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Deep-Sea Mining–A Bibliometric Analysis of Research Focus, Publishing Structures, International and Inter-Institutional Cooperation

Rolf Arne Kleiv * and Maria Thornhill

Department of Geoscience and Petroleum, Faculty of Engineering, NTNU–Norwegian University of Science and Technology, S. P. Andersens veg 15a, 7031 Trondheim, Norway
* Correspondence: rolf.kleiv@ntnu.no

Abstract: Deep-sea mining is a multidimensional concept that requires interdisciplinary research and development to close the current knowledge gaps. This study conducts a bibliometric analysis of the research focus, publishing structures and international and inter-institutional cooperation as evident in academic publishing. This could aid in the identification of knowledge gaps, research opportunities, potential inter-institutional cooperation and the need for strategic investment and policy development. The analysis is based on a sample of 1935 journal papers (from 1968 to 2021) obtained by searching Elsevier's Scopus database for publications containing an explicit reference to deep-sea mining (or equivalent terms) in their title, abstract or keywords. Publication numbers are broken down by publication year, subject area, author affiliations and source. The scientific output mirrors the commercial interest and the growing environmental concern. A detailed analysis of content is performed on the 2017-2021 subset, containing one third of the total publications. Here, China (152 publ.), the United Kingdom (133), the United States (115) and Germany (107) are the top contributors. China has had a comparatively stronger focus on engineering aspects and produces very few publications with international co-authorship. Almost half of the 2017-2021 publications focus on environmental aspects, whereas engineering aspects (especially vertical transport) are addressed by close to one third. Little is published on site remediation and ore processing, or specifically on ferromanganese crusts.

Keywords: deep-sea mining; seabed mining; ocean mining; ferromanganese nodules; massive sea-floor sulphides; ferromanganese crust

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1. Introduction

1.1. General Introduction

Deep-sea mining, defined as the extraction of minerals from the seafloor at depths exceeding 200 m, is a source of conflicting narratives. In addition to being viewed as both a necessary and environmentally preferred solution to meet the demand for metals required for the shift to greener energy production (i.e., 'the green transition'), deep-sea mining is also seen as a serious threat to marine ecosystems and the common heritage of mankind.

According to the first narrative, seabed minerals are seen as an indispensable supplement to land-based mineral resources in order to secure the critical metals needed for a sustainable future [1–3]. The continuously decreasing grades and accessibility of land-based deposits, combined with technological advances in deep-sea mining, have been a strong economic incentive for developing alternative sources [1,4].

The concept of deep-sea mining has been discussed in a geopolitical context with respect to strategic control of critical raw materials (e.g., cobalt, lithium and rare-earth elements (REEs)) [1,3] and has also been viewed as a mechanism to achieve a fairer distribution of wealth between commodity-rich and industrialised countries [4]

At the core of the opposing narrative, we find the inherent uncertainty associated with the environmental impact of conducting deep-sea mining operations in the abyss. Critics argue that the exploitation of seabed resources could cause irreversible damage to unique ecosystems and that the precautionary principle must be given precedence [5–7].

All the above aspects are mirrored in scientific publishing, where, irrespective of narrative, there is a consensus regarding the need for more knowledge. This paper attempts to map and analyse the development in scope and publishing patterns in academic publishing with particular emphasis on the last five years.

A brief overview of main resource types, the proposed production concepts and the history of deep-sea mining is given in the following paragraphs before the scope of the paper is outlined in more detail. For a more comprehensive picture, refer to the recent general overview provided by Miller et al. [5], the seminal work by Hein et al. [1,8], the historical perspectives offered by Sparenberg [4] or the range of publications available from the webpages of the International Seabed Authority (ISA).

1.2. The Main Resource Types

Seabed mineral resources are generally divided into three main types: 1) ferromanganese (or polymetallic) nodules, 2) seafloor massive sulphides and 3) ferromanganese (or polymetallic) crusts. These are briefly described in the following paragraphs.

1.2.1. Ferromanganese Nodules

Ferromanganese nodules are polymetallic mineral concretions found on the sediment-covered abyssal plains at water depths of from approximately 3500 to 6500 m [1,8]. The largest known deposits are found on the abyssal plains of the Clarion-Clipperton Zone (CCZ) in the western Pacific Ocean, but extensive nodule fields are also found in the Peru Basin, around the Cook Island and in the Central Indian Ocean Basin [1,8].

