BIBLIOMETRIC ANALYSIS OF THE GREATEST NUCLEAR DISASTERS: WHAT IS KNOWN SO FAR AND WHAT ARE THE PROSPECTS?

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ABSTRACT:

The high potential of nuclear power to combat climate change and support sustainable development plays a critical role in achieving the goal of the Paris Agreement. Moreover, with the ever-increasing demand for electricity, it is essential to consider nuclear power as a reliable source of energy. However, it should be noted that although the risk of a radiological accident is small, it always exists, and therefore it is crucial to have a complete understanding of the management of nuclear power. Herein, we present a statistical review of nuclear accident research at Chernobyl and Fukushima Nuclear Power Plants using bibliometric analysis to identify key patterns in scientific results and current issues in accident research. More than 10,000 articles have been collected from the SCOPUS database covering the periods 1986–2022 and 2011–2022 on Chernobyl and Fukushima, respectively. The results were obtained from two perspectives: first, we identified stages through which pre- and post-accident researches have evolved, and then we analysed the spatial correlation between energy-economic performance and scientific literature for the leading productive countries. From the analysis of research trends, it was found that the number of articles increased sharply immediately after the accident and slightly decreased over time. Among the most attractive subject categories in terms of the largest number of publications and received citations were environmental sciences, medicine and energy policy. The productive country ranking was mostly topped by the country in which the accident occurred. Spatial statistical analysis revealed a strong correlation between the scientific productivity and energy-economic performance of the leading countries.

1. INTRODUCTION

Nuclear power plays an important role in the global energy scenario from several perspectives. Firstly, unlike renewables, nuclear sources can continuously provide the required amount of electricity. Secondly, nuclear power increases the energy independence and energy security of a particular country, and above all, nuclear is a clean source of energy and therefore is essential for reducing carbon emissions. The nuclear industry is considered fairly safe (Ha-Duong and Journe, 2014). However, even with a minimal probability, there is always a risk of an accident which consequences can spread over large areas and adversely affect environment and human health. This underlines the importance of studying the nuclear industry as a part of the quality and control system. Over the past few decades, nuclear power has attracted a lot of attention from scientists, especially after the Chernobyl and Fukushima disasters (Visschers and Siegrist, 2013). A failed technical experiment was the direct cause of the accident at the Chernobyl Nuclear Power Plant (NPP) in Ukraine in April 1986. The explosion of a nuclear reactor, followed by a huge fire, led to the release of radioactivity, which subsequently spread over long distances. The consequences of this accident still haunt many countries and continue to attract the attention of scientists. Another high-profile nuclear disaster occurred in March 2011 in Japan. The Great East Tohoku earthquake caused a devastating tsunami, the waves of which damaged the Fukushima Daiichi NPP, leading to the meltdown of three nuclear reactors and a subsequent hydrogen explosion. This accident led to active radioactive contamination of both vast areas of Japan and the Pacific Ocean (Batur and Alkan, 2023). There is no other energy technology that could require such a diverse and at the same time specific scientific base as nuclear energy. Since the above-mentioned accidents, knowledge of nuclear power has expanded, ranging from environmental engineering, physics, biochemistry, materials science to social sciences and disaster management. So, what was studied? What topics have been of constant interest of researchers? What subjects were not covered or received little attention? Which countries contributed the most? In order to identify the primary questions for further research, it is necessary to answer the above questions and clarify areas in which there is a need for additional knowledge or understanding. One of the fastest and most reliable scientific methods for identifying major research gaps by covering all publications related to a given field is a scoping review methodology called bibliometric analysis. Bibliometric approach helps to understand the discipline as a whole, trace its evolution and grasp the geographical landscape of a particular scientific field (Donthu et al., 2021). Bibliometric analysis has already been explored in previous studies in nuclear power domain. Negeri (2005) and Mryglod et al. (2016) focused on the publication analysis of Chernobyl accident. However, these studies are limited in terms of the database used. Thus, in the first case, the scope of research was limited to the International Nuclear Information System (INIS) database, and in the second case, the authors paid attention only to the Ukrainian academic database. Kaur et al. (2019) provided some information about the background of the Fukushima disaster, paying special attention to the most significant contributors to the literature.

