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Research Article

Research Trends on Coal Tar in Infrastructure Decommissioning: A Systematic Review Revealing Scientific Performance and Knowledge Gaps

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ABSTRACT

Coal tar and its derivatives have long been recognized for their industrial applications and environmental significance due to the presence of Polycyclic Aromatic Hydrocarbons (PAHs). This study presents a comprehensive analysis of scientific research on coal tar, encompassing its environmental and toxicological impacts, structural applications, and the use of Computational Fluid Dynamics (CFD) for computational modeling. A dataset of 6,805 documents from the Scopus database was analyzed. Thematic mapping revealed that the retrieved coal tar research predominantly focuses on environmental contamination and PAH characterization, whereas industrial process studies and CFD applications appear less frequently represented within these specific parameters. Strategic diagram analysis classified research clusters into motor themes, specialized but isolated topics, basic transversal subjects, and emerging or declining areas. Notably, CFD modeling of coal tar behavior represents a prospective area for further exploration within the mapped literature. This analysis highlights well-established knowledge and potential opportunities for expansion, identifying priority areas for future research, including environmental risk assessment, material applications, and numerical modeling of coal tar and PAHs.

Keywords: Coal Tar, Demolition Waste, Ecotoxicology, Marine Infrastructure, Pollutants, POP.

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INTRODUCTION

Tar-derived materials, particularly those originating from coal tar, have historically played a critical role in industrial corrosion protection (Serednitskii *et al.*, 1987; Velazquez *et al.*, 2009). From the 1930s through the 1980s, Coal Tar Enamels (CTEs) were extensively applied to pipelines and maritime structures due to their strong adhesion, low permeability, and chemical resistance (Merten, 2017; Yin *et al.*, 2018). These coatings were regarded as highly valuable technical solutions, especially for projects exposed to harsh saline environments and prolonged immersion.

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However, from the mid-20th century onwards, scientific investigations began to reveal the environmental and toxicological risks associated with these materials. Coal tar-based products contain high concentrations of Polycyclic Aromatic Hydrocarbons (PAHs), a class of organic pollutants that are persistent, bioaccumulative, and toxic (Ghosh *et al.*, 1974; Kay, 1976; Li *et al.*, 2011; Feng *et al.*, 2015). Initial studies primarily focused on exposure and localized contamination, but over time, attention expanded to encompass broader ecological and human health risks, particularly in aquatic environments (Marvin *et al.*, 1995; Kocan *et al.*, 1996; Bryer *et al.*, 2006; McIntyre *et al.*, 2016). Due to their toxicity, the use of coal tar as a sealant in subsea pipelines has become increasingly restricted (Husain *et al.*, 2004), and several regions, including the United States, Europe, and Japan, have banned its use.

While much of the literature has concentrated on PAH toxicity, contaminated sediments, and exposure pathways, relatively little

is known about the legacy impacts of these materials in marine environments (Coulon *et al.*, 2009; Stout and Brey, 2019; Temel *et al.*, 2024). Many older subsea pipelines and maritime structures coated with CTEs remain in operation or were decommissioned in past decades without comprehensive environmental risk assessments (Francis, 2015; Capobianco *et al.*, 2022).

With growing awareness of their ecological and toxicological risks, particularly in aquatic systems, international regulatory frameworks were established to restrict the use of these materials (Van *et al.*, 2005; GC, 2023) and promote the development of safer alternatives (Dennis *et al.*, 2015; 2016). Initiatives such as the European Union's REACH legislation and the Stockholm Convention on Persistent Organic Pollutants (POPs) have significantly reshaped both the scientific and industrial landscapes, prioritizing the management and remediation of hazardous substances. These advances spurred increased environmental research and ecotoxicological assessments of tar-derived materials, though certain topics, particularly those related to marine structures, have remained relatively underexplored.

Similarly, modern analytical and modeling tools, such as Computational Fluid Dynamics (CFD) and coupled biogeochemical models to simulate the behavior and fate of these complex mixtures, have not been widely applied to evaluate the dispersion, leaching, or degradation dynamics of coal tar coatings in marine settings. Such techniques could substantially enhance our understanding of residual contamination and its environmental implications.

In this context, bibliometric analysis emerges as a valuable approach for systematically mapping the evolution of research on tar-derived materials, identifying thematic concentrations, and highlighting underexplored niches. By analyzing publication trends, collaboration networks, and thematic clusters, this study aims to provide a comprehensive overview of scientific output in the field, revealing patterns, critical knowledge gaps, and emerging opportunities for future research.

Accordingly, this study conducts a bibliometric analysis to systematically map the scientific literature on coal tar-derived materials, with an emphasis on offshore and marine applications. Through keyword co-occurrence analysis, thematic clustering, and citation mapping, it identifies prevailing research trends and underexplored areas within the discipline. Special attention is given to gaps in the environmental risk assessment of legacy infrastructure and to opportunities for interdisciplinary research that integrates environmental science, ocean engineering, and computational modeling.

By highlighting the historical development, current research frontiers, and regional disparities within the literature, this review offers a roadmap for future investigations, especially in developing economies with aging and abandoned offshore infrastructure, such as Brazil. It also seeks to support regulatory agencies, environmental managers, and industry stakeholders in formulating science-based guidelines for the decommissioning and ecological monitoring of tar-derived materials.

METHODOLOGY

Database

A methodological approach using bibliometric analyses was employed. We integrated several tools to provide a more comprehensive understanding of our main subject. Figure 1 shows the main steps, from database selection to graphical analysis. The Scopus database was used to collect bibliometric information. The choice was made because Scopus has a database with over 53 million references published in more than 24,000 scientific journals (Vasconcelos *et al.*, 2020; 2023). The Scopus web access system offers a variety of tools that enable efficient literature searches in specific fields, whether basic or advanced research. These resources facilitate the rapid and consistent acquisition of information, offering a detailed and comprehensive overview.

