

Using Bibliometric Analysis to Review Research on International Cooperation in Radiation and Nuclear Safety, Nuclear Security, and Nuclear Safeguards

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ABSTRACT: Bibliometric analysis has become an essential methodological tool for mapping the intellectual and structural landscape of academic fields, yet it remains rarely applied to the study of international cooperation in radiation and nuclear safety, nuclear security, and nuclear safeguards. This paper uses a bibliometric approach, following the PRISMA 2020 protocol, to review the literature on this topic indexed in the Scopus database between 1957 (the year the International Atomic Energy Agency, IAEA, was established) and 2026. Three independent, reproducible Scopus searches were run for each domain, combining a fixed set of international-cooperation terms with domain-specific terms, restricted to the Social Sciences and Multidisciplinary subject areas, English-language documents, and defined document types. Performance analysis was conducted with Biblioshiny (Bibliometrix package, R), and science mapping was performed with VOSviewer to explore keyword co-occurrence and citation patterns by country. After screening, 479 documents on radiation and nuclear safety, 1,523 on nuclear security, and 122 on nuclear safeguards were retained for analysis, together with four smaller cross-domain sets. The results show a steady increase in publications across all three domains since the Nuclear Non-Proliferation Treaty entered into force in 1970, with nuclear security recording both the largest volume and the fastest annual growth rate, while nuclear safeguards remain the smallest and least internationally co-authored domain. Science mapping reveals thematic clusters centred on nuclear safety culture and nuclear power for the safety domain, on geopolitics, non-proliferation and terrorism for the security domain, and on IAEA safeguards verification instruments for the safeguard's domain. In-depth review of four representative international studies confirms the IAEA's central, model role in global governance of complex technology, while showing that none of the existing literature treats a single bilateral cooperation relationship as its primary research object. The findings provide a structural, evidence-based overview of the field and identify a clear methodological gap that the present line of research is positioned to address.

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1. INTRODUCTION

Over the past two decades, bibliometric analysis has become an indispensable methodological tool for evaluating and mapping academic activity across a wide range of disciplines, from the natural and engineering sciences to the social sciences and international relations research. By combining quantitative information (publication output, citation levels, collaboration networks) with qualitative insight (intellectual structure, thematic trends), this method helps researchers assess academic productivity, identify emerging research trends, and systematically and objectively pinpoint gaps in knowledge (Donthu et al., 2021).

Methodologically, bibliometric analysis is typically carried out through two complementary approaches: performance analysis, which indicates the contribution of research components (authors, countries, publication sources); and science mapping, which describes the relationships and intellectual structure among these components through co-citation analysis, bibliographic coupling, co-word analysis, and co-authorship analysis (Van Eck & Waltman, 2010). Building on this approach, the present study uses keyword co-occurrence analysis as its central tool for exploring the intellectual structure and developmental trajectory of the field – a method whose systematic rigour and effectiveness have been well established in social science research (Üsdiken & Kieser, 2004; Backhaus et al., 2011).

To ensure the standardisation and reproducibility of the review process, this study applies the PRISMA 2020 framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) developed by Page et al. (2021), currently regarded as the leading standard for reporting the procedures of systematic reviews. Accordingly, the review process was carried out in three successive stages – identification, screening, and data analysis (Zakaria et al., 2020) – applied independently and identically to each of the three domains under review, so that the resulting datasets are directly comparable.

Despite the wide application of bibliometric methods across many fields, studies specifically mapping international cooperation in radiation and nuclear safety, nuclear security, and nuclear safeguards remain scarce, and no existing bibliometric review has compared the volume, growth, and intellectual structure of research across all three domains within a single, reproducible search design. This paper addresses that gap by using bibliometric analysis to provide a structural overview of the research landscape on international cooperation in these three interrelated domains, with every quantitative claim and interpretive statement in this paper traceable directly to the datasets, tables, and network maps presented below.