In our study, we aim to analyse the literature on both the Chernobyl and Fukushima accidents from the SCOPUS database using a bibliometric methodology. We are specifically interested in the aspects of research trends, major subject areas and geographical distribution of the published literature as they pertain to reveal a number of gaps and shortcomings. The ultimate goal is to explore the possible correlation between economical productivity, energy performance, nuclear capability and scientific productivity of a particular country.

2. DATA AND METHODOLOGY

2.1 Bibliometric analysis: research questions, objectives, and motivation of the study.

Bibliometric analysis is a common and exhaustive method for researching and analyzing large amounts of scientific data (McBurney and Novak, 2022). It allows to uncover the evolutionary trends of a particular area, indicating the need for new research and deriving novel ideas for it. Despite bibliometric analysis is relatively new, it has been already used in many scientific fields. A number of scholars have used this approach in medicine (Kokol et al., 2021), it has been also applied in geosciences (Liu et al., 2012), engineering (Vilutiene et al., 2019), economic sciences (Zapata and Mukhopadhyay, 2022), etc. In this study, the main aim is to analyze the literature on the Chernobyl and Fukushima accidents. The particular interest is in the aspects of research trends, major subject areas and geographical distribution of the published literature. In line with this, the following Research Questions (RQ) were formulated: (RQ1) How the period of scientific production has changed? (RQ2) What are the most important research topics studied? (RQ3) Which countries are the most interested in nuclear research? Answering the RQ1 will allow to identify and analyse potentially significant patterns in historical data, as well as give an idea of the development of the research patterns over time. RQ2 contributes to the main works and subject areas and can identify the potential research gaps opportunities. Finally, RQ3 will help to identify the most prolific countries.

2.2 Bibliometric analysis: data collection and research methodology.

The research methodology used in our bibliometric study included three main stages: (1) Data collection, (2) Data cleaning, and (3) Data analysis. Data for our study was compiled from SCOPUS database using a keyword-based search of "Fukushima", "Fukushima Daiichi", "Chernobyl", "Nuclear accident", and "Nuclear disaster" in the *Title-Abstract-Keywords* searching field. Currently, SCOPUS is the largest multidisciplinary database that summarizes peer-reviewed scientific literature including journals, conference proceedings, book series and trade journals with more than 70 million records available. For the two accident studies, we used time period that starts 6 years prior to the accident and ends in 2022. That is, Chernobyl and Fukushima studies cover 1980 – 2022 and 2005 – 2022 years, respectively. The reason for choosing this time was to observe the publishing trends and their changes due to accidents which occured in 1986 and 2011, each. We narrowed our study to the publications in English language because this language dominates the academic community and is a basic requirement for any publication in most fields of science. The collected data was then filtered and arranged for further analysis. Thus, we excluded duplicate records and non-author's files. In total, 8,122 and 7,667 publications were collected in the Chernobyl and Fukushima studies, respectively, and after appropriate data cleaning, the number of documents remained 7,876 and 7,647 for each study. For the performance analysis, interpretations and scientific mapping we used VOSviewer tool which was originally developed for the purpose of bibliometric analysis. This software allows to calculate basic descriptive statistics, including publication and citation-related metrics such as total number of publications, number of contributing authors, productivity of publications, and total number of citations received (Contreras and Abid, 2022). In addition, it allows science mapping, which is necessary for understanding the relationship between publications, analysis of co-words occurence, analysis of co-authors and bibliographic links (Van and Waltman, 2010). Thus, our data analysis consists of scientific production analysis, subject area analysis, and an analysis of countries contributing to the accident literature.

