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From Waste to Shield: A Bibliometric Analysis (2004-2024) on Sustainable Radiation Protection Materials

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Abstract: The considerable increase in waste poses an ecological, economic and regulatory challenge which requires an innovative solution. The recycling and reuse of industrial by-products from treatment process is one of the pillars of circular economy, which is linked to sustainable development and environmental preservation. However, the depletion of natural resources by the current linear development model has allowed the emergence of the circular economy which means that waste can be used as raw material for others, as a substitute for non-renewable resources. The transition to this new type of economy in the construction field relies on incorporating industrial waste into the production of radiation shielding materials (RSM). However, despite exhaustive research on these materials, until now, no comprehensive bibliometric analysis has been carried out to map research trends, identify major contributors, and highlight scientific gaps in this field. The present study examines the benefits of using trash in the production of RSM through bibliometric analysis. Every study done between 2004 and 2024 is examined using Vosviewer, a tool for network and similarity visualization. The findings show that 60% of the studies focused on the mechanical properties of RSM. Nearly 28% of the examined material comes from China's most productive university, Beijing University of Chemical Technology. Moreover, an analysis of scientific cooperation suggests that nations or areas (such the United States, India, Saudi Arabia, Turkey, or Egypt) with a greater inclination for international cooperation are probably going to grow faster.

1. Introduction

The civil construction sector makes extensive use of non-renewable natural resources. The mining of these minerals exacerbates air pollution, biodiversity loss, and climate change. This bibliometric study provides an overview of the literature on the use of industrial waste from treatment processes as by-products in construction materials and radiation-protective applications. Several experimental studies have also examined the effectiveness of radiation shielding materials (RSM). However, no bibliometric study has been conducted to map research trends and identify scientific gaps in this field. This study examines the publication history and identifies key research axes using a bibliometric approach based on the Scopus database and the VOSviewer application (José de Oliveira *et al.*, 2019; N'diaye, *et al.*, 2022; Hammouti *et al.*, 2025).

Prior to focusing on suitable materials for RSM, one of the modes of heat transfer, i.e., radiation, also exhibits in day-to-day life, which cannot be separated from us. The sun and cosmic rays are natural sources of radiation that are emitted in the atmosphere via the earth, bodies, houses, food, etc. Radiation

shielding is used for protection from internal and external exposure of our bodies in contact with either or both of natural or source of radiation in small areas (Oto *et al.*, 2015; Singh *et al.*, 2014; Frane and Bitterman, (023).

The fundamentals of radiation protection are covered by these shielding products, including safe working circumstances, radiation kinds, source activity, dosage type and rate, etc. The choice of shielding material is largely controlled by two factors: the cost and the acceptable limit to resist this exposure. High absorption per c/s area, reduced energy loss and emission, fewer irradiation impacts on mechanical and optical qualities, etc., were some characteristics of appropriate shielding materials. Therefore, by designing the use of various structures and techniques, accordingly, it is possible to obtain prepared materials for radiation protection (Verma Sarika *et al.*, 2024).

Tyagi *et al.* (2020) have examined various industrial wastes utilized in radiation shielding concrete. One of its uses is as an alternative energy source that uses nuclear power to meet global power demands. Nuclear reactors based on thorium are one of the main sources of electricity produced in India (Sinha and Kakodkar, 2006). Nuclear energy has been shown to be highly efficient and clean, and it finds use in a variety of fields, including research, energy, and health (Rhodes, 2018; Tyagi *et al.*, 2020) have published a comprehensive compilation on radiation shielding concrete that addresses several risks.

In their research, (Prajapati, *et al.*, 2022; Trotta, *et al.*, 2021; Aguilar-Penagos *et al.*, 2017; Quiroga-Barriga *et al.*, 2025) have incorporated recycled concrete aggregates. Additionally, the integration of this research to improve sustainability in the building field was clear. Some of the researchers conducted their experiments using a combination of three types of steel shot (Lermen *et al.*, 2020), fly ashes (Doğan, *et al.*, 2022), and synthetic shielding aggregates based on red mud that are useful for gamma radiation shielding (Chauhan. *et al.*, 2017). These materials are utilized in construction in addition to recycled concrete aggregates, glass, and fiber. Other studies also explored the viability of recycling asphaltene or PVC (Saleh *et al.*, 2022), and substituting waste glass powder, silica fumes, and environmental debris (Bayraktar, 2021) for Portland cement.

The aims of this study are to: (i) to map scientific developments (2004–2024) in the use of industrial waste in RSM based on a rigorous bibliometric analysis.; (ii) to identify the main contributors in the studied field (countries, institutions, researchers, journals) and analyze their scientific collaboration networks.; (iii) to identify research and innovation possibilities for the successful integration of recycled materials in nuclear, medical, and industrial applications, as well as to expose gaps in the areas of long-term sustainability and environmental evaluation.

To identify the most relevant subjects addressed in the journals, an analysis of 4,589 publications indexed in the Scopus database was conducted in December 2024. Focusing on the recovery of waste for use as RSM, this study employs bibliometric techniques to statistically examine publications from 2004 to 2024, thereby providing a comprehensive overview of the research landscape. The present analysis is the first systematic mapping: Unlike narrative reviews (e.g., Tyagi *et al.*, 2020; Verma *et al.*, 2024) that only summarize technical aspects, our study uses a bibliometric and scientometric approach to map the field. It presents interdisciplinary dimension: It bridges distinguished fields (materials, nuclear physics, engineering, environment), which has never been done before. The use of VOSviewer, which reveals keyword co-occurrences, author networks, and thematic clusters, offers a predictive reading of research, networks and trends (Aria & Cuccurullo, *et al.*, 2017; Elmsellem, *et al.*, 2023; Merzouki, *et al.*, 2025; Nandiyanto *et al.*, 2026). Indeed, this study provides a critical framework for identifying future avenues (multi-scale modeling, international standardization, LCA, industrial integration).