2. METHODOLOGY

2.1 Identification

Data were collected from Scopus, a database widely recognised for its scope and reliability in bibliometric research (Wang et al., 2024). Two keyword groups were combined using Boolean logic: a fixed group of terms denoting international cooperation (“international cooperation”, “IAEA member states”, “technical cooperation”, “international relation”, “cooperation programmes”, “projects”, “support plan”), combined with a domain-specific group of terms identifying each of the three substantive fields under review: radiation and nuclear safety (“nuclear safety”, “radiation safety”), nuclear security (“nuclear security”), and nuclear safeguards (“nuclear safeguards”). To ensure reproducibility, three separate, self-contained Scopus searches were executed – one per domain – each applying the identical search-field, subject-area, language, and time-span parameters: search fields limited to Article title, Abstract, and Keywords; subject area limited to Social Sciences and Multidisciplinary, to ensure relevance to international relations research; document language limited to English; and the publication time frame limited to 1957 (the year the IAEA was established) through 2026, the most recent year for which data were available at the time of the search. The search was executed on 13 September 2026. The initial (pre-screening) search returned 531 documents for radiation and nuclear safety, 1,613 documents for nuclear security, and 131 documents for nuclear safeguards.

2.2 Screening

Two exclusion criteria were applied to narrow each domain-specific corpus to documents suited to the research objective. First, by document type: only documents classified as article, conference paper, book or book chapter, editorial, conference review, or data paper were retained; documents classified as note, short survey, review, letter, erratum, or retracted publication were excluded. Second, by publication stage: only documents already in Final publication status were retained; documents still in Article-in-Press status were excluded. After applying these two criteria, the retained corpus comprised 479 documents on radiation and nuclear safety (52 excluded: 50 by document type, 2 by publication stage), 1,523 documents on nuclear security (90 excluded: 80 by document type, 10 by publication stage), and 122 documents on nuclear safeguards (9 excluded: 8 by document type, 1 by publication stage). In addition, four cross-domain sets were identified for documents addressing more than one field simultaneously: 108 documents addressing both radiation/nuclear safety and nuclear security, 19 documents addressing both radiation/nuclear safety and nuclear safeguards, 52 documents addressing both nuclear security and nuclear safeguards, and 13 documents addressing all three domains jointly. Figure 1 summarises this identification-and-screening process for all three domains side by side.

2.3 Data Analysis

To clarify both the bibliometric structure and the intellectual structure of the literature, this study adopts a multi-tool analytical approach. Performance analysis – providing descriptive statistics on publication and citation trends – was conducted using Biblioshiny version 5.0 (running on RStudio), a visualisation tool built on the Bibliometrix package (Aria & Cuccurullo, 2017). Science mapping – used to decode thematic networks and international collaboration patterns – was conducted using VOSviewer version 1.6.21 (Van Eck & Waltman, 2010), a tool widely adopted in bibliometric research for its powerful visualisation capabilities (Lim et al., 2024). Specifically, author-keyword co-occurrence analysis (minimum occurrence threshold of five) was used to trace the evolution of research themes within each domain, while country-level citation analysis was used to identify international academic collaboration networks.

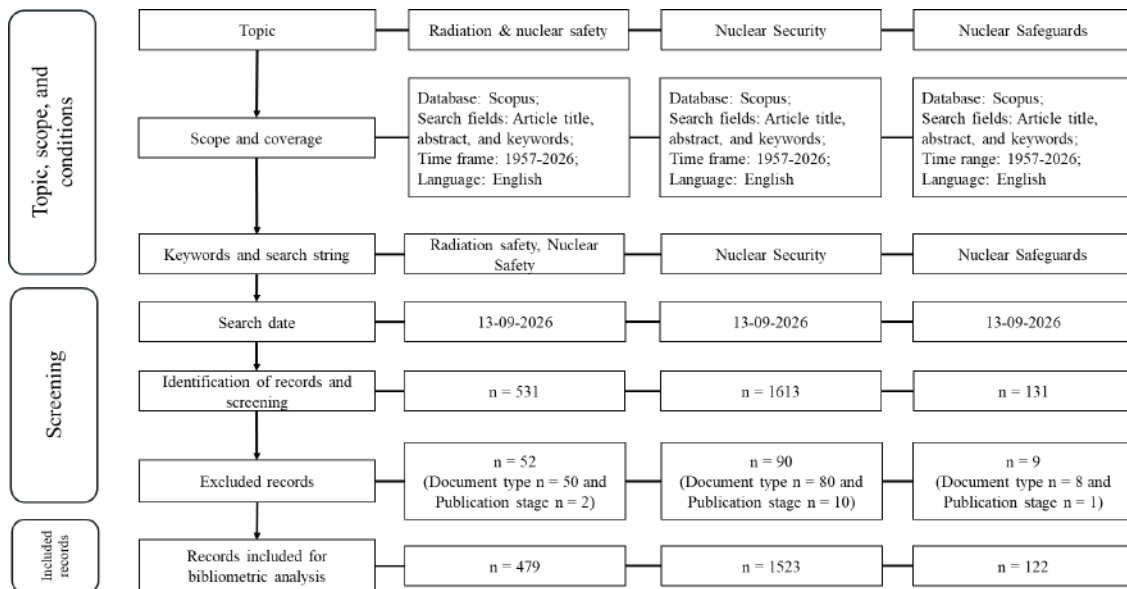


Figure 1. PRISMA 2020 identification and screening flow, applied identically to the three domains (radiation and nuclear safety, nuclear security, nuclear safeguards)