The choice of keywords

A search strategy was formulated using targeted keywords and Boolean operators aiming to maximize the retrieval of relevant literature while minimizing thematic deviations. Initially, articles on coal tar were retrieved without additional filters. In later stages, separate sets of keywords were used to search for articles on structures, HPA, toxicology, and computational simulation. The specific search commands are detailed in Table 1. The selection of these four specific subsets was intentionally established to construct a comprehensive evaluation framework. Together, these domains represent the critical multi-disciplinary pillars required to assess the environmental liabilities, material degradation, and ecological risks associated with the decommissioning of legacy offshore and marine infrastructure.

The final keyword selection was refined through multiple iterations, adjusting based on the returned results. This optimized combination, along with logical connectors, aimed to minimize thematic deviations and streamline the inclusion of literature relevant to our research framework.

Following the initial data retrieval, a data cleaning process was conducted to ensure dataset integrity. Due to the precision of the Scopus indexing system, duplicate entries were found to be minimal and were readily removed. Furthermore, a manual screening of titles and abstracts was performed to eliminate false positives and exclude irrelevant documents that did not align with the core environmental, toxicological, or engineering themes of this study. The search strategy applied in the Scopus database was refined through a set of restrictions designed to ensure the thematic relevance, document quality, and consistency of the retrieved data. These restrictions included limitations by document type, source type, subject area, language, and publication stage, as summarized in Table 2.

It is worth noting that the specific keyword boundaries established in this methodology might affect the perceived size of certain research niches, potentially under- or overrepresenting technical subareas where alternative terminology or adjacent descriptors are preferred.

Statistical of results

The Bibliometrix package, developed for the R statistical environment, was employed to perform the bibliometric analysis. This software suite offers resources for quantifying and visualizing scientific production patterns, including citation metrics, co-authorship mapping, and identifying thematic trends within the literature (Aria and Cuccurullo, 2017; Derviş, 2019). All analyses and graphical representations were generated using R version 4.0.4, integrated with RStudio version 1.4.1106, the ggplot2 package version 3.3.5, and Bibliometrix version 3.1.4.

Co-occurrence Term Mapping

VOSviewer version 1.6.17 was applied to conduct both quantitative and qualitative analyses of the selected publications to construct co-occurrence networks of terms. This software allows for the visualization and analysis of bibliometric networks, including co-authorship, co-citation, and keyword co-occurrence. Through its interactive features, VOSviewer facilitates the detection of research clusters and emerging topics in the field (Van and Waltman, 2014; Perianes-Rodriguez *et al.*, 2016). This study generated co-occurrence maps based on the combined data from article titles, abstracts, and keywords. A threshold value was established for the minimum frequency of term occurrence to refine the resulting networks. Further details regarding the co-occurrence maps and their interpretation are presented in the Results and Discussion section.

RESULTS AND DISCUSSION

Tar-derived materials have attracted sustained scientific community's interest over the past decades (Figure 2). The earliest known work on tar-derived material dates back to 1846 (Anderson, 1846), a paper aimed at deepening the understanding of the constitution and properties of picoline, an organic base derived from coal tar, and its implications for organic chemistry. A total of 12 publications were identified in the 19th century, suggesting that the applications of tar-derived materials were considered promising at that time.

As illustrated in Figure 2, indexed publications on this topic exhibit a substantial upward trend in recent decades, with a noticeable intensification since the beginning of the 21st century. Additionally, introductory queries in the Scopus database for recent publication years indicate that this momentum is sustained, reflecting ongoing scientific output. This expanding literature is widely discussed as being responsive to emerging environmental, public health, and industrial concerns, where various regulatory initiatives appear to have further propelled these investigations.

One of the first steps towards implementing regulatory policies was when the European Commission presented the first draft of a major revision of European chemicals management legislation (EC, 2003). This proposal, known by the acronym "REACH" (Registration, Evaluation, and Authorization of Chemicals), represented a significant shift in the way risks associated with chemicals were to be managed within the European Union. It required the registration and authorization for the use of substances of very high concern, such as tar-derived materials.

Around the same period, the Stockholm Convention on Persistent Organic Pollutants (POPs), adopted in 2001 and enforced in 2004, emerged as an important step in the global fight against pollution and its harmful effects on health and the environment (Lallas, 2001). The convention had a significant impact on scientific research, public health, and environmental awareness, to the point that it continues to shape how Persistent Organic Pollutants are addressed worldwide (Xu *et al.*, 2013), including in developing countries (Akinrinade *et al.*, 2024).

In the United States, the Environmental Protection Agency (EPA) leads studies on environmental and human health risks (EPA, 2020). Several states have banned coal tar sealants on public roadways following findings of contamination by Polycyclic Aromatic Hydrocarbons (PAHs) (Mahler *et al.*, 2012; Needleman, 2015).

However, despite several regulatory milestones, the retrieved data suggest that topics addressing marine oil and gas extraction structures appear less frequently represented compared to total number of publications on tar-derived materials within this specific dataset. Studies focusing on PAHs within this specific context show some, albeit limited, prominence in the mapped literature. It is noteworthy, given the environmental significance of analyzing such extracts due to their contamination potential. Nevertheless, the toxicity of tar-derived materials appears to be a more specialized niche in terms of indexed publication numbers. Within this parameter, the most cited documents are published in open access journals and date from before 2010 (Mueller *et al.*, 1991; Collins *et al.*, 1998; Neff *et al.*, 2005). Furthermore, when applying an additional exploratory search filter to include the explicit term 'ocean' in the abstract, title, or keywords, only four articles were retrieved (Simpson *et al.*, 2020; Wu *et al.*, 2022; Yang *et al.*, 2018; Oziolor *et al.*, 2014), highlighting how specific terminology choices can significantly restrict document retrieval in these subfields.

Regarding pipelines, the 120 documents retrieved indicate that research specifically linking coal tar to offshore or marine structures appears to be relatively limited compared to broader industrial applications. Interestingly, coal tar enamel was the primary pipeline coating material between the 1930s and 1980s

Table 1: Set of keywords used to search for articles in the Scopus database.