2.3 Geospatial analysis: data collection and research methodology.

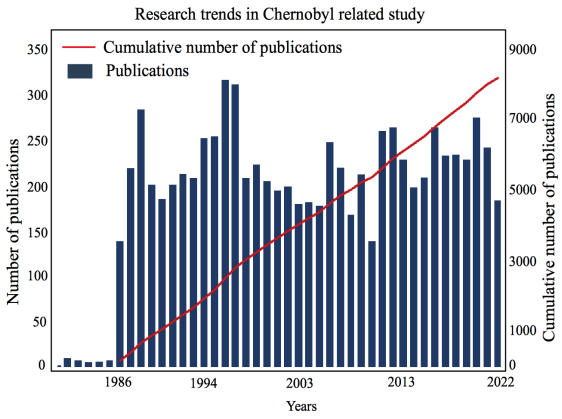
To examine the complex impact of energy-economic indicators on scientific productivity at the country level, we implemented a Multiscale Geographically Weighted Regression (MGWR) model to assess the impact of the above-mentioned factors in this area. MGWR modelling is a spatial analysis technique that explains differences in geospatial patterns, thereby allowing us to explore variations in influencing factors. MGWR has previously been used by many scholars to quantify the influence of covariate effects of variables. Xu and Lin (2021) used GWR to investigate the spatial variability of carbon emissions in heavy industry. Mizrak and Cam (2022) utilized global (OLS) and local (GWR) models to analyse the main factors affecting the disaster resilience. They found that GWR can capture local-scale variability measure better than traditional OLS. Wang et al. (2020) focused on empirical analysis of energy intensity by utilizing the GWR.

We initially collected a data set of nine candidate response variables including the number of operating nuclear reactors, gross domestic product (GDP), carbon emissions, electricity production and consumption from renewables, fossils and nuclear sources. The explanatory variable was scientific productivity at the country-level. We then calculated Moran's I to examine the spatial autocorrelation of the explanatory and response variables. After determining spatial autocorrelation, we used an Ordinary Least Square (OLS) to select the independent variables from the nine indicators for modelling. In this framework, MGWR was utilized to identify local variations in each significant factor. The above analysis was performed in ArcGIS software.

3. RESULTS

3.1 Research Trends

The evolution of scientific literature per year, from 1980 to 2022 and from 2005 to 2022 for the accident study at the Chernobyl and Fukushima NPPs is given in Figure 1. Considering the selected periods, interest in research is visible from the moment of the nuclear accident. Thus, there are negligible number of publications in the Chernobyl study prior 1986. As for the Fukushima, during the 5 years before the accident, the number of publications was constant, averaging 40 articles per year. In subsequent years, this number increased dramatically and averaged 680 articles per year for the period 2012 – 2022. Between 2016 and 2022 there was a slight decrease in the number of publications, averaging 638 articles per year. The results do not appear to show a clear trend in Chernobyl-related publications over the entire study period. However, in two periods, from 1986 to 1988 and from 1995 to 1997, they rose sharply to 30% and 23% respectively, and then fell again in subsequent years. The most likely reason for these fluctuations can be explained by the intensive study of oncological diseases during this period of time (Ivanov et al., 1998). After the Fukushima accident, the rate of Chernobyl publications has grown by 88%.



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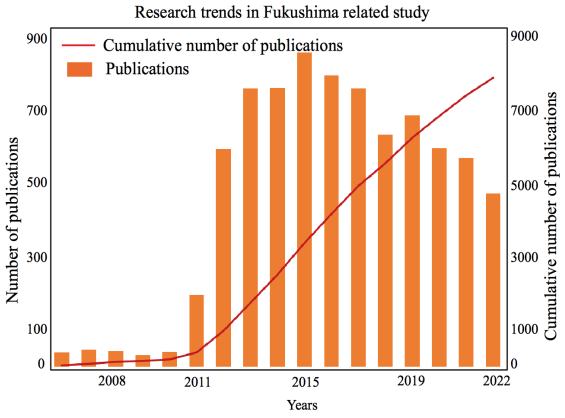


(b)

Figure 1. Research trends: (a) Number of publications in Chernobyl study; (b) Number of publications in Fukushima study.