3. RESULTS

3.1 Descriptive Overview of the Literature

Table 1 summarises the descriptive statistics of the seven extracted datasets – the three single-domain sets and the four cross-domain sets. The bibliometric record shows that social-science publication on international cooperation in these three domains began in 1971, shortly after the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) entered into force on 5 March 1970. Among the three single domains, nuclear security accounts for the largest volume of publications (1,523 documents) and nuclear safeguards the smallest (122 documents). The international co-authorship rate is markedly higher for radiation and nuclear safety (19.42%) than for nuclear security (11.10%) or nuclear safeguards (7.38%). Notably, research integrating all three domains simultaneously first appeared only in 2007 and remains limited in volume (13 documents), reflecting a broader tendency in the international literature to treat the three 3S pillars – safety, security, safeguards – separately rather than within an integrated analytical framework.

Table 1. Descriptive statistics of the bibliometric datasets on international cooperation in radiation and nuclear safety, nuclear security, and nuclear safeguards

Key data information	Radiation & Nuclear Safety (1)	Nuclear Security (2)	Nuclear Safeguards (3)	(1)&(2) Combined	(1)&(3) Combined	(2)&(3) Combined	(1)(2)(3) Combined
Time span	1971–2026	1972–2026	1985–2026	1998–2026	1995–2025	1994–2025	2007–2025
Sources (journals, books, etc.)	275	861	88	85	18	44	12
Documents	479	1,523	122	108	19	52	13
Total references	13,783	1,000,232	4,031	3,721	336	1,691	230
Average citations per document	7.49	7.09	3.14	4.33	4.05	2.06	3.77
Keywords	1,256	2,383	263	306	70	99	47
Total authors	1,522	4,553	149	243	31	57	23
Single-authored documents	152	873	59	48	10	23	7
Co-authors per document	3.58	1.61	3.56	2.50	1.74	2.06	1.77
International co-authorship rate	19.42%	11.10%	7.38%	18.52%	5.26%	7.69%	7.69%
Annual growth rate	6.44%	7.88%	3.44%	8.16%	2.34%	3.61%	3.93%

Source: Compiled by the author from RStudio output (Bibliometrix/Biblioshiny package), Scopus database.

Analysis of publication dynamics over the full 1971–2026 span shows that publication output grew across all three domains, with nuclear security recording the highest average annual growth rate (7.88%) – a pattern plausibly linked to rising global concern over nuclear proliferation and nuclear terrorism, particularly after the events of 11 September 2001. Figure 2 presents this full-period growth pattern for all three domains side by side.