Restriction	Search only in: Title, Abstract or Keywords
Without distinction of area (6,805 documents found)	(TITLE-ABS-KEY ("coal tar") OR TITLE-ABS-KEY (coal-tar) OR TITLE-ABS-KEY ("petroleum tar") OR TITLE-ABS-KEY (petroleum-tar) OR TITLE-ABS-KEY ("tar pitch")) AND PUBYEAR > 1845 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "d")) AND (LIMIT-TO(SUBJAREA, "CHEM") OR LIMIT-TO (SUBJAREA, "CENG") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "PHYS") OR LIMIT-TO (SUBJAREA, "EART") OR LIMIT-TO (SUBJAREA, "BIOC") OR LIMIT-TO (SUBJAREA, "PHAR") OR LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "MATH") OR LIMIT-TO (SUBJAREA, "IMMU")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (PUBSTAGE, "final")).
Focused on structure (120 documents found)	(TITLE-ABS-KEY ("coal tar") OR TITLE-ABS-KEY (coal-tar) OR TITLE-ABS-KEY ("petroleum tar") OR TITLE-ABS-KEY (petroleum-tar) OR TITLE-ABS-KEY ("tar pitch") AND TITLE-ABS-KEY (pipeline*)) AND PUBYEAR>1972 AND PUBYEAR<2025 AND (LIMIT-TO (DOCTYPE, "ar")) ".
Focused on HPA (736 documents found)	(TITLE-ABS-KEY ("coal tar") OR TITLE-ABS-KEY (coal-tar) OR TITLE-ABS-KEY ("petroleum tar") OR TITLE-ABS-KEY (petroleum-tar) OR TITLE-ABS-KEY ("tar pitch") AND TITLE-ABS-KEY (pah) OR TITLE-ABS-KEY (polycyclic AND aromatic AND hydrocarbon*) AND NOT TITLE-ABS-KEY (toxicit*)) AND PUBYEAR>1845 AND PUBYEAR<2025 AND (LIMIT-TO (DOCTYPE, "ar").
Focused on toxicology (215 documents found)	(TITLE-ABS-KEY ("coal tar") OR TITLE-ABS-KEY (coal-tar) OR TITLE-ABS-KEY ("petroleum tar") OR TITLE-ABS-KEY (petroleum-tar) OR TITLE-ABS-KEY ("tar pitch") AND TITLE-ABS-KEY (toxicit*)) AND PUBYEAR>1845 AND PUBYEAR<2025 AND (LIMIT-TO (DOCTYPE, "ar").
Focused on computational simulation (13 documents found)	(TITLE-ABS-KEY ("coal tar") OR TITLE-ABS-KEY (coal-tar) OR TITLE-ABS-KEY ("petroleum tar") OR TITLE-ABS-KEY (petroleum-tar) OR TITLE-ABS-KEY ("tar pitch") AND TITLE-ABS-KEY ("computational fluid dynamics")) AND PUBYEAR>1845 AND PUBYEAR<2025 AND (LIMIT-TO (DOCTYPE, "ar").

due to its excellent chemical resistance. Its current disuse is attributed to its environmental persistence and the leaching of PAHs, which limited its modern applications, leading to its gradual replacement by alternative coatings (Jagtap *et al.*, 2014; Dennis *et al.*, 2015; Dennis *et al.*, 2016). However, a notable increase in publications was observed when comparing previous years to 2024, with an average of two articles per year rising to 26, within this specific pipeline subset.

Finally, when applying a filter to identify studies involving Computational Fluid Dynamics applications in coal tar research, only 13 publications matched the search string. Most of these works are focused on modeling processes or optimization mechanisms (Seo *et al.*, 2024; Rezapour and Deymi-Dashtebayaz, 2024; Singh *et al.*, 2024; Yun *et al.*, 2024) or on simulating the influence of degrading factors (Gera *et al.*, 2001; Zeng *et al.*, 2011; Chen *et al.*, 2021; Isa *et al.*, 2019).

This context suggests that the scientific community's interest, as reflected in the retrieved research, appears to be more oriented toward new types of coatings, optimization of installation processes and applications, and the assessment of extracts for contaminant analysis. The gathered data indicate that comparatively fewer indexed studies explicitly address the environmental impacts of legacy coal tar enamel coatings applied to pipelines, particularly those installed in the early to mid-20th century.

The publications produced over time showed that China leads in the number of publications in the field of tar-derived materials, followed by the United States. Figure 3 illustrates the contribution of each country to research on tar-derived materials, along with the number of studies involving international collaborations (Single Country Publication-SCP; Multiple Country Publication-MCP). This distribution reflects common bibliometric trends, since single-country publications often benefit from uniformity and proximity. In contrast, multiple-country publications encounter additional layers of complexity related to coordination, regulation, and communication, making them more challenging to execute and publish (Sweileh *et al.*, 2016). Nevertheless, the literature suggests that although MCPs are more demanding, international collaborations can enhance citation impact and increase the potential for globally relevant innovation.

Interestingly, among the ten institutions with the most publications, five are based in China: the Ministry of Education of the People's Republic of China, the Chinese Academy of Sciences, Northwest University, Taiyuan University of Technology, and the China University of Mining and Technology. Two others are Spanish institutions: CSIC - Instituto de Ciencia y Tecnología del Carbono INCAR, and the Consejo Superior de Investigaciones Científicas. Additionally, one French, one British, and one Russian institution appear in this ranking: CNRS (Centre National de la Recherche Scientifique), Imperial College London, and the Russian Academy of Sciences, respectively.

In this context, North American institutions are notably absent from the top ranks, with the University of Notre Dame appearing only in the 21st position. This indicates a shift in publication volume, suggesting that U.S. institutions focus on more specialized subfields rather than leading in gross document count within this specific dataset. Their efforts are directed primarily toward areas emphasizing sustainability and/or energy production (LaVerne and Kleemola, 2017; Choi *et al.*, 2011), or in varied applications with a focus on environmental and energy-related issues (Wang *et al.*, 2020; Tarábek *et al.*, 2009; LaVerne *et al.*, 2020; Lisovskaya *et al.*, 2019).

While the retrieved scientific literature highlights specific consumer product regulations in China (Wang, 2006), industrial regulatory frameworks are less frequently discussed within the analyzed academic dataset. Meanwhile, U.S. institutions are increasingly concentrated in research areas such as nanomaterials and renewable energies.