3.2 Core research areas

3.2.1. Top source journals, books, and book chapters: According to the current search parameters, a total of 77 books on Chernobyl accident study were found. These books have been published in the period of 1998 – 2022. Book titled as "Normal accidents: living with high-risk technologies" and written by Perrow (1999) received the most citations – 2,260. Regarding the book chapters, a total of 421 can be found in the SCOPUS database and published between 2002 and 2022. All these book chapters have been cited more than 900 times. The most cited book chapter is titled as "Dark tourism, heterotopias and post-apocalyptic places: the case of Chernobyl" received a total of 60 citations (Stone, 2013). 149 books and 869 book chapters were published on Fukushima accident study between 2011 and 2022. The most cited book (143 citations) is titles as "Fukushima accident: radioactivity impact on the environment" (Povinec et al., 2013). The most cited book chapter (33 citations) is "Reading the changing energy landscape" (Pasqualetti, 2012). Articles on Chernobyl study were published in more than 150 different journals. The most productive journals were selected based on a certain threshold, that is >50 papers per journal. Table 1 represents the top 10 journals extracted from SCOPUS in the Chernobyl and Fukushima-related studies. These journals accounted for 15% of total articles. Obviously, "Journal of Environmental Radioactivity" ranked as first in the list in terms of publications and received citations, followed by "Health Physics" (second rank), "Radiation Protection Dosimetry" (third rank), "Problemy Radiatsiinoi Medytsyny ta Radiobiolohii" (firth rank), and "Radiation and Environmental Biophysics" (fifth rank). Articles published in these journals have received 26% of total citations, indicating to have substantial influences on these subjects.

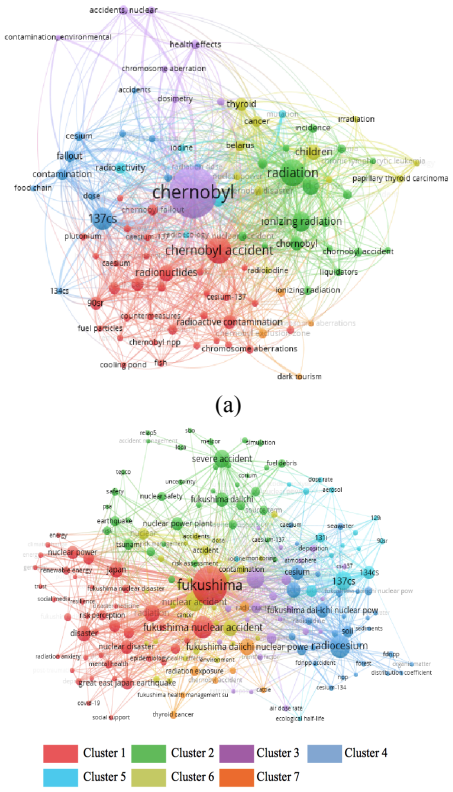
No.	Journal information	Publications (%) of total	Citations (%) of total
Chernobyl study			
1	Journal of Environmental Radioactivity (Elseiver; Q2)	3.4	7.6
2	Health Physics (Wolters Kluwer Health; Q2)	2.7	4.8
3	Radiation Protection Dosimetry (Oxford University Press; Q3)	1.9	2.4
4	Problemy Radiatsiinoi Medytsyny ta Radiobiolohii (Naukovyi Tsentr Radiatsiinoi Medytsyny; Q4)	1.8	0.2
5	Radiation and Environmental Biophysics (Springer Nature; Q2)	1.0	0.2
6	Nature (Springer Nature; Q1)	1.0	1.8
7	Atomic Energy (Springer Nature; Q3)	1.0	3.4
8	Radiation Research (Radiation Research Society; Q1)	0.9	2.8
9	Science of the Total Environment (Elseiver; Q1)	0.7	2.8
10	Hydrobiological Journal (Begell House; Q4)	0.6	0.1
Fukushima study			
1	Journal of Environmental Radioactivity (Elseiver; Q2)	6.4	24.0
2	International Conference on Nuclear Engineering Proceedings ICONE (Organization country is Japan; Q4)	2.6	0.4
3	Scientific Reports (Springer Nature; Q1)	2.2	8.9
4	Journal of Radioanalytical and Nuclear Chemistry (Springer Nature; Q2)	2.1	2.7
5	Journal of Nuclear Science and Technology (Taylor&Francis; Q3)	1.8	5.0
6	Radiation Protection Dosimetry (Oxford University Press; Q3)	1.7	1.5
7	Plos One (Public Library of Science; Q1)	1.7	1.6
8	Journal of Radiological Protection (Institute of Physics Publishing; Q3)	1.5	3.0
9	Health Physics (Wolters Kluwer Health; Q2)	1.5	1.6
10	Annals of Nuclear Energy (Elseiver; Q2)	1.4	1.5

Table 1. Top source journals in Chernobyl and Fukushima studies.