The nodules consist predominantly of Mn-oxides [1], with lesser amounts of amorphous Fe-oxyhydroxides and are formed by hydrogenetic and diagenetic precipitation around a hard nucleus [8]. Hydrogenetic precipitation is a very slow process, which yields nodule growth rates of 1–5 mm/Ma [1], whereas rates due to purely diagenetic precipitation can reach 250 mm/Ma [9]. Since most nodules are formed by a combination of both hydrogenetic and diagenetic processes, typical growth rates are found to be several tens of mm/Ma [8].

The size of ferromanganese nodules (longest dimension) typically ranges from 1 to 12 cm, with 1–5 cm being the most common [1]. However, specimens up to 20 cm have been found in the Peru Basin [9]. Nodules vary in dry bulk density and porosity, but respective mean values of 1.35 g/cm^3 and 60% have been reported [10].

Ferromanganese nodules typically contain from three to six times more manganese than iron [1] and the manganese content can exceed 30% [9]. In addition to the high concentrations of manganese and iron, they also contain economically interesting and potentially exploitable amounts of nickel and copper (around or above 1%), lithium, cobalt, molybdenum and REEs [1,5].

1.2.2. Seafloor Massive Sulphides

Seafloor massive sulphides are mineral deposits associated with both active and inactive hydrothermal vents along mid-ocean ridges, in back-arc basins and along submarine volcanic arcs [11,12]. Most deposits are found at depths of 1000-4000 m [12,13]

The deposits form when circulating hot hydrothermal fluids enriched in sulphur and base metals encounter a change in temperature or redox conditions as they are gradually or suddenly mixed with seawater [11,12]. This will cause the sulphide minerals to precipitate. Depending on where and how fast the mixing occurs, precipitation can occur within the oceanic crust, in stockwork beneath venting chimneys or as precipitation on the surrounding seafloor after the hot fluid has been expelled [14]. Given time, sulphide mounds can form from collapsing and coalescing chimneys [15]. As a result, the deposits can have a complex topography with a significant vertical and horizontal zonation with respect to mineral assemblies, texture and chemical composition [11,12,15].

The size of individual seafloor massive sulphide deposits will vary, but the larger identified mound-shaped deposits have diameters of 100-300 m, with heights ranging from 5 to 50 m [11,12].

The exact chemical and mineralogical composition of a deposit will depend on the tectonic setting and the nature and extent of the hydrothermal activity [11,12], but they are typically enriched with metal sulphides containing base metals such as iron, zinc, copper and lead, in addition to gold, silver, arsenic, cobalt, molybdenum, platinum and REEs [11,12] Compared to their land-based counterparts, the known deposits are small but typically hold much higher concentrations of valuable metals (up to tens of % of copper and zinc) [11]. Noteworthy deposits include the Solwara 1 copper-gold deposit at 1600 m depth in the Bismarck Sea off the coast of Papua New Guinea [16].

1.2.3. Ferromanganese Crusts

Ferromanganese crusts are polymetallic mineral concretions found at water depths between 400 and 7000 m on the slopes and summits of seamounts, rising several hundred to a few thousand metres above the seafloor [1,8]. The thickest deposits have been found at depths of 800–2500 m [1,17]. The largest deposits are thought to be in the Pacific Ocean where there is a greater abundance of sediment-free seamounts, but crusts are also found in the Atlantic and Indian Oceans as well as in the polar regions [1]. Ferromanganese crusts are the least-studied of the three main resource types.

Ferromanganese crusts form by hydrogenetic precipitation from cold bottom waters onto surfaces that have remained sediment-free for millions of years [1,8]. They consist predominantly of Mn-oxides and amorphous Fe-oxyhydroxides in subequal amounts [1]. Compared to ferromanganese nodules the crusts have an even higher specific surface area (typically 325 m^2/g) and, due to being formed predominantly by hydrogenetic precipitation, a very low growth rate (1–5 mm/Ma) [1]. The thickness of the crust is generally higher on older seamounts. The value varies from < 1 mm to 260 mm [18], with 2–4 cm as a typical mean on a regional scale [8].