This condition explains the countries' collaboration map presented in Figure 4. The figure shows the existence of three distinct collaboration clusters. The first cluster is led by the United States, which maintains strong collaborative ties with European Union countries and Canada - the latter also stands out for its firm commitment to renewable energy use and regulatory

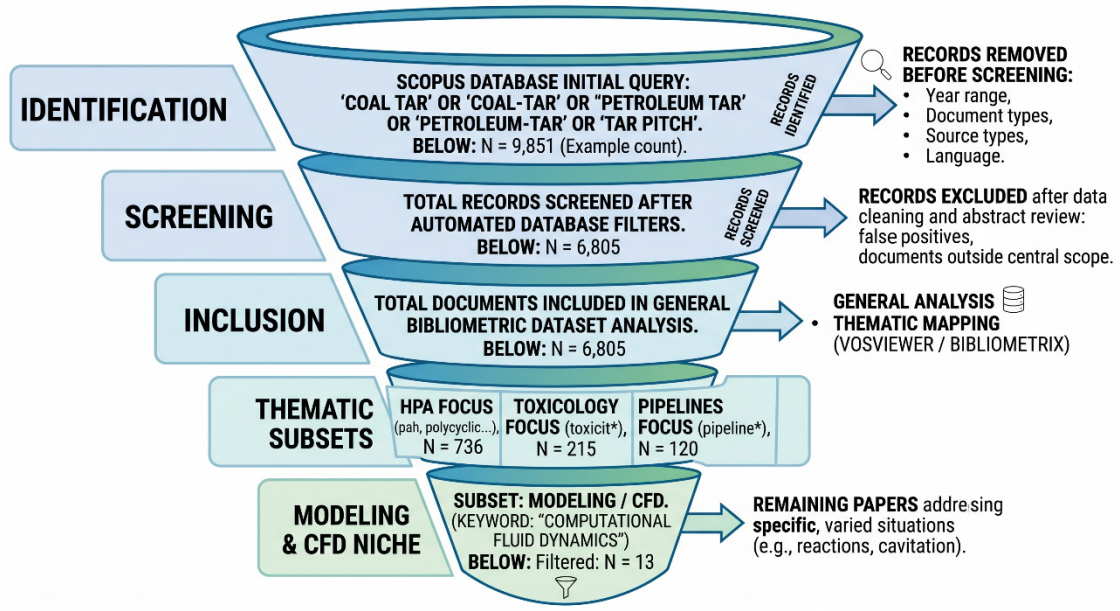


Figure 1: Diagram of the methodological sequence employed in this study.

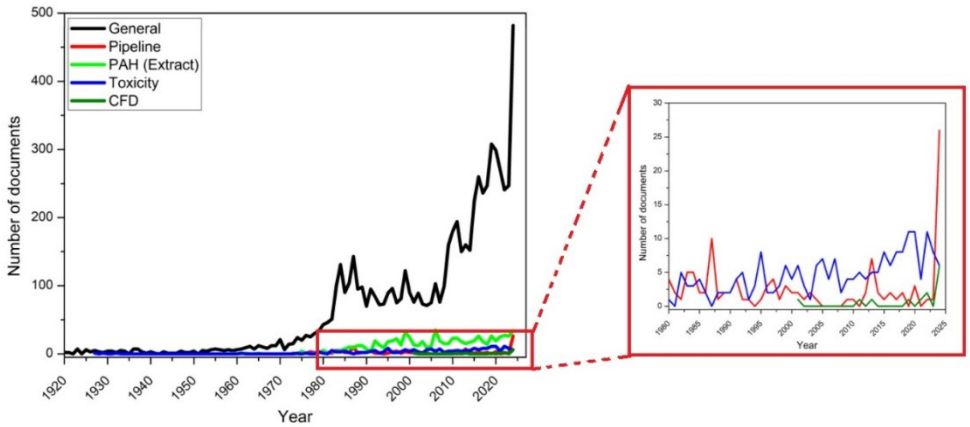


Figure 2: Comparison of Publications on Tar-derived Materials Related to Marine Oil and Gas Extraction Lines.

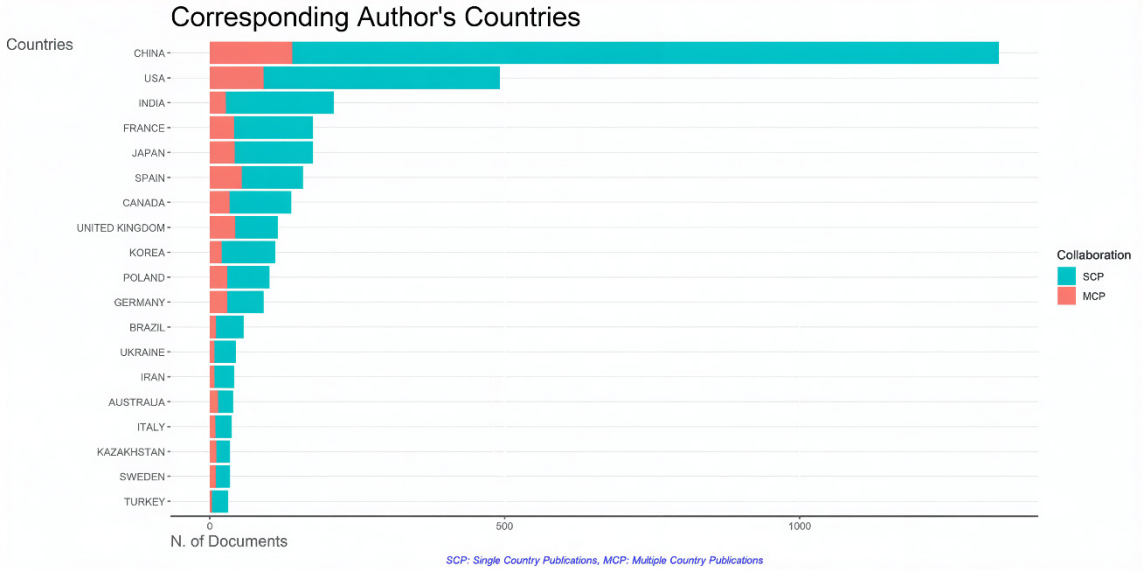


Figure 3: Number of corresponding authors' countries and their collaborations.

initiatives (Anderson and Gough, 2022; CEP, 2025). A second cluster is headed by China, in association with countries typically from Eastern Europe and India. Spain leads a third, more discrete cluster, demonstrating intense collaboration with Central and South American countries. It is mainly due to the activity of the CSIC - Instituto de Ciencia y Tecnología del Carbono INCAR, which stands out as Spain's leading public research agency and one of the most active globally in establishing international partnerships.