As a result, this research seeks to address the following questions:

1. How has research on waste recovery for RSM evolved over the past 20 years?
2. Which journals and researchers are most influential in the study of waste recovery for RSM?
3. Which countries have been the most productive in this field of research?
4. What are the main research themes and keywords that have emerged in studies on waste recovery for RSM over the past two decades?

2. Materials and methods

The purpose of this study is to present an overview of studies on waste recovery and its repurpose as RSM that have been carried out during the previous 20 years. Bibliometric and graphical techniques were used to accomplish this. Bibliometric analysis involves tracking research on a specific topic and presenting the findings through a variety of analytical approaches. Relevant publications indexed in the Scopus database were included in the analysis to identify high-quality studies. The data collection was carried out on December 25, 2024, by searching for keywords in the title, abstract, and keyword fields using the "Topic" option. The dataset included the largest proportion of English-language and open-access papers among those retrieved through the search. The relevant keywords and phrases used were waste recovery and RSM. Scopus provides advanced tools for tracking, visualizing, and analyzing research output across multiple disciplines, including engineering, chemistry, environmental science, physics and materials science, and chemical engineering. For this reason, it was selected as the primary database to identify studies on waste recovery applied to RSM. To ensure the relevance of the selected publications, additional manual screening was conducted to exclude papers that did not meet the criteria outlined in **Table 1**. Therefore, 4,589 publications were retained for further analysis. The PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) standards, adapted for bibliometric analysis through the PRISMA-S extension, were followed in this bibliometric review. The protocol clearly specified the study topic, database selection, search strategy, inclusion and exclusion criteria, and screening procedure. Table 1 lists the inclusion and exclusion criteria, while **Figure 1** depicts the analytical research structure. This study validated the Scopus data Boolean query to mitigate database bias: (TITLE-ABS-KEY ("radiation shielding" AND ("waste recycling" OR "industrial by-products"))
Duplicate data were removed and affiliations were standardized using OpenRefine to resolve inconsistencies (e.g., "Beijing Univ Chem Technol" vs. "BUCT"). Non-English publications and patents were not considered.

Table 1. Criteria for inclusion and exclusion in data screening

Inclusion criteria	Engineering, Materials Science, Environmental, Chemical Engineering, Science Chemistry, Physics and Astronomy
	Documents type limited to Article and review
	Language limited to English
Exclusion criteria	An excluded keyword is the term article, which is repeatedly used within the body of the article itself.
	Mathematics, Computer science, Health professions Energy,
	Conference review, Conference paper, Note, Book chapter, Letter, short Survey

3. The bibliometric analysis

The most cited publications, the most popular search terms, the journals that published the largest number of studies on the subject, the most active research areas, potential international collaborations, the keywords used, the most cited authors, the co-cited journals, and the most frequently published research domains are all considered in bibliometric analysis. The VOSviewer software, a widely used tool for visualizing bibliometric networks, is then employed to generate the network visualization. VOSviewer facilitates the development of co-occurrence networks of key phrases extracted from a corpus of scientific literature using text-mining techniques. It was developed by the Center for Science and Technology Studies (CWTS) at Leiden University in the Netherlands. Data files from RIS, WoS, Scopus, Dimensions, and PubMed can be used to generate bibliographic networks. Network data maps can be visualized and analyzed through the Java-based application VOSviewer. However, despite its potential, VOSviewer has not been widely applied to text analysis and visualization outside bibliometric datasets. Although there are many bibliometric analysis programs and tools available, including CiteSpace, HistCite, and CitNetExplorer, VOSviewer has superior visualization features and can manage data input and export from a variety of sources with ease (Moral-Munoz *et al.*, 2020). Numerous scholars who examine bibliometric networks (Van Eck and Waltman, 2014; Rialti *et al.*, 2019; Vaio *et al.*, 2022; Yu *et al.*, 2019) have confirmed that VOSviewer works well in their investigations.