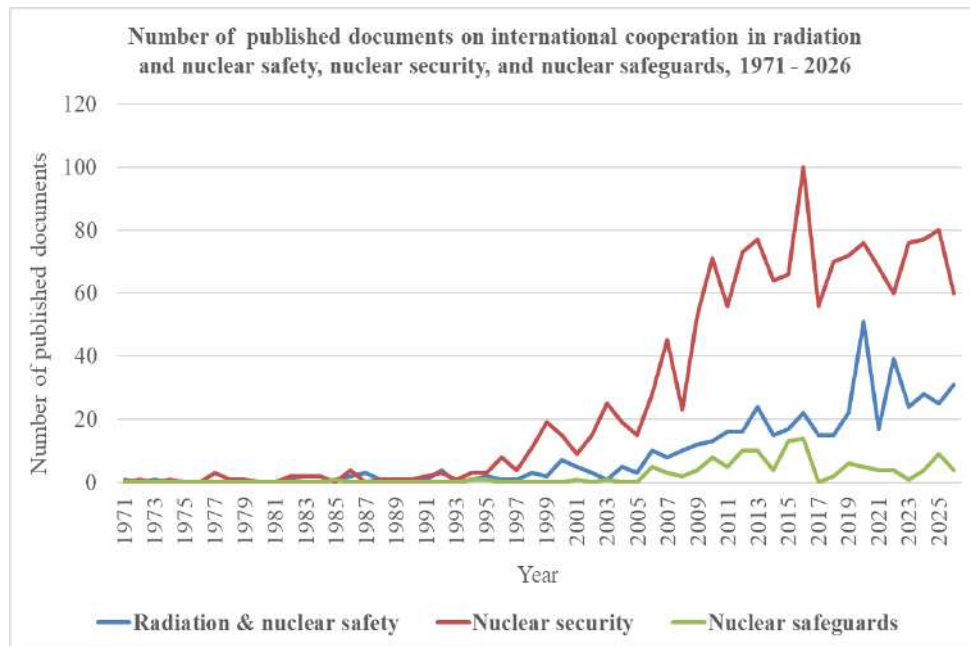


Figure 2. Number of published documents on international cooperation in radiation and nuclear safety, nuclear security, and nuclear safeguards, 1971 - 2026

3.2 Science Mapping by Domain

Author-keyword co-occurrence mapping (minimum occurrence threshold of five) for the radiation and nuclear safety domain identifies five clusters, centred on: (1) nuclear safety; (2) safety; (3) nuclear energy; (4) nuclear power plant; and (5) reliability. The co-occurrence of “safety” and “nuclear security” within a cluster closely linked to “nuclear energy” and “sustainability” indicates that, in the international literature, these two domains are frequently studied in relation to one another, particularly following the Fukushima accident (2011) – indirect evidence supporting the integrated “3S” approach that this line of research adopts.

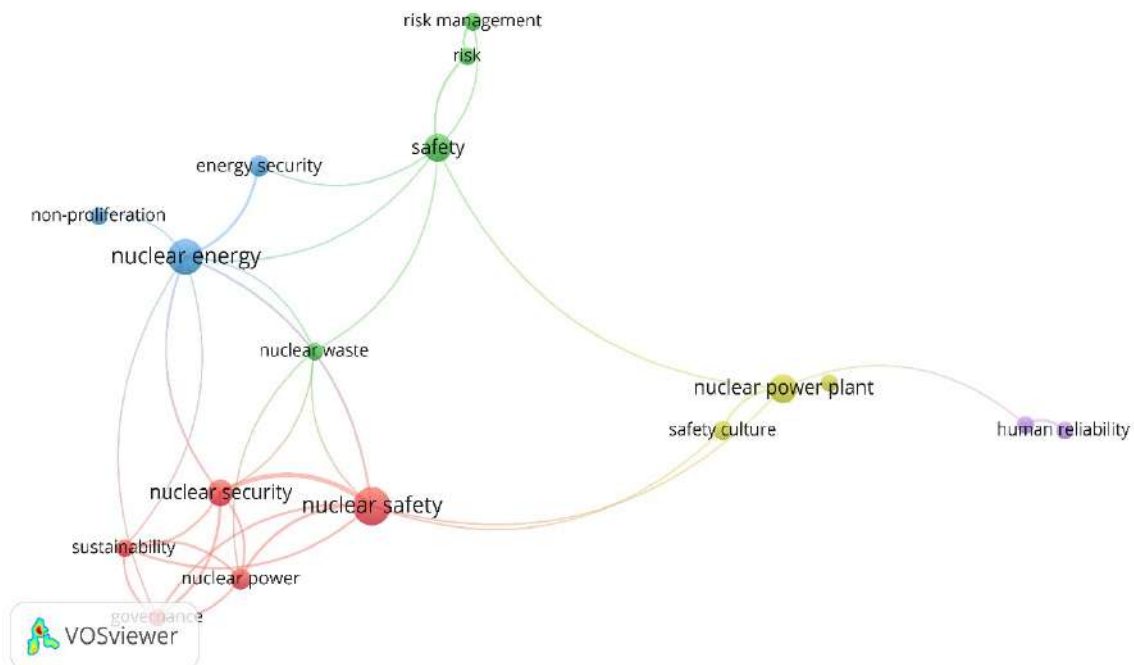


Figure 3. Network visualisation of author keywords for international cooperation in radiation and nuclear safety (VOSviewer)

Country-level citation analysis for the radiation and nuclear safety domain identifies clusters centred on China, the United Kingdom, France, Sweden, the Netherlands, and Japan, reflecting strong academic interaction among countries operating established nuclear power programmes. Other countries with active but comparatively smaller and less densely connected nodes within their respective clusters include Germany, South Korea, Austria, Italy, Finland, Norway, and Canada.