The ferromanganese crusts are a source of cobalt, nickel, copper, platinum and REEs. The REE concentrations of crusts are typically from two to six times higher than that of nodules [1]. Historically, the main economic interest has been linked to the content of cobalt [5,8], and the deposits are frequently and increasingly being referred to as Co-rich crusts or Co-rich ferromanganese crusts. The mean cobalt concentration ranges from 0.30% to 0.67% for various parts of the global ocean [1].

1.3. General Features of Proposed Production Concepts

Technological solutions for mining the mineral resources will depend on a number of factors, including resource type, water depth and geographical location [19,20]. However, the majority of the proposed concepts can be said to consist of three main parts: 1) a mining/collecting unit on the seafloor, 2) a system for transporting the ore from the seafloor to the surface, and 3) a surface mining/support vessel receiving the ore and controlling the subsea production chain [5,19].

Of the three main resource types, the extraction of ferromanganese nodules is regarded as the least challenging prospect, since the nodules reside on a sediment substrate [8]. Most concepts for nodule collection are based on hydraulic suction, but solutions for mechanical scooping or more selective picking have also been proposed [19,21]. In contrast, the extraction of sulphide ores or ferromanganese crusts typically relies on remotely operated tracked mining vehicles that cut, dig or drill into the seabed [5,22,23]. Selectively extracting crusts without simultaneously collecting significant amounts of the underlying rock (i.e., substrate) poses a particular challenge [1]. Here, water jet stripping or vibration fragmentation have been proposed as alternative extraction technologies [8].

Irrespective of resource type, the mining/collecting unit could, if necessary, contain an additional fragmentation step to prepare the ore for vertical transport [19,22].

Vertical transport of the ore has been the subject of extensive research [19,24]. Following the mining/collecting step, the ore could be pumped to the surface as a slurry using a series of pumps or an airlift system (i.e., the injection of compressed air to produce a three-phase flow) or it could be transported by a continuous-line bucket system [5,19,21,24]. Several configurations have been proposed, but solutions based on pumps or airlifts would typically make use of a shorter flexible pipe to connect the mining/collecting unit to a rigid vertical riser system [5,19,21].

At the surface, the mining/support vessel receives the ore and performs the necessary dewatering prior to loading the ore into bulk carriers for transport to onshore processing facilities [20,25–27]. Various degrees of pre-separation could also take place on the mining/support vessel, which could facilitate the return of tailings to the ocean floor [27].

1.4. Historical Development

Commercial interest in deep-sea mining emerged in the 1960s, largely due to the publications [28,29] of John L. Mero, who advocated and discussed exploitation of the mineral resources of the oceans. Mero's work focused on ferromanganese (or polymetallic) nodules found on the abyssal plains, a resource type that had been discovered almost a hundred years earlier during the Challenger expedition (1872-76). Throughout the 1960s and 1970s the concept of deep-sea mining was synonymous with the extraction of nodules, but over the following decades, commercial interest came to include seafloor massive sulphides vents and ferromanganese crusts [1,4,11].

Spanning more than 60 years, the history of deep-sea mining as a commercial concept can be divided into three main phases [4]. The first phase comprises the initial emergence and growth of commercial interest that culminated in the late 1970s before the coming to an abrupt end in the early 1980s. This was followed by at least two decades (i.e., the second phase) where deep-sea mining was shelved as a commercial concept. At the turn of the millennium, the concept was revisited and gradually gained momentum. This represents the third and current phase.

As emphasised by Sparenberg [4], the commercial interest in deep-sea mining has largely been governed by the metal prices and the state of the global economy, but also by the regulatory framework to which potential investors must adhere. During the commodity boom of the late 1960s, mineral resources in the oceans were regarded as a 'free-for-all', ready to be exploited by anyone with sufficient capital and know-how [4]. These liberal terms were restricted by the gradual development of the United Nations Convention on the Law of the Sea (UNCLOS) [30] which, by 1982, had created a regulatory regime to manage seabed mining in areas beyond the limits of national jurisdiction. The Convention, ratified in 1994, set up the International Seabed Authority (ISA), who would issue exploration and exploitation contracts and distribute part of the profits to developing nations. Less favourable terms for investors, combined with the global recession of the early 1980s, effectively suspended the commercial interest in deep-sea mining [4].

When commercial interest re-emerged after the 20-year hiatus, once again spurred by rising metal prices [4], potential investors faced a different scene. Activities in international waters were now subject to an established regulatory framework. The discovery of economically interesting deposits of massive sulphides and ferromanganese crusts diversified investment opportunities. Compared to ferromanganese nodules, these resources can, to a greater extent, also be found within the national exclusive economic zones (EEZ) outside ISA jurisdiction [4,5].