The most productive journals in Fukushima study represents 23% of the total articles, receiving 50% of the total citations. Similar to Chernobyl study, the journal named as "Journal of Environmental Radioactivity" received the most publications and citations, followed by "International Conference on Nuclear Engineering Proceedings ICONE" and "Scientific reports".
Information linked to the journals leads to several considerations. The researches of both, Chernobyl and Fukushima studies, covered different subject areas, however, the most common categories were environment and those related to radiation protection. Journal publishing on these topics received also the most citations.

3.2.2. Most influential papers: Analysis of citations is the most prevalent method to measure the influence of publication. Paper that received the most citations can be identified as the most essential in the research field, thus referring to the subject of interest. Regarding the articles published on Chernobyl accident-related study, the followings have received the greatest number of citations: (1) Kazakov et al. (1992) – 637 citations, (2) Dubrova et al. (1996) – 347 citations, and (3) Rabes et al. (2000) – 328 citations. Among the total of 7,647 articles published on Fukushima accident, the following three has received the most citations: (1) Chino et al. (2011) – 820 citations, (2) Steinhauser et al. (2014) – 645 citations, and (3) Yasunari et al. (2011) – 520 citations.
It can be seen from the analysis of papers, estimates of health effects were of the most interest after the accident at the Chernobyl NPP, while environmental science category with attention to the radioactive release and its spatial distribution was of interest after the Fukushima disaster.

3.2.3. Keywords analysis: Analysis of articles' keywords provides insight into the main areas of research. Figure 2 illustrates the network map of keywords that co-occurred more frequently and their relationship in Chernobyl and Fukushima studies, respectively.
In total, 170 and 240 different keywords were obtained in Chernobyl and Fukushima studies. In each study, 7 different cluster were identified which facilitate the thematic grouping and patterns of the keywords. The circles on the network map represent the particulate keyword, and the size of circles is proportional to the total number of keywords. The lines indicate the strength of co-occurrence. In Chernobyl study, the first cluster corresponds to the radionuclides dispersion into the atmosphere, the second cluster is focused on radiation dose estimation, the third is aimed on dosimetry study and its corresponding health effects, the fourth is focused on contamination and fallout of Cs-137, the fifth and the sixth clusters are centred on radiation-induced mutation and thyroid cancer investigations, and finally, the last seventh cluster which was paid little attention is focused on the exclusion zone and dark tourism. In Fukushima study, clusters are as follows: (1) Fukushima accident: reasons and accident sequence, (2) Nuclear accident and nuclear safety, (3) Contamination and deposition of radionuclides, (4) Environmental contamination, (5) Iodine and Cs-137, (6) Health effects, (7) Comparison of Fukushima accident to Chernobyl in terms of environmental and health effects.



(a)

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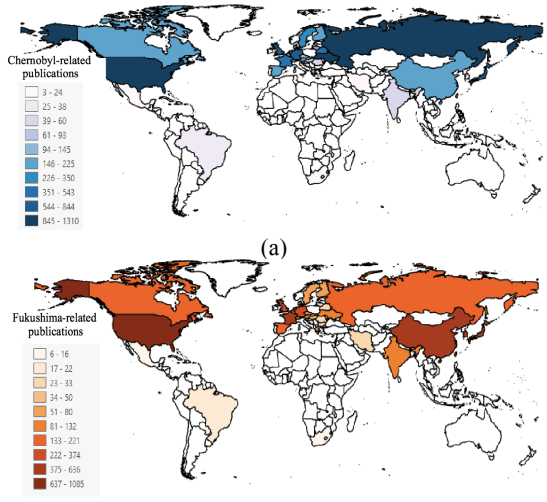
Figure 2. Keywords analysis: (a) Chernobyl study; (b) Fukushima study.