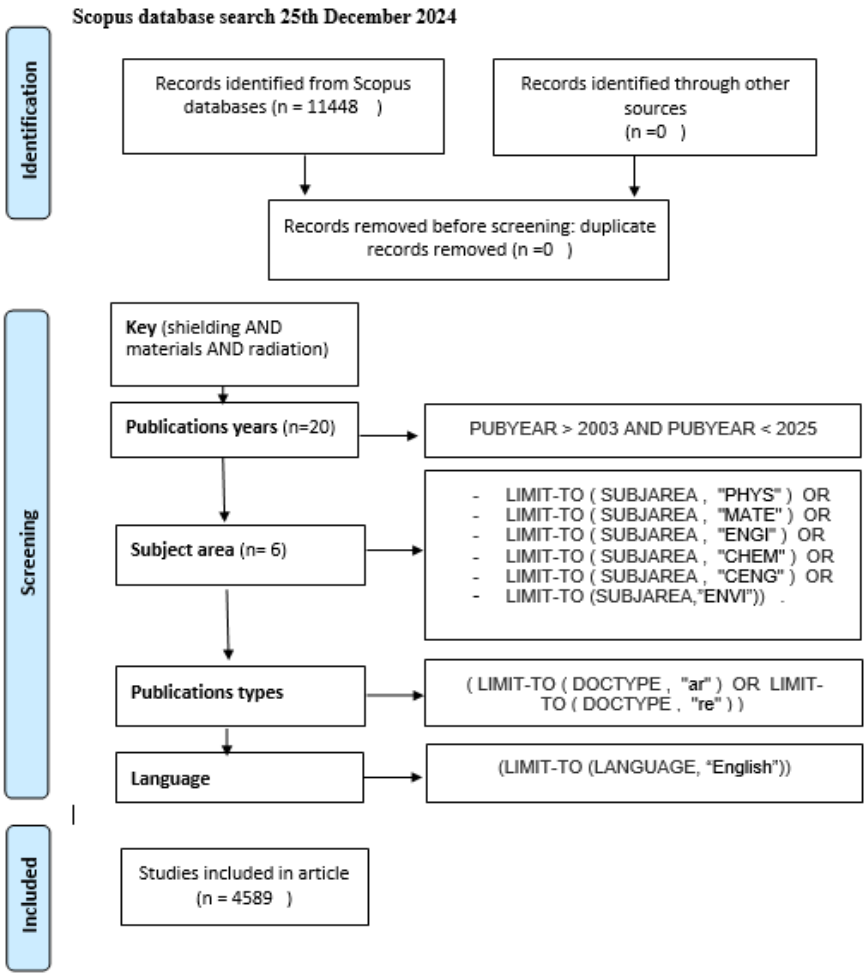

Figure 1. PRISMA (Preferred Reporting Items for Meta-Analyses) Flowchart for finding and adding papers to a review

The VOSviewer's ability to visualize and create text maps using bibliometric data is exceptional (Xu, *et al.*, 2021). However, for VOSviewer to function properly, certain data must be included in the Excel input file, such as author, abstract, and keywords. Accordingly, "Author" should be treated as the identifying column and "Abstract" as the column containing the text to be analyzed. This review is based on the aforementioned items. First, RSM waste recovery is considered. With an increasing number of studies being conducted, RSM has become an emerging and dynamic area of research. To evaluate the structural development of this field, a precise method is required to analyze the vast body of recorded literature. This is followed by an overview of ongoing research that helps shed light on these issues.

4. Results

The paper provides a profile of investigations conducted over the past 20 years on waste recovery as RSM. The results of the review are analyzed in relation to the research topics.

4.1.Research question 1

How has research on waste recovery for RSM evolved over the past 20 years? To address this question, the publication years of the studies were examined. It was observed that most publications appeared in recent years. In 2024, there were 773 papers on waste recovery as RSM; in 2023, there were 600 publications on radiation shielding; and in 2021, there were 473 publications. As illustrated in **Figure 2**, the remaining papers were spread over the other years.

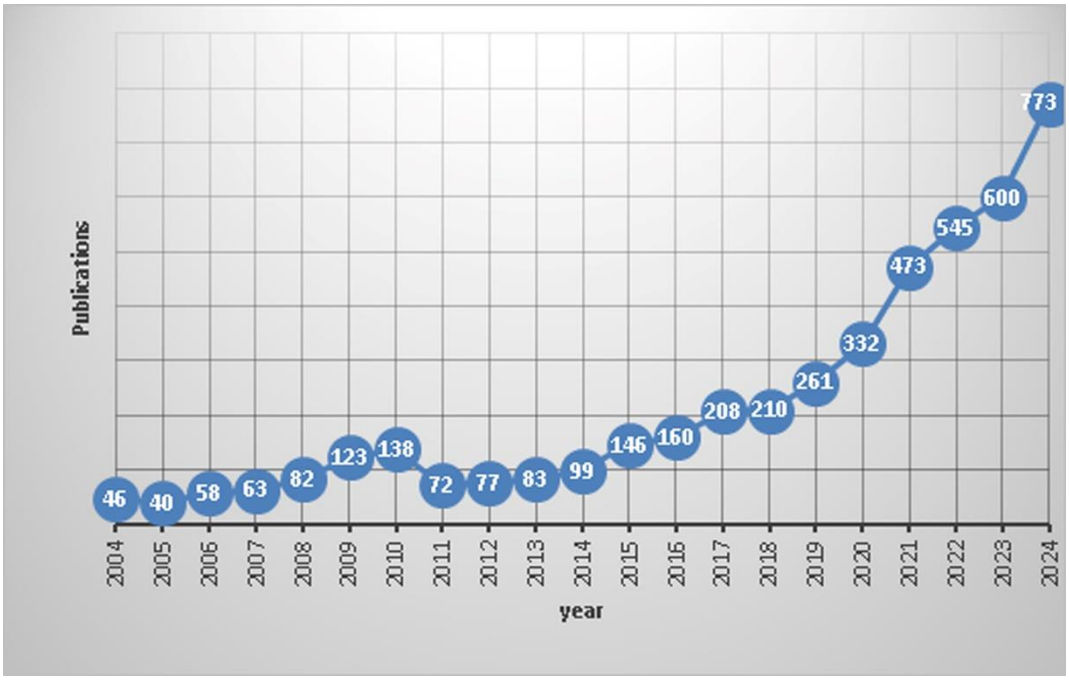

Figure. 2. Distribution of publications by years (2004-2024).

4.2 Research question 2

Which journals and researchers are most influential in the study of waste recovery for RSM? The criteria used to analyze the most cited journals, as shown in **Table 2**, include *total publications*, *total citations*, *journal cite score*, *most cited article*, *times cited*, and *publisher*.