The strong focus on the environment at present has also introduced a new dimension. Since the growing environmental concern in the 1980s, the concept of deep-sea mining has caught the public eye and environmental aspects are now centre stage. The last decade has revealed a polarizing duality in which deep-sea mining is perceived as both an environmental threat and an environmental solution.

To date, no deposits have been put into commercial operation. However, successful pilot tests on the extraction of nodules were conducted by different international consortia during the late 1970s [21]. These tests had a production capacity in the range of 40-50 tonnes/hour, retrieved in total more than 1300 tonnes of nodules, and thus confirmed the technological feasibility of the production concepts [21].

Until their bankruptcy in 2019, the Canadian mining company Nautilus Minerals was planning to commence production of the Solwara 1 massive sulphide deposit off the coast of Papua New Guinea [16,26], which was expected to be the first deposit in operation. Their preparations included the construction and acquisition of a new mining ship and the world's first deep-sea mining robots [23].

Parallel to the recent technological advances, there is an ongoing development of the regulatory framework. In June 2021, the Republic of Nauru invoked the so-called 'two-year rule' in the UNCLOS agreement [31,32]. The rule stipulates that if a state party that is ready to submit an exploitation for approval, requests the ISA to complete the elaboration of all relevant rules, regulations and procedures (RRPs), the ISA must comply within two years of the request. If they fail to do so, the ISA shall provisionally approve the plan of work based on the draft RRPs in place at the time. Nauru is a sponsoring state of Nauru Ocean Resources Inc, a subsidiary of The Metals Co, which are developing plans for the exploitation of polymetallic nodules in the Clarion-Clipperton Zone.

1.5. Scope of Present Study

As illustrated by the previous paragraphs, deep-sea mining is a multi-dimensional concept (e.g., technological, environmental, strategic and legislative) requiring an extensive interdisciplinary research effort to both identify and close the most critical knowledge gaps. This paper is not a review summarizing the current state of knowledge, but a bibliographic analysis (using Elsevier's Scopus database) that aims to elucidate temporal and geographical patterns in academic research focus, publishing structures and international and inter-institutional research cooperation.

Mapping the scope and patterns in scientific publishing could aid in the identification of knowledge gaps, precipitate strategic investment and guide the development of policy.

2. Methodology

2.1. Scope and Strategy

A sample of scientific publications on deep-sea mining was subjected to a bibliometric study using Elsevier's Scopus database. The Scopus database was chosen as the basis for the study since it is considered to be the most comprehensive collection of the peer-reviewed scientific literature. This database is frequently used for bibliometric analytical studies due to its high number of indexed publications, its availability and the functionality offered by its built-in analytical tools [33–35].

Deep-sea mining is a concept that requires broad and interdisciplinary research and the body of scientific publications of potential relevance is vast. However, the majority of the geological, geochemical and biological studies on deep-sea mineral deposits and the associated ecosystems are not initiated and conducted from a resource utilisation perspective; hence, a meaningful bibliometric analysis of the trends and structures in deep-sea mining research requires a more precise focus. Hence, only publications containing an explicit reference to deep-sea mining (or an equivalent term) in their title, abstract or keywords were targeted. As a result, the search was implicitly limited to publications equipped with a title and an abstract in English.

The search was further limited to journal publications to ensure a level of scientific quality and to avoid issues arising from comparing research in different publication formats. The search was performed and concluded on 1 June 2022.

2.2. Definition of the Search

The following Scopus search (i.e., query string) was defined by a combination of predefined field codes and operators: TITLE-ABS-KEY(t_1 OR t_2 OR … t_n) AND SRCTYPE(j) AND PUBYEAR BEF 2022.

The use of the field code TITLE-ABS-KEY(t_1 OR t_2 OR … t_n) will return publications where one or several of the search terms t_1, t_2… t_n appear in the publication title and/or in the abstract and/or in the keywords, whereas the combination of the remaining field codes limits the search to journal papers published prior to (not including) 2022.