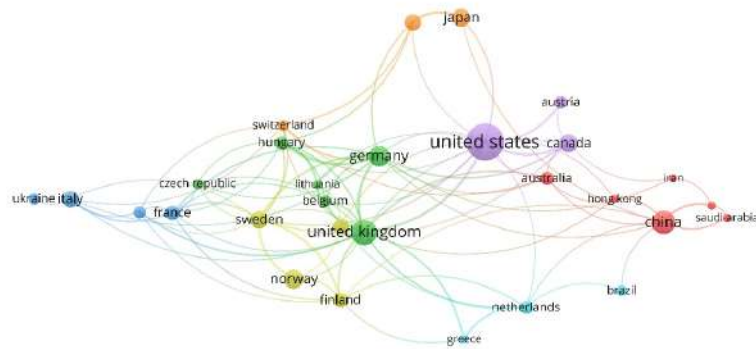


Figure 4. Country-level citation analysis for international cooperation in radiation and nuclear safety (VOSviewer)

For nuclear security – the domain with the largest publication volume – keyword co-occurrence mapping identifies nine clusters, centred on: energy security, international relations, North Korea, nuclear security, Russia, nuclear weapons, security, terrorism, and India. This keyword structure shows that, in the international academic literature, nuclear security is tied closely to the geopolitics and foreign policy of nuclear-weapon states, together with terrorism and energy-security concerns, rather than to purely technical cooperation.

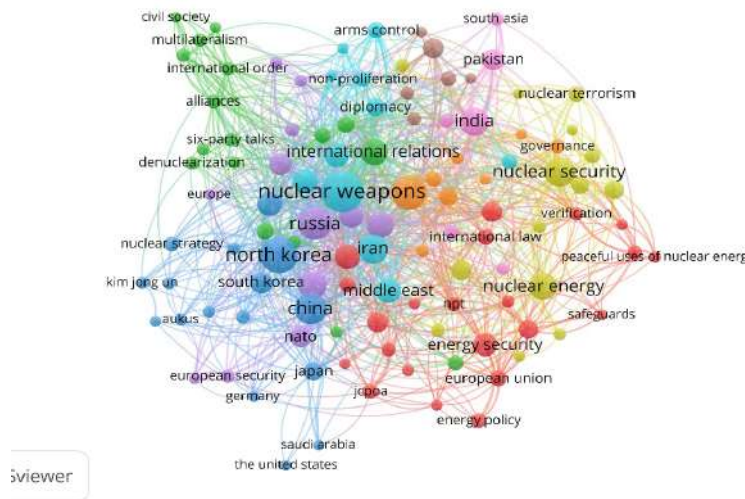


Figure 5. Network visualisation of author keywords for international cooperation in nuclear security (VOSviewer)

Country-level citation analysis for nuclear security identifies clusters centred on Germany, the United Kingdom, China, South Korea, India, Italy, and the United States – a country set that differs appreciably from the radiation-and-safety domain, reflecting the broader involvement of social-science and humanities researchers in nuclear security scholarship, particularly from countries directly exposed to nuclear-security threats.

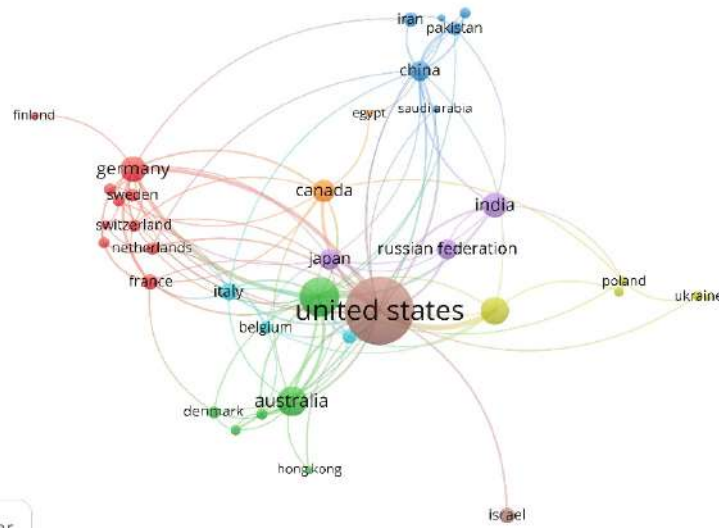


Figure 6. Country-level citation analysis for international cooperation in nuclear security (VOSviewer)