These statistics were specifically taken from the graph of documents by source. This code ‘’TP’’ In fact, it is related to the number of total articles published by the journal before filtering, and it is not limited to the number of articles after filtering, 4589. The number of citations in the first journal is very important and important, and this is clear evidence of the intensity of interest of researchers in this field. With 16,939 publications and 151,323 citations overall, *Ceramic International* is the most prolific journal in the field of radiation shielding, as shown in **Table 2**. Following this, *Fusion Engineering and Design* has 7,559 publications and 2,176 total citations, while *Progress in Nuclear Energy* has 1,502 publications and 7,971 citations. The distribution of the most prolific journals in radiation, waste, and shielding is also presented in **Table 2**.

Table 2: The top 10 productive journals on waste recovery as RSM between 2004 and 2024

Note: TP = Total Publications, TC = Total Citation.

Journal	TP	TC	Cite Score	Article le plus cité	Times cited	h-index	g-index	Citations per publication (CPP)	Editeur
Ceramics International	16,939	151,323	8.9	Structural color tunable intelligent mid-infrared...	79	78	90	8.93	Elsevier
Progress in Nuclear Energy	1,502	7,971	5.3	A binary composite material of nano polyaniline...	23	45	55	5.31	Elsevier
Fusion Engineering and Design	2,176	7,559	3.5	Conceptual design workflow for the STEP Prototype...	9	32	40	3.48	Elsevier
Nuclear Instruments and Methods in Physics Research	3,595	9,638	2.7	Multi-reflection Astral mass spectrometer with...	9	28	35	2.68	Elsevier
Materials	29,882	183,939	6.2	Dynamic Splitting Performance and Energy Dissip...	32	62	75	6.16	MDPI
Polymers	17,789	166,511	9.4	Degradable Polymeric Bio(nano)materials and Thei...	54	58	70	9.36	MDPI
Radiation Effects and Defects in Solids	403	672	1.7	Determination of water-equivalent diameter (Dw)...	9	22	25	1.67	Taylor & Francis
Optical Materials	5,357	34,823	6.5	Influence of Gd_2O_3 on structural, optical, radia...	33	49	60	6.50	Elsevier
Construction and Building Materials	16,759	224,119	13.4	Differing perspectives on the use of high-content...	69	85	95	13.37	Elsevier
Journal of Applied Polymer Science	6,173	34,591	5.6	Rational design of high-performance epoxy/expand...	66	71	80	5.60	John Wiley & Sons

Additionally, Research Question 2 examines the authors who have contributed most extensively to this field. Another common metric for assessing scholarly influence is the h-index and g-index, where higher values reflect a stronger balance of research productivity and citation impact (rather than mere "awareness" or "consistency"). It is worth noting that Elsevier is a leading academic publisher, producing a significant portion of high-impact journals. Research impact can also be observed in citation trends across disciplines: fields such as materials science and civil engineering (or "building science") are examples of domains that frequently attract high citation rates, underscoring their influence in academia.

4.3 Research question 3

Which countries have been the most productive in this field of research? **Table 3** and **Figure 3** show that the leading countries in the field of waste recovery as RSM are analyzed according to the following criteria: *Country*, *Total Publications*, and *Educational Institutes*.

Table 3: Top 10 countries and educational institutions

Country	Educational Institutes	TP	CC	h-index	PAY
China	Beijing University of Chemical Technology	1,520	0.62	58	76
Saudi Arabia	Department of Physics, Faculty of Science, University of Tabuk, Tabuk	212	0.85	12	10.6
India	Central Electrochemical Research Institute, Karaikudi, Tamil Nadu	950	0.50	25	40
United States	Department of Mechanical Engineering, University of Nevada, Reno, NV	1,044	0.70	45	52.2
Turkey	Faculty of Science, Department of Physics, Ataturk University, Erzurum	221	0.55	15	12
Egypt	Department of Medical Equipment Technology, Faculty of Allied Medical Sciences, Pharos University in Alexandria	351	0.60	18	20
Russian Federation	National University of Science and Technology (MISiS), Moscow	283	0.65	20	15
Jordan	Department of Physics, Faculty of Science, Hashemite University, Zarqa	119	0.50	10	8
Italy	Department of Inorganic, Physical and Materials Chemistry, NIS Centre of Excellence, University of Turin, Torino	646	0.75	30	35
Germany	Dept. Wood Technology and Wood-Based Composites, University of Göttingen, Göttingen	174	0.80	28	25

Also Table 3 and **Figure 3**, which identify the ten most productive countries in RSM research, present the topic distributions of the leading countries/regions and their institutions. From a national perspective, most of the listed countries and regions show consistent interest across all research areas related to radiation, waste, and shielding. However, some countries and regions demonstrate particular focus on specific developments. For example, China was the most productive country, with a total of

1,520 articles (h-index 58) produced at Beijing University of Chemical Technology. Following China are the Central Electrochemical Research Institute in India, with 950 articles, and the United States, with a total of 1,044 articles (h-index 45).