In this context, Brazil, which is representative of developing countries, has preferentially published articles in journals focused on environmental chemicals. The most frequently chosen journals include Chemosphere (10), Fuel Science and Technology International (5), Journal of Applied Polymer Science (4), and Energy and Fuels (4). Interestingly, and further reaffirming the importance of the Spanish cluster within the collaboration network, in the context of publications involving Brazil, the Universitat de Barcelona appears as the most relevant institution, with 18 articles.

Figure 5 shows how topics involving coal tar have developed based on the more generic search string presented in the methodology. It was observed that, to obtain a visually acceptable graph, it was necessary to restrict the graph's generation to 350 words with 5 citations per year; otherwise, the high density and overlapping of terms would compromise the visual clarity and interpretation of the thematic trends. In this context, the term 'polycyclic aromatic hydrocarbon' exhibits a prominent position among the trend topics throughout the analyzed period. This frequency aligns with expected literature patterns, since coal tar is a complex mixture rich in Polycyclic Aromatic Hydrocarbons (PAHs), which are closely associated with its toxicological and environmental relevance (Abdel-Shafy and Mansour, 2016; Barbosa Jr *et al.*, 2023; Vijayanand *et al.*, 2023). In recent years, the retrieved data suggest that studies on coal tar have expanded beyond conventional assessments of PAHs, incorporating additional concepts such as molecular weight (Balastegui *et al.*, 2024; Kim *et al.*, 2020; Chibwe *et al.*, 2017), carbon structure characterization/application (He *et al.*, 2012; Rocha *et al.*, 2010), and radiation-induced chemical processes (Kumar *et al.*, 2015; Wang *et al.*, 2021). These trends potentially highlight an increasing interest in molecular-level understanding and innovative treatment approaches for coal tar-contaminated environments within the mapped dataset.

The keyword co-occurrence analysis facilitated the mapping of prominent thematic fields related to research on coal tar, PAHs, their environmental and toxicological impacts, their application in tubular structures, and analyses using CFD through the formation of distinct clusters (Figure 6). The 'full counting' technique was applied because it allows measuring the raw frequency of each term. The number of co-occurrences was carefully calibrated to optimize network readability and ensure a clear visual analysis of these relationships. The information after these threshold definitions is presented in Table 3.

In the more general search, considering the restrictions listed in Table 3 (Figure 6a), terms were grouped into three major thematic clusters: (i) carbonization processes and coal treatment (carbonization, coal tar, coal tar pitch, carbon), (ii) aromatic hydrocarbons and environmental contamination (aromatic hydrocarbons, polycyclic aromatic hydrocarbons, PAH, naphthalene), and (iii) applied chemistry and environmental monitoring (chemistry, degradation, oxidation, environmental monitoring). This grouping illustrates the close alignment between the characterization of chemical contaminants, the industrial processes involved, and environmental control strategies. Regarding bibliometric relevance, the results suggest a central focus on studies addressing environmental contamination and industrial processes within the retrieved scope. The connection

network further points to the role of coal tar in discussions on environmental degradation and mitigation methods. This overview highlights, from a bibliometric perspective, a notable representation of coal tar within this database when no additional filters are applied.

When restrictions are applied to scientific trends, the results are as follows: In the PAHs-focused search (Figure 6b), four clusters stand out: (i) PAH chemical characterization (polycyclic aromatic hydrocarbons, naphthalene, phenanthrene, pyrene), (ii) toxicological studies and risk assessments (controlled study, risk assessment, human), (iii) soil and sediment contamination (soil pollution, sediment, biodegradation), and (iv) analytical techniques and environmental monitoring (environmental monitoring, mass spectrometry, gas chromatography). The term 'polycyclic aromatic hydrocarbons' was the subset's most frequent and cited keyword, underscoring its relevance in contamination and environmental risk studies captured by the query. Gas chromatography exhibits high network centrality, indicating it as a widely used technique in PAH analysis. It is strongly connected to: mass spectrometry, reflecting the typical application of GC-MS; compounds such as naphthalene, phenanthrene, pyrene, and anthracene, all frequently analyzed by this technique; and molecular weight, highlighting the focus on the detailed characterization of these substances. Even within this specific subset, the key compounds and application areas remain visible, with strong connections to environmental and toxicological clusters. This suggests how laboratory methods support these studies and integrate with risk analyses and environmental assessments within the mapped literature.

The analysis of connections suggests that a significant portion of the retrieved literature concentrates efforts on evaluating the impacts of PAHs on aquatic and terrestrial environments, as well as on degradation processes and the monitoring of persistent pollutants. The ten most cited papers in this context show a focus on human health consequences (Jongeneelen *et al.*, 1987; Boffetta *et al.*, 1997), PAH studies, environmental impacts, and bioremediation processes (Mueller *et al.*, 1989; Ghosh *et al.*, 2003; Vidya *et al.*, 2004; Smith *et al.*, 2006; Sofowote *et al.*, 2008),

Table 2: Description of the restrictions applied in the Scopus database search strategy to ensure the relevance, quality, and thematic consistency of the retrieved documents.

Restriction	Description
LIMIT-TO (DOCTYPE, "ar")	Selects only full research articles, excluding other document types such as reviews, conference papers, editorials, or letters. Ensures the inclusion of original and complete studies.
LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "d")	Restricts the sources to scientific journals (j) and serial publications (d), excluding books, book chapters, or conference proceedings. Ensures that documents originate from peer-reviewed, periodical publications.
LIMIT-TO (SUBJAREA,...)	Limits documents to specific subject areas in Scopus, selected according to their relevance to the study: • CHEM - Chemistry • CENG - Chemical Engineering • ENER - Energy • ENGI - Engineering • ENVI - Environmental Science • PHYS - Physics and Astronomy • EART - Earth and Planetary Sciences • BIOC - Biochemistry, Genetics and Molecular Biology • PHAR - Pharmacology, Toxicology and Pharmaceutics • AGRI - Agricultural and Biological Sciences • COMP - Computer Science • MATH - Mathematics • IMMU - Immunology and Microbiology
LIMIT-TO (LANGUAGE, "English")	Includes only articles published in English, the dominant language in international scientific communication, ensuring accessibility and standardization for analysis.
LIMIT-TO (PUBSTAGE, "final")	Considers only documents in the final publication stage, excluding in-press, preprints, or early-access documents. Ensures that only peer-reviewed, indexed, and officially published articles are analyzed.