The search terms were placed inside double quotation marks to return what Scopus refers to as *loose phrases*. To exemplify, the search TITLE-ABS-KEY("deep-sea mining") will only return hits where the three words occur together in that order, whereas the search TITLE-ABS-KEY(deep-sea mining) will return hits where the three words occur in any order or separated by other words. Note that the double quotation marks syntax ignores spaces and punctuation, permits different spellings and does not differentiate between singular and plural forms. Hence, the terms "deep-sea mining", "deep sea mining" and "deep sea. Mining" are equivalent, as are "sulphides", "sulphide" and "sulfide".

The terminology referring to deep-sea mining has changed over the decades and a number of alternative terms are currently in use. Several preliminary searches were conducted to refine the search definition by including as many of the relevant search terms as possible, whilst minimizing the possibilities of false hits. The final version was based on 34 different search terms (shown later in Section 3.2.1.), and returned what will be referred to as the *original 1968–2021 dataset* since the first relevant publication occurred in 1968.

2.3. Refinement of the Results for 2017-2021

A subset of the original dataset was obtained by limiting the publication year to the five-year period 2017–2021. All the resulting publications were examined to remove false or irrelevant hits caused by either the multiple meaning of words such as *mining* or *nodule* or by the unfortunate juxtaposition of search terms across punctuation marks (e.g., '..the fate of the *ocean*. *Mining* could be...'). Errata and supplementary material to previously published papers are also treated as irrelevant hits from a statistical point of view. The remaining publications are referred to as *the corrected 2017–2021 dataset*.

2.4. Bibliometric Analysis of the Search Results

The obtained datasets were subjected to bibliometric analysis by employing the 'analyze search results' functions of the Scopus database in combination with the necessary manual set operations. As described in Section 3.1.1, the extent of the analysis differs for the original and the corrected dataset due to differences in the relevance, completeness and quality of the data.

Search term occurrences and publication numbers were recorded as a function of time (i.e., publication year), and the latter was also broken down by combinations of registered subject area and country affiliation. The description of each specific subject area can be found on the Scopus website.

The extent of international cooperation, as indicated by international co-authorship, was explored by calculating the pairwise intersections between countries (i.e., number of publications with mutually shared authorship) and by manually registering the number of different country affiliations for each paper. At the same time, the number of different authors and research institutions (i.e., organization affiliations) was also registered.

Lists of the top journals (i.e., publication source) and research institutions with respect to publication numbers were compiled, and the most prominent examples of bilateral inter-institutional cooperation (in terms of shared authorship) were identified.

Note that the search operations in the Scopus database are based on use of an 'inclusive or' (i.e., A or B or both) and that the 'limit to' and 'exclude' functions will include any publication where the function argument is true. To exemplify, in order to limit the search to publications with only Norwegian authors, it is necessary to first limit country affiliation to 'Norway' and then, as the next step, exclude all other country affiliations from the search result.

2.5. Classification of Content

The abstracts of the 606 publications in the corrected 2017-2021 dataset were reviewed by the authors of this paper and the content was classified according to a predefined classification system (Table 1). When necessary, the full papers were examined.

Prior to analysis, the classification system was refined by iterative testing and modification in order to achieve a robust system and a unified interpretation. The final analysis was conducted independently by each of the two reviewers and any inconsistency (less than 7% of the publications) was examined and resolved. Note that the classification system permits a publication to be classified as belonging to several parallel (sub)categories not only with respect to geography or resource type, but also with respect to topic/scope.

The content of the publications was classified according to geographical location, resource type and topic/scope. A large number of publications could not be attributed to a specific resource or geographical location and were classified as 'General or non-specific' ('GNS') with respect to each respective feature.

With respect to geographical location, publications pertaining to the Clarion-Clipperton Zone were allocated a separate subcategory, along with 'Other Pacific Ocean', 'Atlantic Ocean', 'Indian Ocean', 'Other specified location' and 'GNS'. The subcategories 'Manganese nodules', 'Seafloor massive sulphides', 'Manganese crusts', 'Other specified resource' and 'GNS' were used in the classification of resource type.

The classification according to topic/scope was based on the system outlined in Table 1, and further distinctions between the categories are given during the presentation and discussion of the results.

Table 1. System for classification of topic/scope.