Some European institutions, have a strong balance between productivity and citation influence despite their limited publication, such as Germany's University of Göttingen (h-index 30) and Italy's University of Turin (h-index 28), However Jordan's Hashemite University lags in both output (119 publications) and impact (h-index 10). While, Saudi Arabia's University of Tabuk achieves high citation quality (citation rate 0.85) with modest output (212 articles) in Middle east, demonstrating that impactful research is not only dependent on volume. Russia's National University of Science and Technology (MISiS) have relatively steady contributions (283 publications, h-index 20), whereas India's Central Electrochemical Research Institute and Egypt's Pharos University, considered as emerging contributors, are confronted between output (950 and 351 publications) and global influence (h-index 25 and 18). In summary, the landscape shows that while China and the U.S. are leaders in scale, Europe combines productivity with reach, and some institutions in regions like the Middle East or Russia prove niche expertise can generate outsized scholarly impact.

These results could be explained by a global research ecosystem shaped by economic power, political priorities, and institutional strategies. International economic weight and infrastructure favor the dominance of China and the United States. Smaller players leverage their niche expertise and collaboration to amplify their impact. Emerging economies, however, face structural barriers, limited funding, limited global integration, and academic incentive systems that hamper their ability to convert research volume into global influence. Closing these gaps requires more targeted investments, international partnerships and projects, and reforms to academic assessment frameworks.

The analytical findings of leading countries' studies on waste recovery as RSM are shown in **Figure 3**. The institutions in these countries demonstrated particular interest in specific research areas. The most prolific nations are China, Saudi Arabia, India, and the United States, followed by Turkey and Egypt. Additionally, Germany, Italy, Jordan, and the Russian Federation rank among the top contributing countries. The analysis also indicates that countries and regions belonging to the same organizations or continents, with similar research objectives, tend to collaborate more closely in the study of waste recovery as a source of RSM.

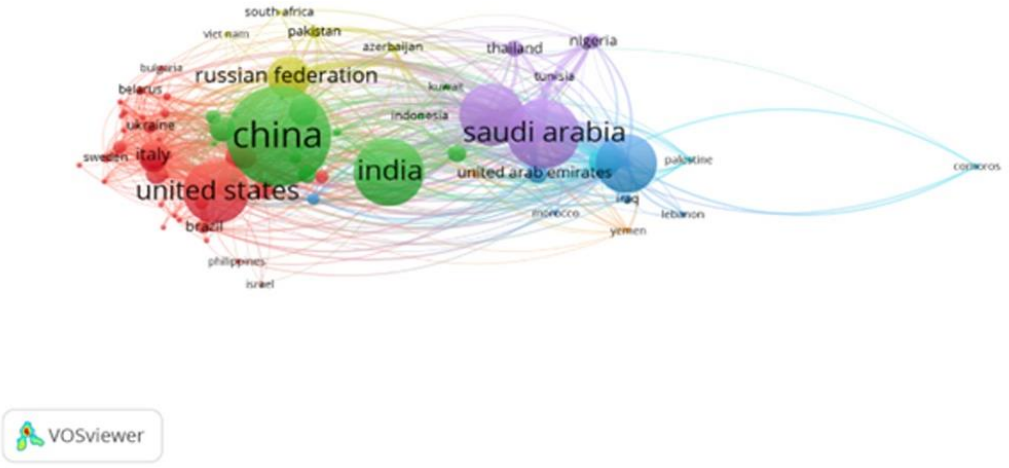

Figure 3. Analysis of the most productive countries in the field of waste recovery as RSM

Germany's high eigenvector centrality (0.80) highlights its role as a collaborative link between European and Asian institutions, even though China leads in terms of production (TP = 1,520) (**Figure 3**). The keyword analysis overlooked a subset of Middle Eastern research focused on cost-effective shielding, but the Louvain algorithm was able to identify it.

4.4 Research question 4

What are the main research themes and keywords that have emerged in studies on waste recovery for RSM over the past two decades?

The main research terms used in the field of waste recovery over the past 20 years are related to RSM. Bibliometric analysis can be used to evaluate the relationships between publications and keywords, allowing readers to quickly classify research interests within the topic. To perform a keyword co-occurrence analysis on a selected set of publications, VOSviewer imports data files in Research Information Systems (RIS) format. A minimum of two keyword occurrences is required. From 4,589 articles, co-occurrences of 2,764 keywords were extracted. Keywords that appear together in the articles are listed in **Table 4**. The most frequently occurring terms are *electromagnetic shielding* (914 occurrences), *gamma-ray* (916 occurrences), and *radiation shielding* (2,274 occurrences).

Figure 4 shows the whole keyword network. 183 keywords were identified in this context from the data set, considering general co-occurrence.
(Occurences "Oc" = 2274), "Gamma ray" (Oc = 916), "Electromagnetic shielding" (Oc = 914), "shielding" (Oc = 805), and "radiation protection" (Oc = 458) are the most used terms in the study.