Table 3: Details of the restrictions applied for generating co-occurrence maps.

	keyword co-occurrence			Total link strength	Number of documents Analyzed
	Items	Clusters	Links		
General	39	3	716	39024	6802
Structure	39	5	287	637	120
HPA (extract)	40	4	756	17083	735
Toxicology	40	4	687	6971	215
Modeling	22	2	131	187	13

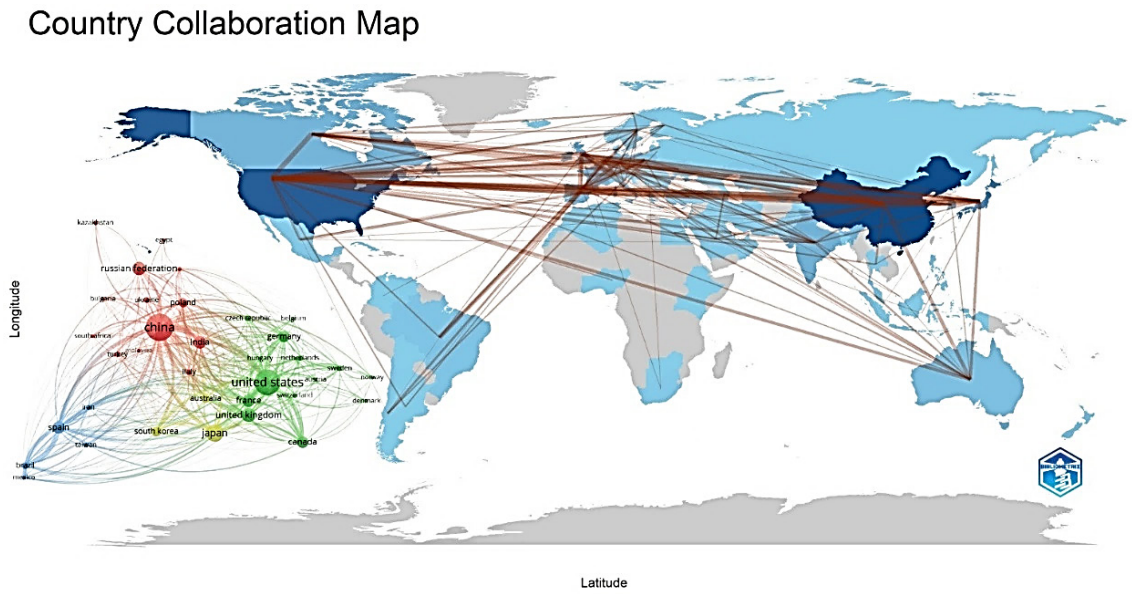


Figure 4: Mapping International Collaborations and Cluster Formation.

analytical techniques (Wise *et al.*, 1988), and catalytic reforming (Guo *et al.*, 2018).

From the toxicological perspective (Figure 6c), the terms were organized into four main groups: (i) animal testing and toxicity studies (animal experiment, controlled study, toxicity testing), (ii) environmental pollutants and PAHs (aromatic hydrocarbons, PAH, polycyclic aromatic hydrocarbons), (iii) soil and water contamination (contamination, soil pollution, water pollutant), and (iv) chemical processes and environmental degradation (chemistry, radiolysis, toxicity). The network of connections indicates the visibility of coal tar and PAHs in toxicological studies, highlighting their importance as priority contaminants in marine (Neff *et al.*, 2005; Huang *et al.*, 2014; Yang *et al.*, 2018; Shi *et al.*, 2023) and terrestrial environments (Long *et al.*, 2017; Aabbar *et al.*, 2024), as well as the potential human health risks associated with such exposures (Mueller *et al.*, 1991; Linak *et al.*, 2007; Li *et al.*, 2011).

In the subset focused on coal tar in structural applications (Figure 6d), four thematic clusters stood out: (i) chemical and gas industries (chemical industry, gas industry, petroleum transportation), (ii) anticorrosive protection (cathodic protection, coal tar, coating, corrosion protection), (iii) pipeline infrastructure (natural gas pipelines, water pipelines), and (iv) corrosion and energy (coal, corrosion, pipeline corrosion). This grouping highlights the historical importance of coal tar as an anticorrosive coating, particularly in hydrocarbon transport systems, aligning with historical accounts regarding its durability in aggressive and industrial environments. In this context, enamel appears as a relevant keyword in co-occurrence analyses. Coal tar enamel is a protective coating known for its corrosion resistance and durability. It is typically applied to metallic surfaces and is particularly effective in harsh environments (Yin *et al.*, 2018; Coates, 1991; Linchtenstein, 2003). Although coal tar enamel is still in use, the analyzed trends reflect that it has been gradually replaced by safer, more sustainable alternatives in recent decades (Jagtap *et al.*, 2014; Dennis *et al.*, 2015; Dennis *et al.*, 2016).

Lastly, in the CFD-focused search (Figure 6e), the terms were grouped into two clusters: (i) numerical modeling and computational fluid dynamics (computational fluid dynamics, coal tar) and (ii) industrial processes involving petroleum derivatives (petroleum tar). The connection analysis reinforces the seemingly incipient application of computational modeling in coal tar analysis, with this refined search returning a limited set of 13 documents. This restricted number of studies makes it challenging to identify definitive observational patterns or

established research niches. Each of the 13 papers addresses specific, highly distinct situations, ranging from secondary reactions (Zeng *et al.*, 2011) to cavitation in centrifugal pumps (Yun *et al.*, 2024). This characteristic suggests a potential thematic fragmentation within this specific dataset, which may point to an underexplored niche.