Main Category / Subcategory / Description
A. Engineering aspects (of the production process)
a1. The mining process
Design, operation and performance of mining vehicles and collecting systems. Rock mechanic and geotechnical properties of the seabed relevant for rock breakage or mining vehicle traction.
a2. Vertical transport
Design, operation and performance of systems for ore transport between the seabed and the support vessel (e.g., pumps and vertical risers). Characteristics of multiphase flow. Systems integration with mining units and support vessel.
a3. Other aspects
Solutions for ore prospecting, production monitoring and communication. Ore handling and storage on the support vessel. Mineral processing including hydrometallurgical processing. Other relevant engineering aspects.
B. Environmental aspects
b1. Environmental status
Environmental, biological and physical baseline studies. Mapping of biodiversity. Ecological connectivity studies.
b2. Impact assessment and assessment methodology
Impact assessment and environmental risk analysis. Assessment of demonstrated/historic impact. Prediction, description and characterization of potential emissions and waste materials. Methodology for impact assessment.
b3. Other environmental aspects
Strategies and framework for environmental governance and management. Technology, procedures and protocols for environmental sampling and monitoring. Strategies and technology for prevention, mitigation and remediation. Other relevant environmental aspects.
C. Political and legal aspects

Legal framework for deep-sea mining. Policies for governance of seabed resources. Public perception of deep-sea mining. Ethical considerations and challenges for decision making. Other relevant political or legal aspects.

D. Strategic and economic aspects

Strategic and economic importance of seabed resources. Resource estimates. Economic feasibility studies. Other relevant strategic or economic aspects.

E. Other aspects of deep-sea mining

Any relevant aspect not covered by categories A-C.

3. Results and Discussion

3.1. Overview of Search Result and Data Presentation

3.1.1. Datasets, Sample Volumes and Quality

The Scopus search returned a total of 1937 journal publications. The first relevant publication occurred in 1968 [36], preceded only by two publications [37,38] which were both excluded as irrelevant since they pertained to 'submarine mining' and 'sea-mining' in a military sense. The remaining 1935 publications comprise what will be referred to as *the original 1968–2021 dataset*, and their annual distribution is shown in Figure 1.

Manual examination of all the 652 publications found in the 2017–2021 subset of the original 1969–2021 dataset revealed that 46 (7.1%) of these could be classified as irrelevant. The remaining 606 relevant publications are referred to as the *corrected 2017–2021 dataset*. The examination also showed that the fraction of irrelevant hits within this fraction remained relatively stable throughout the given time period. Hence, it is not unreasonable to assume that a similar proportion of the pre-2017 papers falls into this category.

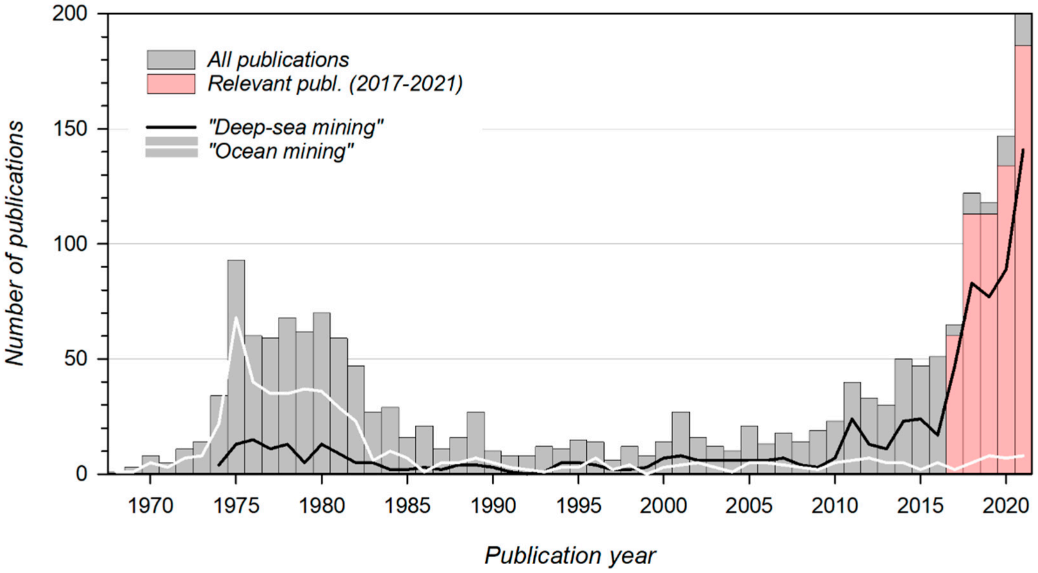

Figure 1. Scientific output (i.e., annual number of publications) from 1968 to 2021. The number of hits returned by the top two search terms are also shown.