For nuclear safeguards – the domain with the most limited publication volume – keyword co-occurrence mapping identifies only three clusters, centred on: safeguards; nuclear energy; and the International Atomic Energy Agency. Smaller, closely linked keywords include verification, additional protocol, and nuclear security. This result shows that safeguards research is tied almost directly to the role and operations of the IAEA, reflecting the verification activities carried out under the Safeguards Agreements that NPT member states conclude with the IAEA and, where applicable, the Additional Protocol, both of which affirm that nuclear material is used exclusively for peaceful purposes.

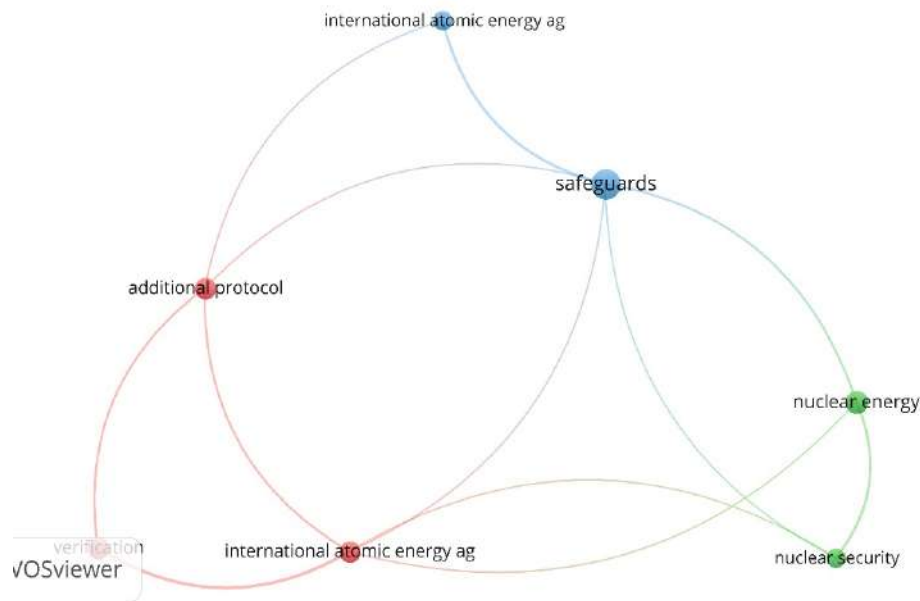


Figure 7. Network visualisation of author keywords for international cooperation in nuclear safeguards (VOSviewer)

Country-level citation analysis for nuclear safeguards identifies four clusters, centred on the United States (in the same cluster as Germany), Austria (host of IAEA headquarters), the United Kingdom, and Australia – a compact structure consistent with the domain's small publication volume and its concentration around the IAEA's home institutional base. Given the limited number of documents in the four cross-domain sets (safety–security, safety–safeguards, security–safeguards, and all three domains jointly), these sets were not separately visualised with VOSviewer; their descriptive statistics are reported in Table 1.

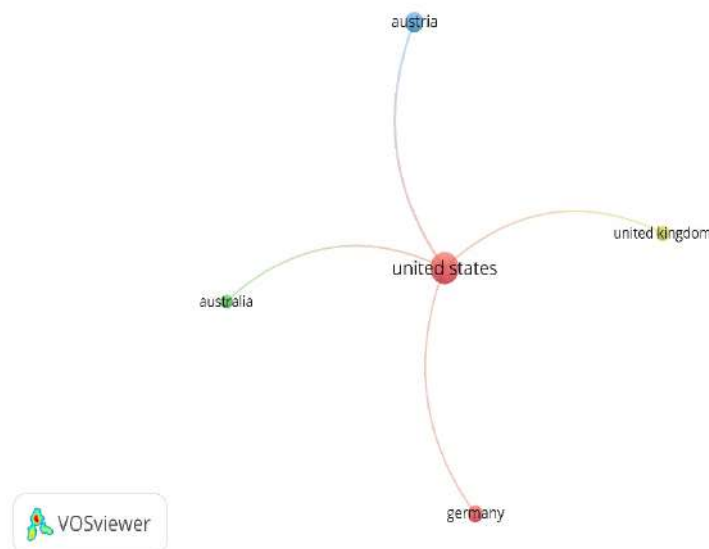


Figure 8. Country-level citation analysis for international cooperation in nuclear safeguards (VOSviewer)

3.3 In-depth Review of Representative Studies

Building on the bibliometric findings above, this study examines in depth several representative works, selected according to their direct relevance to the analytical framework pursued in the broader research programme – namely, the institutional architecture of international cooperation, the role of the IAEA, and the Southeast Asian regional case.