The limited number of studies potentially reflects the inherent challenges associated with modeling the highly complex composition of this mixture (Russo *et al.*, 2019; Koolen *et al.*, 2015; Niemeier, 2001), which complicates the definition of physicochemical properties for modeling. Additionally, a shortage of experimental data for validation and a predominant focus on chemical and toxicological analyses have limited the application of CFD in this context.

Overall, the visualization networks demonstrate a strong interconnection between industrial processes, soil and water contamination, toxicological impacts, and environmental monitoring strategies, with coal tar and PAHs standing out as central objects of investigation.

The results from keyword co-occurrence corroborate those presented in Figure 7, representing a thematic strategic map in the development degree (density) vs. relevance degree (centrality) plane. Thematic analysis based on the relationship between development and relevance levels identifies the strategic positioning of predominant subjects in the literature. The cluster formed by coal tar, results, study, and chemical occupies the motor theme position, characterized by high density and centrality, suggesting that these highly frequent terms are deeply integrated with other research topics, representing a central thematic concentration within this dataset.

Conversely, topics such as pitch, carbon, temperature, obtained, and method are highly developed but display low centrality, representing specialized and isolated themes. This position suggests that, despite being well developed, these topics have limited interaction with other thematic clusters, potentially indicating segmented research lines or highly specific techniques not closely linked to environmental or toxicological issues.

Meanwhile, the cluster comprising products, water, society, reaction, and rate appears in the basic themes zone, denoting moderate centrality and low density. These terms appear to function as transversal concepts, frequently present in various studies, reflecting lower internal thematic density within this specific dataset. This positioning suggests their role as support elements for different research lines, showing a more dispersed structure in the current retrieved literature.

Finally, special attention is warranted for the group formed by aromatic, compounds, hydrocarbons, polycyclic, and concentrations, located in the emerging or declining themes zone, indicated by low density and centrality. This position could signal either the recent emergence of new approaches involving these compounds - such as studies of their behavior in aquatic environments or their computational modelling via CFD - or a progressive decline in interest within more recent literature. Considering the historical environmental and toxicological significance of polycyclic aromatic hydrocarbons, it is plausible that this cluster represents an opportunity for the resumption and updating of research, particularly from the perspective of environmental dynamics in aquatic and petroleum systems, areas which appear to have significant potential for expansion regarding numerical modelling applications.

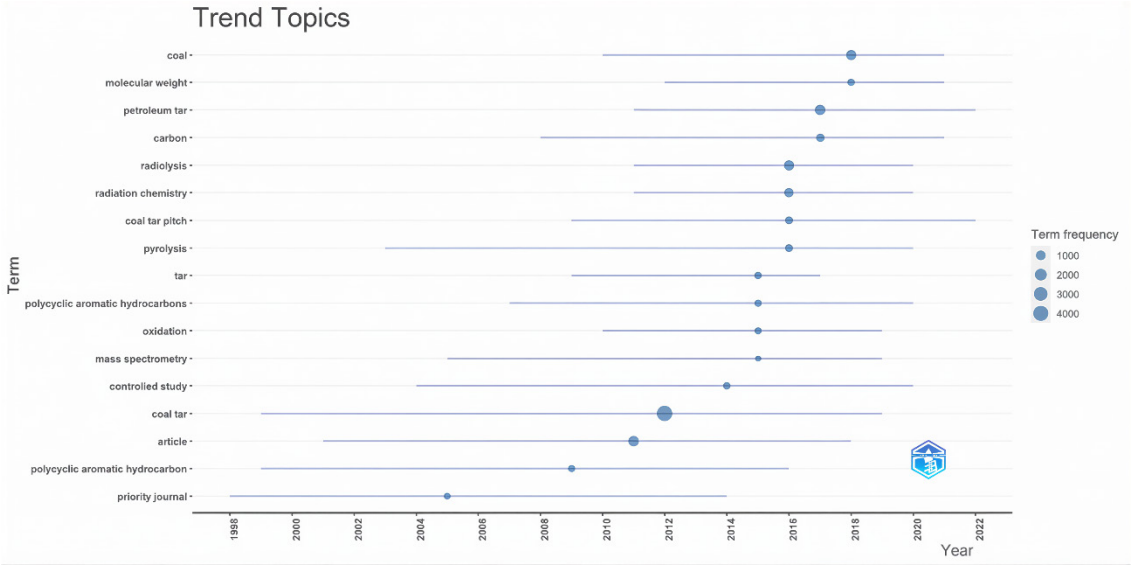


Figure 5: Bibliometric analysis of trending topics in tar-derived materials research.