3.3 Geographical distribution of research

The contribution to the study of accidents at the Chernobyl and Fukushima NPPs has been significantly evolved worldwide. Figure 3 represents the scientific production of the most contributing countries. As can be seen, Ukraine and Japan leaded with 1,300 (13%) and 4,000 (42%) publications withing the corresponding study period, followed by the USA with 11% and 12% for the Chernobyl and Fukushima studies, respectively.



(a)

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Figure 3. Geographical distribution of the most productive countries according to the number of published papers: (a) Chernobyl study; (b) Fukushima study.

The country collaboration is visualized in Figure 4. In Chernobyl study, a remarkable links can be seen between Ukraine and Russia, UK, Belarus, and Japan. In case of European countries, a high degree of collaboration is observed between Sweden-Norway-Finland and France-Germany-USA. While such countries as China and Australia introduced very few works in cooperation with other countries. From Fukushima study, it is seen that most publications have been done by Japan and its collaboration with USA, Australia, China, and South Korea. USA also strongly collaborated with France, Germany, and Canada. A few publications were done by New Zealand, Singapore, and counties of South America.

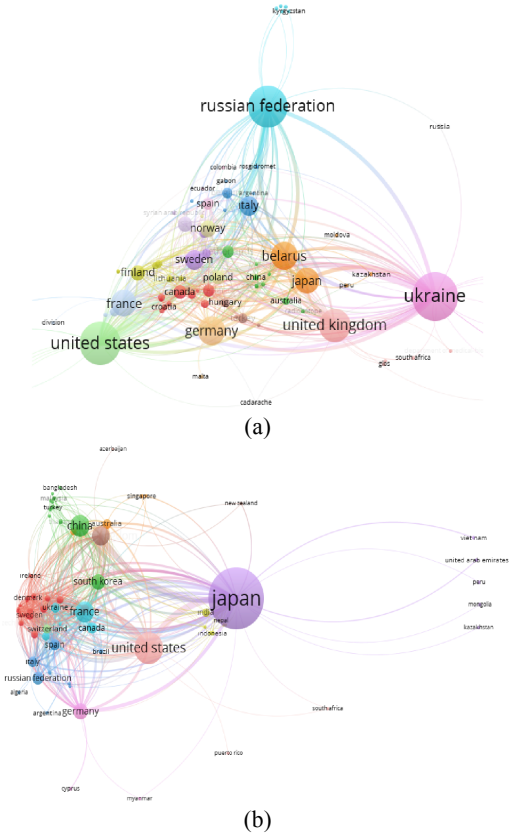

Figure 4. Global collaborative network between the most productive countries: (a) Chernobyl study; (b) Fukushima study.

3.4 Compound impact of energy and economic indicators on the spatial distribution of global scientific production.

We calculated the Moran's I indexes to examine the spatial autocorrelation of the response and explanatory variables. From the results, z-scores were found to be greater than 1.96 and corresponding p-values less than 0.05, meaning the variables passed the significance test at the 95% level. OLS modelling was performed to choose explanatory variables that could explain the variation in the response variable. Therefore, based on the p-value obtained for each coefficient in OLS, the statistical significance was found between the dependent variable and the following independent variables: (1) GDP; (2) nuclear reactors; (3) electricity production from nuclear; and (4) electricity consumption from nuclear. The above-mentioned indicators were selected to measure the local spatial variations using MGWR model.