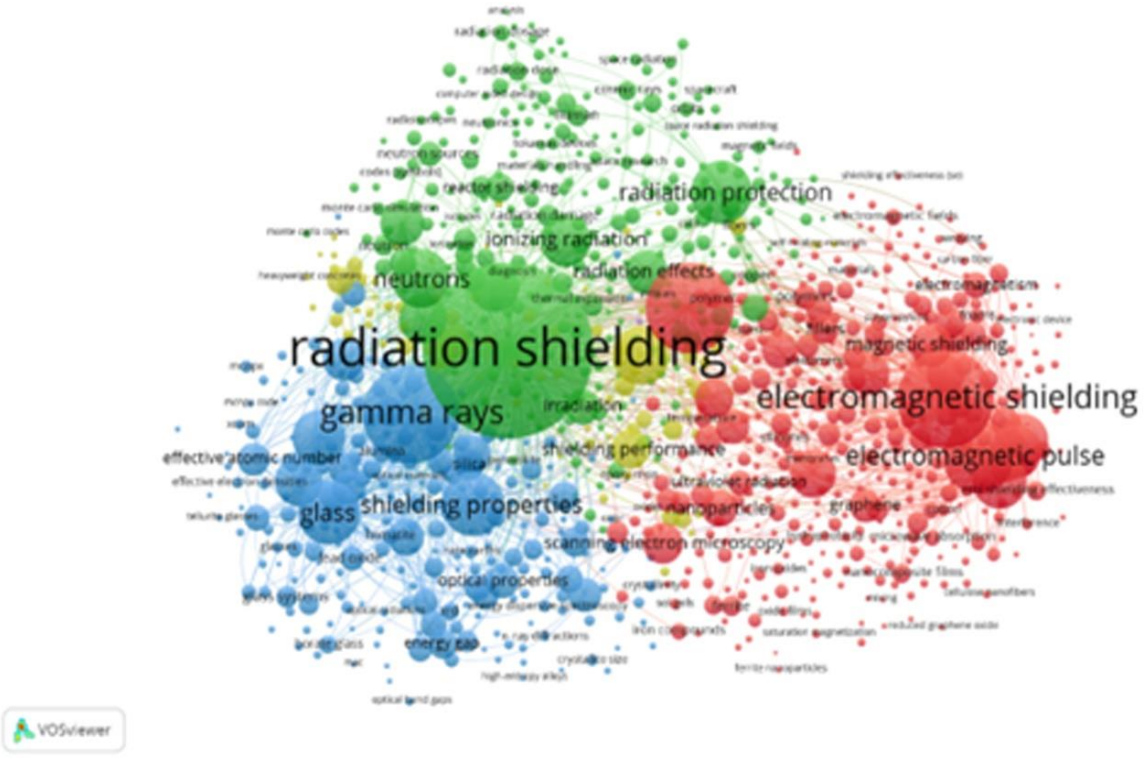

Figure 4. Analysis of publications according to keywords

Table 4: Summary of co-occurrence keywords for selected publication.

Keyword	Occurrences	Total link strength
Radiation shielding	2274	24137
Gamma-ray	916	11774
Electromagnetic shielding	914	11675
Shielding	805	9457
Electromagnetic pulse	569	8294
Glass	471	6588
Shielding properties	460	6181
Electromagnetic interference shielding	374	5480
Radiation protection	458	5431
Signal interference	345	5257
Electromagnetic wave interference	337	5212
Atoms	357	5141
Shielding materials	400	4852
Neutrons	410	4751
Nanocomposites	288	4411
Mass attenuation coefficients	306	4368
Neutron irradiation	312	3890
Radiation	311	3500
Scanning electron microscopy	234	3424
Magnetic shielding	253	3396

5. Discussions

The urgent need for active, multidisciplinary research in this area may lead to a sharp increase in publications on waste recovery for RSM. Researchers draw perspectives from multiple fields, including materials science, which represented the highest percentage (32%), and other lower percentages, including physics (24%), engineering (22%), chemistry (11%), chemical engineering (6%), and environmental science (5%), to create a more successful solution. The incorporation of research subjects and domains is shown in **Figure 5**.

The current study provides a summary of waste recovery as RSM based on 4,589 research papers retrieved from the Scopus database, using bibliometrics and content analysis. The data indicates that waste recovery is increasingly recognized as a promising research topic in the field of RSM. The results of this analysis of publication sources are often valuable to interdisciplinary sectors investigating the relationship between technology and its impacts. See **Figure 6**. The most productive university is in China, specifically Beijing University of Chemical Technology (**Table 3**), accounting for approximately 18% of the reviewed material. Furthermore, a review of scientific collaboration indicates that countries or regions, including Saudi Arabia, China, Egypt, and Turkey, that prioritize international cooperation tend to progress more rapidly. The bibliometric analysis reveals that China, India and the United States dominate the field of research on radiation protection materials. This trend can be explained by several factors: (i) safe nuclear expansion in China (Wu *et al*., 2019), (ii) the rise of new generation nuclear reactors in India (Zohuri, 2020), and (iii) the growing interest and very

advanced research on polymers and nanocomposites in the United States (Maniar, 2004). On the other hand, some nuclear countries such as France and Russia are not well represented in this analysis. This could be explained by the fact that the funds allocated are relatively low compared to other fields (green energy, AI, climatic change etc.) or their research is published in institutions or journals not indexed in Scopus.