Kjondal (2020) examines cooperation among the radiation and nuclear safety regulatory authorities of five Nordic countries (Iceland, Denmark, Norway, Sweden, and Finland), drawing on 37 in-depth interviews with officials from these agencies. Applying

historical institutionalism combined with organisational theory, the author analyses the degree of integration across four criteria: frequency of contact, level of trust, institutionalisation, and resource sharing. The findings show that Nordic cooperation exhibits “differentiated integration”: very close in the areas of radiation protection and emergency response (the safety pillar), but considerably looser in nuclear security and safeguards. The author attributes this pattern to historical path dependency and the distinction between issue areas belonging to “core state powers” (linked to security and foreign affairs) and “non-core” areas, in which international cooperation is harder to establish and sustain on matters touching sovereignty and national security. This framework offers an important point of reference for interpreting variation in the intensity of cooperation across the safety, security, and safeguards pillars.

Cha (2024) explores whether the IAEA's nuclear safety regulatory framework could serve as a reference model for building an international regulatory framework for artificial intelligence (AI) safety. The study analyses the IAEA's five-tier safety standards system (from Fundamental Safety Principles to specific Safety Guides) together with eight core regulatory functions – including standard-setting, independent oversight, emergency response, nuclear-material management, and non-proliferation – and proposes applying analogous principles to AI governance: international standardisation of AI behaviour and decision-making, a neutral oversight body, incident-response procedures, and an international information-sharing platform. Although its subject matter lies outside the nuclear-energy field, the work is valuable for systematically codifying the IAEA's functional pillars, while candidly acknowledging the limits of transplanting this governance model to other sectors given their distinct risk profiles.

Bowen, Cottee, and Hobbs (2012) analyse the state of multilateral cooperation to prevent nuclear terrorism after the events of 11 September 2001, focusing on initiatives such as the Global Initiative to Combat Nuclear Terrorism (GICNT), the G8 Global Partnership (GP), United Nations Security Council Resolutions 1373 and 1540, the Nuclear Security Summit (NSS) process, and the role of the IAEA's Office of Nuclear Security. The authors argue that, given the complexity of nuclear terrorism, divergent threat perceptions among states, and political disputes over nuclear governance – particularly between Non-Aligned Movement states and major powers over a putative “fourth pillar” of nuclear security – a pragmatic, incremental approach is the only feasible path forward, rather than pursuit of a single comprehensive, legally binding framework. The article draws a clear distinction between “nuclear security” (countering terrorism and sabotage) and “nuclear safeguards” (verifying non-proliferation commitments), and notes that although the IAEA plays a central role in standard-setting (e.g., INFCIRC/225) and technical assistance, it lacks enforcement authority and relies heavily on voluntary member-state contributions through the Nuclear Security Fund, unlike the regular-budget financing that underpins the safety and safeguards pillars. The study proposes four directions for strengthening cooperation: solidification of legally binding conventions, reassurance of developing countries regarding their right to peaceful nuclear energy use, maintaining political momentum through periodic summits, and improving governance by better integrating the safety, safeguards, and security functions within the IAEA.

Caballero-Anthony and Trajano (2015) examine the development of nuclear energy in three ASEAN countries (Vietnam, Indonesia, and Malaysia) following the Fukushima accident, and assess the prospects for a regional normative framework on nuclear safety, security, and safeguards (3S) built on the 1995 Treaty on the Southeast Asia Nuclear-Weapon-Free Zone (Bangkok Treaty). The study finds that, although ASEAN has established a regional normative framework requiring member states to comply with IAEA safety standards and NPT safeguards, implementation still depends heavily on national nuclear-infrastructure capacity – particularly the legal and regulatory framework, human resources, radioactive-waste management, and emergency-response mechanisms. For Vietnam specifically, the authors describe in detail the preparation process for the Ninh Thuan nuclear power project (in cooperation with Russia and Japan) and the country's cooperation with the IAEA through the Integrated Nuclear Infrastructure Review (INIR) missions of 2009 and 2012 and the Emergency Preparedness Review (EPREV) mission of 2012, while also noting limitations in the independence of Vietnam's radiation and nuclear safety regulatory authority (VARANS) and shortages of specialised human resources. On this basis, the authors recommend that ASEAN develop a regional 3S blueprint modelled on the European Atomic Energy Community (EURATOM), establish a regional nuclear crisis-response centre, and strengthen the role of the ASEAN Network of Regulatory Bodies on Atomic Energy (ASEANTOM).