Figure 5 shows the coefficient surfaces extracted from MGWR. These maps provide an explanation of the spatial relationship between observed publications and energy-economic factors. The GDP coefficients highlight the strong relationship between the number of publications and GDP in Western Europe and North America (Figure 5a). This model shows that the state of a country's economy has a major impact on scientific productivity in these regions. The nuclear reactors coefficients surface illustrates an overall positive relationship around the world (Figure 5b). This indicates that as the number of reactors increases, so does the number of publications. There are several countries where this relationship is particularly strong, such as Canada, the USA, Mexico, Brazil, China, and Russia. The share of electricity production and consumption from nuclear sources also shows an interesting division between countries. Country-level electricity production and consumption appear to have a positive relationship with scientific productivity (Figure 5c and 5d). This means that as nuclear energy production and consumption increases, the level of publications also tends to increase. The coefficients estimated in Figures 5c and 5d show that almost all European countries have similar patterns in explaining the spatial relationship between these variables. Hovewer it was surprising to see the low coefficients for France, as the country has the highest share of nuclear power generation in Europe.

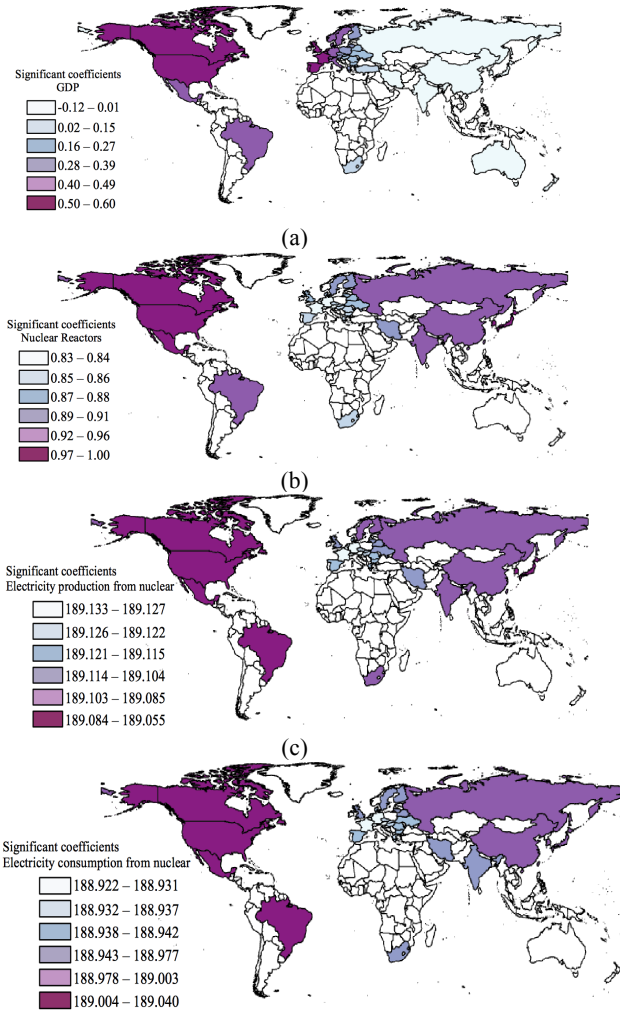

Figure 5. Spatial distribution of significant coefficients for each variable: (a) GDP; (b) Number of active nuclear reactors; (c) Electricity production from nuclear; (d) Electricity consumption from nuclear.

4. DISCUSSIONS

The Fukushima disaster, without a doubt, caused a significant resonance in the scientific community. After Chernobyl, a total of 7,876 articles were published in a 36-year period, while only in the 11-year period after the Fukushima accident there were 7,647 scientific literature. Therefore, it could be argued that Fukushima-related literature is substantially ahead the number of publications linked to Chernobyl. Among the most productive countries, there are six that contributed to research, accounting for a total of 75% of publications – Canada, the USA, China, Russia, Ukraine, and Japan. In the wake of Chernobyl accident, scholars form Ukraine, Russian Federation and Belarus have focused mostly on studies dedicated to radiation syndromes, cancer incidence among emergency workers, and then to the thyroid cancer among children, while most of European countries concentrated their research on the environmental issues (Saenko et al., 2011). A large volume of post-Fukushima publications in Japan's neighboring countries was aimed on describing the apparent environmental consequences of the disaster. The majority of European countries, in turn, have focused on energy issues. Over the years, the reported literature has become increasingly exploratory, giving attention to the consequences of emergency response (Hasegawa et al., 2016). However, most work in this area still suffers from a lack of analytical attention. Thus, literature related to urban evacuation has mainly focused on its mental and psychological implications and lessons learned rather than problem solving and rational decision making. There is still very little literature on urban planning based on predetermined acceptable levels of risk. In particular, hazard identification, population risk analysis and urban risk planning have great potential for modification, adaptation, and mitigation for applications in city planning. It was also noted that there was a lack of research examining the risks caused by both natural and radiation hazards. These findings are derived from the interpretation of scientific mapping results in the VOSviewer tool based on the evolution of keywords co-occurrence analysis, analysis of journals, papers, as well as collaborative network analysis between countries.