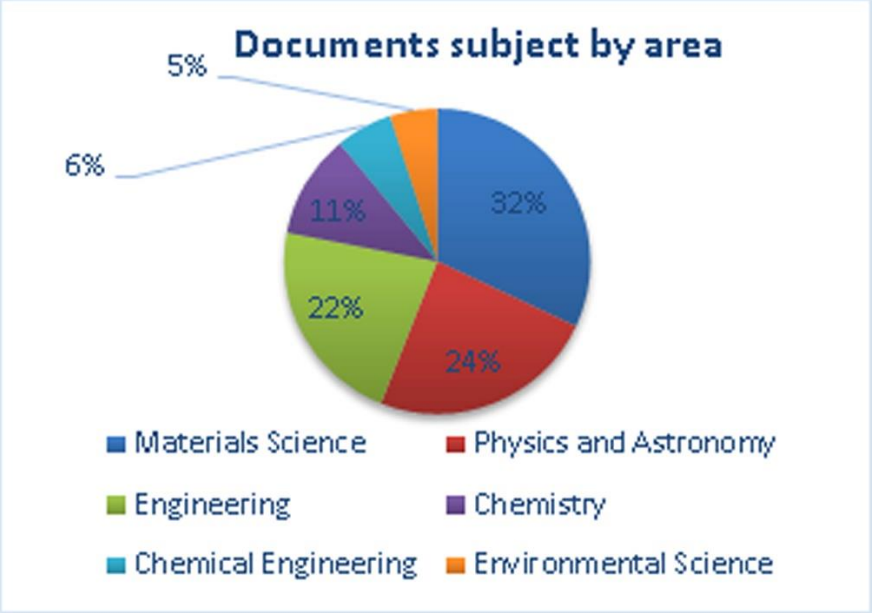

Figure 5. Document distribution across subject areas

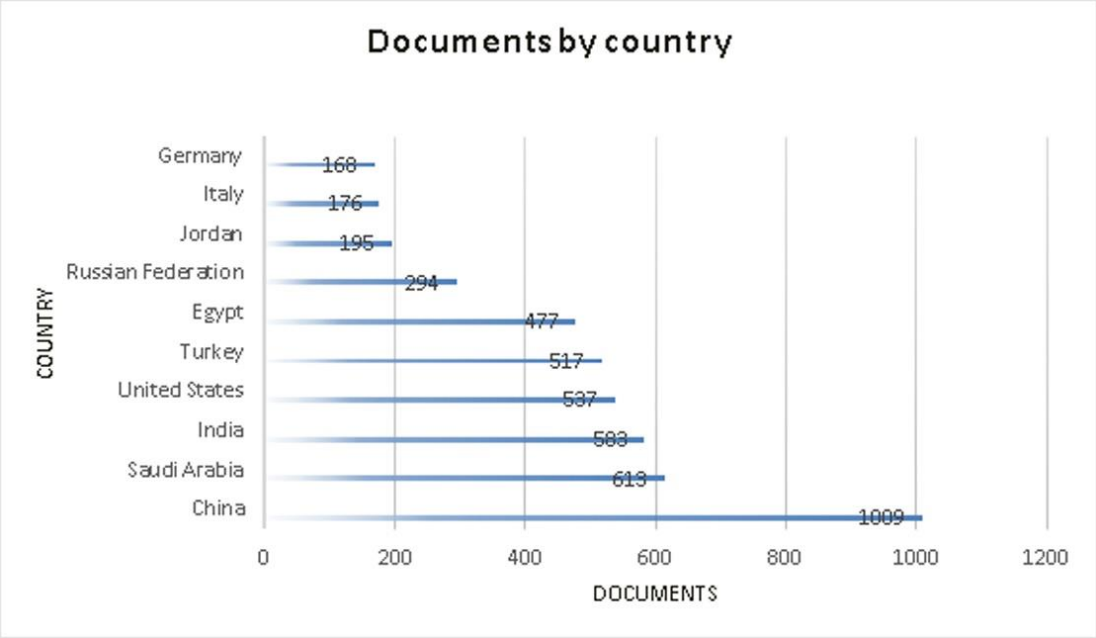

Figure 6. Country-wise distribution of total publications

Collaborations between regions or organizations within the same area are also highly significant. According to this study, RSM and waste are among the most relevant research topics. Durability and the microstructure of high-performance concrete are also important subjects. Additionally, the study highlights the most common patterns and trends in radiation shielding research,

which can be grouped into three primary themes: (1) concrete manufacturing; (2) technological innovations to enhance the microstructure of concrete; and (3) the development of environmentally friendly shielding materials for use in nuclear plants and medical facilities. The multi-domain recycling of these inexpensive wastes demonstrates how these crucial radiation protection materials can be strategically useful and how they can be used in a variety of industries, such as nuclear power plants, healthcare, space, etc. According to the review's figures, a new approach to using a lot of inexpensive waste to create sophisticated radiation protective materials should be taken. The importance of this has been shown in the names of the research mentioned in **Table 2**; for example, the article A binary composite material of nano polyaniline intercalated with Nano-Fe_2O_3 for enhancing gamma-radiation-shielding properties: Experimental and simulation study, which was published in a magazine, Progress in Nuclear Energy, the number of quotes was very important. TC = 7971, and another article titled Multi-reflection Astral mass spectrometer with isochronous drift in elongated ion mirrors, which was published in a magazine, Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors, and Associated Equipment," the number of quotations was as high as 9638 quotations.

The obtained results confirm the conclusions of Abualroos *et al*., 2023 and Bekhit *et al*., 2024, who had already identified conductive polymers as emerging solutions which significantly improve the shielding properties of the materials they contain. In the other hand, our analysis also highlights the significant increase in research on the use of fly ash and recycling of glass waste, which underlines during the last decade a transition towards eco-friendly materials. This trend could be related to recent regulations and allocated funds promoting the circular economy and the valorization of industrial waste in construction materials in order to minimize CO_2 emissions.

In summary, this bibliometric mapping attests to the significant growth in the study of waste-derived RSM, mainly driven by China, India, and the United States. However, in contrast to previous analyses (Tyagi, 2020; Verma, 2024), our study highlights the notable absence of European leaders such as France or Russia. This could reflect different funding priorities or possible publications not listed in Scopus database. Furthermore, the predominance of terms related to “electromagnetic shielding” indicates a thematic overlap that distorts the statistics and makes it necessary. Despite these biases, the findings highlight the increasingly significant importance attributed to ecological approaches (fly ash, red mud, glass…), in line with international circular economy and reduced carbon footprint policies. Future work should go to address concrete issues such as sustainability, certification, and life cycle Analysis. Incorporating accelerated aging protocols and machine learning-based predictive models, as suggested in this research, could reduce the gap between experimental results and their implementation at industrial scale.