Taken together, these four studies provide an important theoretical and empirical backdrop for identifying the complex institutional architecture of the international cooperation system underpinning radiation and nuclear safety, nuclear security, and nuclear safeguards, in which the IAEA's central, model role as a governance mechanism for complex technology is consistently affirmed. The studies also codify the IAEA's core functional pillars – standard-setting, safeguards, technical assistance, non-proliferation, and emergency response – while pointing to the organisation's internal institutional limitations, particularly in the nuclear-security pillar. This body of work forms an important theoretical foundation for the broader analytical framework of the wider research programme on Vietnam–IAEA cooperation. However, as illustrated by both Kjøndal (2020) and Caballero-Anthony and Trajano (2015), most of this literature is set either within a regional or multilateral context (the Nordic countries, ASEAN, the global non-proliferation regime) or treats a given country, including Vietnam, only as an illustrative case within a broader regional picture; no existing study takes a single bilateral cooperation relationship – such as that between Vietnam and the IAEA – as its central, sustained research object.

4. DISCUSSION

Three evidence-based conclusions follow from the results above. First, the reproducible, domain-by-domain Scopus search design (Section 2.1, Figure 1) shows that research on international cooperation in these three domains has grown steadily since 1971, with nuclear security accounting for both the largest volume and the fastest growth rate among the three single domains (Table 1) – a pattern directly attributable to the field's entanglement with geopolitics, non-proliferation, and counter-terrorism, as confirmed independently by the keyword network in Figure 5. Second, the science-mapping results place the IAEA and its normative instruments – safety standards, safeguards agreements, the Additional Protocol – at the centre of the intellectual structure of the safeguards domain in particular (Figure 7), reinforcing the Agency's role as a model of international governance for complex and sensitive technology, a finding corroborated by the in-depth review of Cha (2024) and Bowen et al. (2012). Third, the near-absence of research integrating all three domains (13 documents; Table 1) and the exclusively regional or multilateral framing of the four representative in-depth studies reviewed in Section 3.3 together indicate that a systematic, empirically grounded study of any single bilateral cooperation relationship within this field – examined through the integrated safety–security–safeguards lens that the present bibliometric evidence supports – would address a gap that is both real and, on the evidence assembled here, currently unaddressed in the international literature.

5. CONCLUSION AND RECOMMENDATIONS

This paper has used bibliometric analysis, following the PRISMA 2020 protocol with an identical, reproducible search design applied independently to three domains, combining performance analysis (Biblioshiny) with science mapping (VOSviewer), to review the global literature on international cooperation in radiation and nuclear safety, nuclear security, and nuclear safeguards indexed in Scopus between 1957 and 2026. The results show a growing but unevenly distributed literature, dominated by nuclear security and concentrated among a relatively small group of countries with established nuclear programmes, with the IAEA occupying a central position in the intellectual structure of the safeguards domain specifically. Integrated three-pillar research remains rare, and in-depth review of representative studies confirms that no existing work treats a single bilateral cooperation relationship as its primary object of analysis. These findings offer a structural, evidence-based map of the field and a clear methodological basis for future research applying an integrated 3S framework to specific bilateral cases.

This study is subject to several limitations. The bibliometric analysis relies on a single database (Scopus) and a specific subject-area restriction (Social Sciences and Multidisciplinary), which may exclude relevant technical or natural-science literature indexed elsewhere. One descriptive statistic in Table 1 (total references for the nuclear security domain) displays an anomalous magnitude relative to the other domains and should be re-verified against the underlying RStudio export before the figure is cited elsewhere. Future research could extend the search to additional databases and languages, and could build on the gap identified here – the near-absence of integrated, bilaterally focused 3S research – to conduct an in-depth empirical study of the mechanisms, achievements, and challenges of a specific country's cooperation with the IAEA across all three domains.

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