas Tragedy reveals sustained and evolving scholarly interest spanning over four decades, marked by notable surges around significant anniversaries. The persistent academic engagement underscores the enduring importance of this disaster within the global discourse on industrial safety, environmental protection, and public health. Research output is concentrated within a core group of journals specializing in industrial risk and health, led by the *Journal of Loss Prevention in the Process Industries*. Author productivity patterns conform to Lotka's Law, illustrating a field dominated by many one-time contributors alongside a dedicated core of repeat authors, which reflects both the niche nature of the topic and challenges in maintaining long-term scholarly focus despite its global significance.

Geographically, India and the USA are the primary contributors, with domestic research efforts predominating. However, smaller, research-intensive countries demonstrate higher levels of international collaboration, highlighting diverse approaches to advancing knowledge on industrial disasters. The thematic progression of research reveals a clear shift from early technical and chemical analyses to broader concerns encompassing disaster management, health outcomes, and environmental sustainability. This evolution reflects the field's adaptability and its alignment with contemporary global challenges such as pandemics and climate risks. Network analyses underscore the interdisciplinary fabric of Bhopal Gas Tragedy research, with clusters around chemical exposure, health impacts, safety management, and governance. Core themes are well developed in toxicology and public health, while emerging areas such as accident prevention, environmental law, and oral history point to promising avenues for future inquiry that emphasize systemic and human-centered perspectives.

The thematic evolution further highlights the scholarly journey from localized chemical concerns to complex analyses of regulation, risk, and justice, establishing the Bhopal disaster as a perennial case study in industrial safety and environmental governance. Factorial analysis confirms a bifurcation between institutional-technical dimensions and biomedical-public health outcomes, illustrating the field's bridging of environmental engineering and social medicine to comprehensively address the disaster's multifaceted impacts.

The collaboration networks emphasize India and the USA as central hubs driving global research, supported by strong international linkages and diverse bilateral partnerships. This combination of concentrated expertise and expanding global engagement bodes well for the continued advancement of interdisciplinary scholarship aimed at preventing future industrial catastrophes and mitigating their consequences. This study not only maps the rich and complex landscape of Bhopal Gas Tragedy research but also highlights critical gaps and emerging themes, offering valuable directions for scholars, policymakers, and practitioners committed to industrial safety, environmental justice, and public health resilience.

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Conflict of Interests: The Authors declare that there is no conflict of interest

Data availability statement: This study is based on bibliometric data retrieved from the Scopus and Web of Science databases. Due to licensing restrictions of the databases, the complete datasets cannot be shared publicly; however, processed data and analytical outputs used in the study are available from the corresponding author upon reasonable request.

Sample availability: The author(s) declare that no physical samples were used in this study.

Supplementary materials: The author(s) declare that no supplementary materials are associated with this study.

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