We then measured the productivity score for each country and examined the correlation between the number of publications and the economic and energy performance of those countries. We applied MGWR modelling to determine whether there was agreement between the number of publications and parameters including GDP, number of active nuclear reactors, and electricity generation and consumption from nuclear. Model interpretations indicate that nuclear-dependable countries are showing more interest in nuclear power research. Most of publications come from countries that rely heavily on nuclear energy sources and, accordingly, have the largest number of nuclear reactors, although these countries were not affected by either accident. In addition, the rapid increase in NPP construction in the last decades has given an unprecedented impetus to nuclear energy use, which is expected to double in the nearest future. For these reasons, we would like to encourage scientists from around the world to focus on the research of emergency response, nuclear disaster management, urban planning and design for better risk assessment and therefore better protection of the population.

5. CONCLUSIONS

We conducted a bibliometric analysis of the scientific literature on accidents at the Chernobyl and Fukushima NPPs using the SCOPUS database. Based on over 10,000 articles, this study provides a comprehensive overview of global research activities on the current topic. In bibliometric analysis, we mainly focused on the scientific literature published over the periods of 1986-2022 and 2011-2022 on Chernobyl and Fukushima, respectively. According to the postulated research questions, our analysis consisted of performance analysis, including total number of publications, research trends over the study period, number of active years of publications, as well as scientific productivity per year. Science mapping was performed using VOSviewer tool. Here, the most influential publications, journals, and books on the topic were identified. Additionally, geographical interactions among the most productive countries were studied. Regression-driven analysis was developed to assess the spatial relationship between the most productive countries and energy-economic indicators. For this, a MGWR techniques was used. The results were visualized in GIS platform using ArcGIS software. We draw the following main conclusions:

(1) The scientific interest is clearly visible shortly after the particular nuclear accident.
(2) The most explored topics were ecology, medicine and energy, with little attention to multidisciplinary and social sciences.
(3) The most productive countries were those directly affected by the accident or those geographically neighboring with the "accident country".
(4) We found a positive correlation between the number of publications and energy efficiency indicators.
(5) Countries with the highest GDP and with the greatest number of operating NPPs were significantly productive.
(6) MGWR analysis revealed a tendency towards the positive spatial relation. In particular, independent variables such as GDP, nuclear reactors, and electricity production and consumption from nuclear sources are directly proportional to the volume of scientific input. Therefore, these factors should be considered in future bibliometric studies since the ever-growing demands in electricity over the last decades.

Our analysis will provide researches involved in nuclear energy, sustainable decision making and nuclear disaster management with essential information about accident research, such as its major scientific topics, its primary journals, its active countries, and its most frequently used keywords from a historical point of view. With this information, researchers can identify the key points and boundaries for future studies.

The present study has some limitations inherent in the parameters of the bibliometric search. Firstly, the study was narrowed to using only the SCOPUS database, as it was found to be one of the most relevant in this research. Secondly, the literature was skewed towards English-language literature, so documents in "accident-native" languages such as Russian, Ukrainian, and Japanese were underestimated. Finally, our search does not include normative documents or publications of special accident research organizations, as we mainly focused on scientific productivity. Therefore, in future work, it may be important to study other databases than SCOPUS. The inclusion of professional documents and regulations could complement our analysis and improve it from a different perspective. Last but not least, the use of "accident-native" languages, even if it does not greatly contribute to international bibliographic coupling, can be useful to study in depths the scientific performance of a particular country.

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