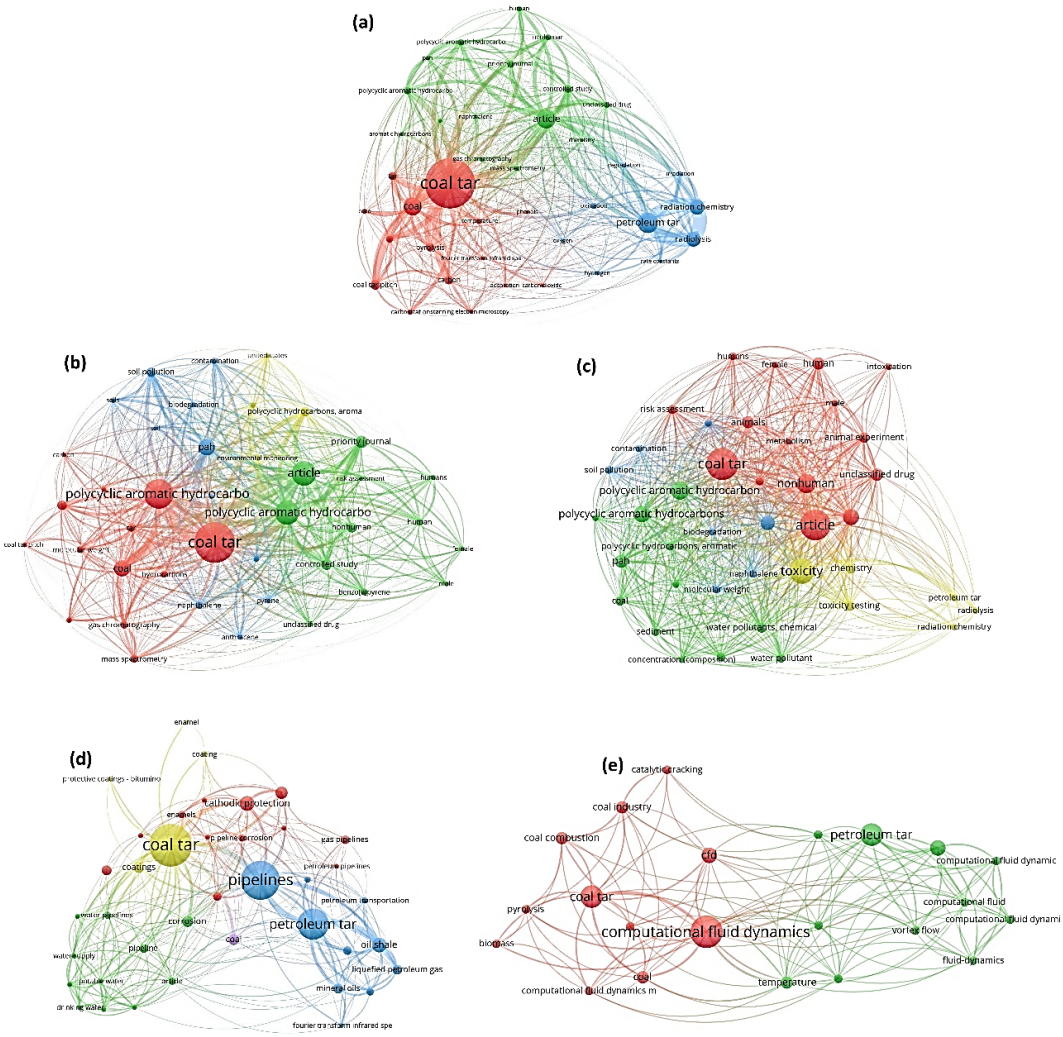


Figure 6: Keyword co-occurrence for coal tar: (a) without restrictions (General), restricted to (b) PAHs (subset), (c) Toxicology, (d) Pipelines, and (e) Computational Modelling.

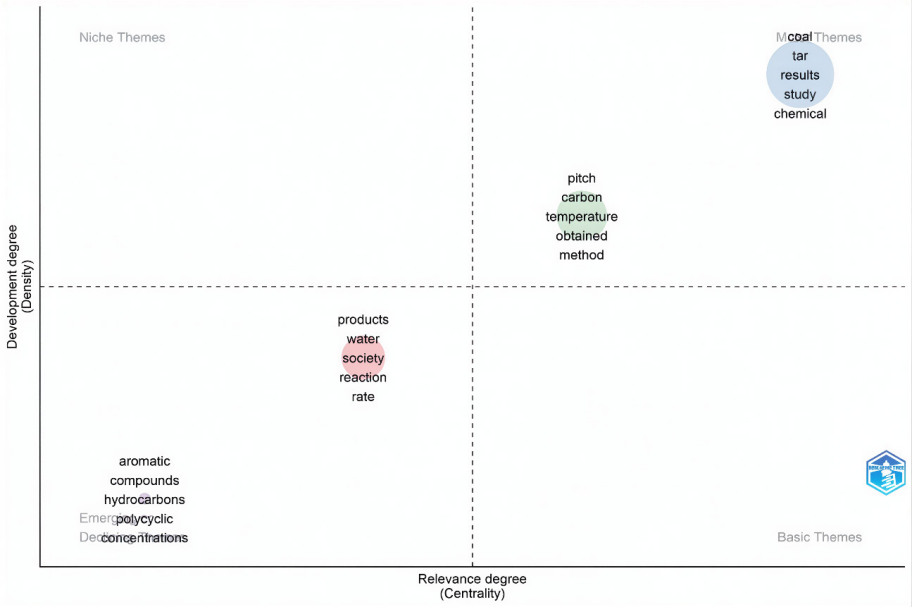


Figure 7: Thematic strategic diagram of coal tar-related research based on development and relevance degrees.

CONCLUSION

This review offers a comprehensive overview of global scientific research on coal tar and its derivatives over the past century, highlighting key trends, potential literature boundaries, and emerging opportunities within the analyzed dataset. The analysis suggests that most indexed studies have focused on environmental contamination and Polycyclic Aromatic Hydrocarbon (PAH) characterization, a trend seemingly driven by regulatory frameworks. However, critical areas such as industrial applications (especially pipeline coatings) and computational modelling using CFD appear to be less prominently represented within these specific search parameters. While China leads in publication volume, international collaborations, particularly those involving the U.S. and the EU, exhibit greater thematic diversity and innovation potential, suggesting that cross-border partnerships could accelerate advancements in this field. The findings point to a relatively narrow volume of literature in the numerical simulation of coal tar behavior, with only 13 identified studies applying the explicit term CFD. Moving forward, this study identifies three priority areas for future research: (i) Enhanced studies on legacy coal tar coatings in marine infrastructure, particularly their long-term ecological impacts; (ii) Development of sustainable alternatives to coal tar-based products aligned with circular economy principles; and (iii) Expansion of CFD and machine learning approaches to predict coal tar behavior under varying environmental and industrial conditions. By addressing these targeted research frontiers, the scientific community can better inform policy decisions, mitigate environmental and health risks, and optimize industrial processes involving tar-derived materials. This bibliometric analysis consolidates existing knowledge and charts a prospective roadmap for future research, bridging disciplinary divides and fostering sustainable innovation.

ABBREVIATIONS

CFD: Computational Fluid Dynamics; **CTE:** Coal Tar Enamel; **PAH:** Polycyclic Aromatic Hydrocarbon; **PAHs:** Polycyclic Aromatic Hydrocarbons; **POPs:** Persistent Organic Pollutants; **SCP:** Single Country Publication; **MCP:** Multiple Country Publication; **EPA:** Environmental Protection Agency; **REACH:** Registration, Evaluation, Authorization and Restriction of Chemicals; **EU:** European Union; **GC-MS:** Gas Chromatography-Mass Spectrometry; **R:** R Statistical Environment.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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