This research, although based on a bibliometric analysis, presents some limitations mainly regarding the potential simulations to be used to examine the interaction of gamma rays with these materials in real conditions. Furthermore, a survey conducted with industrial and medical stakeholders could help to identify barriers to adoption, particularly of new RSM. Thematic analysis highlighted a gap between laboratory studies and industry adoption. in order to solve this problem, we propose a longitudinal framework (**Figure 7**) combining accelerated ageing tests with machine learning models (e.g., NNA, Random Forest) for the prediction of material degradation under real-world conditions. Partnerships with the IAEA and nuclear research centers could facilitate large-scale testing.

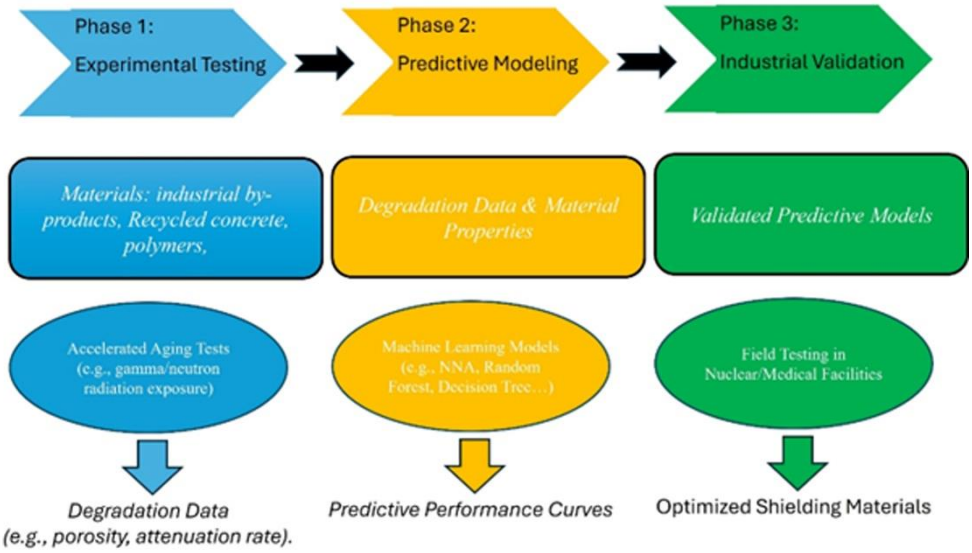

Figure 7. Flowchart for evaluating recycled radiation shielding materials: integrating accelerated aging tests and machine learning predictive models

Conclusion

This study showed that research on the use of recycled materials for radiation protection is growing rapidly, particularly in China, the United States and India. The most studied materials include enriched concrete, reinforced polymers and fly ash composites. However, the bibliometric analysis reveals a lack of in-depth research on the long-term sustainability of these materials and their manufacturing cost.

The use of waste as a supplementary material in concrete has received increasing research attention over the past 20 years. Concrete containing such waste is frequently used in radiation shielding structures. This study evaluates 4,589 RSM-related publications using bibliometric and content analysis methods. The growing interest in this research area is reflected in the annual distribution of published articles on radiation shielding. In this context, Bawab *et al*. (2021) noted that waste CRT glass could serve as a valuable component in the production of environmentally friendly cement-based composites, particularly for radiation protection applications, and also suggested directions for further study. Additionally, radiation can alter the structure of the material as well as its chemical, mechanical, and physical characteristics, as DoganS *et al*. (2022) highlighted.

.. Therefore, further investigation is needed to understand these relationships and their implications. Predicting the properties and manufacturing processes of geopolymeric building materials (GPBM) requires mathematical models, particularly when designing composite materials for specialized applications.

Such ongoing research indicates a promising direction for the future development of the field. In terms of RSM research publications, China is the most productive country, with universities in China leading the way. International collaboration can enhance the capacity for scientific research. Commonly used terms in RSM publications include *gamma-ray*, *radiation shielding*, and *radiation protection*. Researchers studying building and construction materials have shown a marked increase in interest in most topics, including the durability and microstructural characteristics of ultra-high-performance

concrete. BEES 3.0 (Building for Environmental and Economic Sustainability) is one of the significant programs that has been developed by the Building and Fire Research Laboratory of the National Institute for Standards and Technology (NIST). This Windows™-based decision support program, designed for designers, builders, and product developers, helps balance the financial and environmental performance of building materials (SAIC, 2006). Boustead Model 5.0, CMLCA 4.2, Dubo-Calc, Ecoinvent Database v1.2, Eco-Quantum, GaBi 4 Software System and Database, and other tools are capable of handling large volumes of data. Data collection activities, including research, fieldwork, and direct interaction with specialists, generate substantial amounts of information. This approach makes a significant contribution to the overall success of advanced scientific research. In order to identify the gaps, we recommend:

- Conducting more experimental studies to test the performance of new materials in real-world conditions.
- Integrating modeling, simulation and machine leaning approaches to predict the effectiveness of materials before their manufacture.
- Strengthening international cooperation to develop certification standards for recycled materials in radiation protection.

In perspective future research must take in consideration multilingual meta-analyses to degenerate innovations in non-English journals and Patents mining. Furthermore, industrial surveys are critical to identify commercialization barriers and handicaps, such as regulatory hurdles for the use of recycled materials in nuclear facilities.

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