As shown in Section 3.2.4, the analysis of the original 1968–2021 dataset is restricted by the fact that the majority of the papers published prior to the mid-1990s lack a defined country affiliation.

3.1.2. Organisation and Presentation of the Results

The overall trends in the total annual production volume, the total output from the main contributing countries and the evolution and relevance of terminology are described in Section 3.2. These statistics are based on the original 1968–2021 dataset.

The corrected 2017–2021 dataset is of a quality that allows for a more comprehensive analysis with respect to subject area, affiliation (institutional and national) and publishing channels. This analysis is provided in Section 3.3 and is based exclusively on the automatic search functions and the ‘analyze search results’ functionality of the Scopus database. This differs from the more detailed classification of content given in Section 3.4, which is based on the authors’ subjective review of each publication.

Note that although a single publication can only be attributed to a single publication year and a single journal, it could be attributed to several countries, institutions, subject areas, content categories, resource types or geographical locations. Hence, most of the results are not subject to constant-sum constraints.

3.2. Overall Trends in the Evolution of Scientific Production since 1968

3.2.1. Evolution of Terminology and Relevance of Search Terms

As described in Chapter 2, the Scopus search makes use of no less than 34 carefully chosen search terms in the TITLE-ABS-KEY field in order to ensure a result with a high degree of completeness and relevance. Of all the search terms “deep-sea mining” produced the highest number of hits with 751, followed by “ocean mining” (521 hits) and “seabed mining” (334 hits). The results are shown in Table 2.

The relevance or relative popularity of these terms has changed over time. Whereas *ocean mining* was the dominant term of reference during the initial phase of interest in the 1970s, it has now largely been replaced by *deep-sea mining* (as shown in Figure 1). The latter term is arguably more specific than the former, as it excludes mining in shallow waters. However, as opposed to *seabed mining*, neither term makes the distinction between mining of the actual seabed and mining in the sense of extracting dissolved elements directly from seawater. The use of *seabed mining* and *marine mining* has been relatively proportional to total annual output, whilst *offshore mining* has seen little use since the late 1980s. Note that the search term “sea mining” only returns 21 hits when the term “deep-sea mining” is excluded.

Table 2. The total number of hits (publications) returned for each of the 34 search terms.

	Search Term	Publ.		Search Term	Publ.
General terms	“deep-sea mining”	751	*Terms pertaining to SMS*	“seafloor massive sulphides mining”	6
	“ocean mining”	521		“mining seafloor massive sulphides”	8
	“seabed mining”	334		“mining of seafloor massive sulphides”	8
	“marine mining”	141		“mining for seafloor massive sulphides”	0
	“offshore mining”	115		“SMS mining”	15
	“submarine mining”	82		“mining SMS”	13
	“seafloor mining”	46		“mining of SMS”	3
	“sea mining”	772[1]		“mining for SMS”	0
Terms pertaining to nodules	“nodule mining”	223	*Terms pertaining to crusts*	“manganese crust mining”	2
	“mining nodules”	5		“mining manganese crust”	0
	“mining of nodules”	6		“mining of manganese crust”	0
	“mining for nodules”	0		“mining for manganese crust”	0
	“mining manganese nodules”	33		“polymetallic crust mining”	0
	“mining of manganese nodules”	41		“mining polymetallic crust”	0
	“mining for manganese nodules”	6		“mining of polymetallic crust”	0
	“mining polymetallic nodules”	8		“mining for polymetallic crust”	0
	“mining of polymetallic nodules”	26			
	“mining for polymetallic nodules”	5			

[1] “sea mining”AND NOT “deep-sea mining” returned 21 publications.

As for the search terms referring directly to a specific type of resource, only those pertaining to nodules return a substantial number of combined hits (333 publications). The corresponding operation for seafloor massive sulphides produced 46 publications with the first relevant occurrence in 2010 [39].

3.2.2. Total Annual Production

From a historical perspective, the scientific production directly pertaining to deep-sea mining can be divided into three relatively distinct phases (Figure 1). After the first few publications in 1968 and 1969, the scientific output rose rapidly, reaching a peak of 93 papers in 1975. The remainder of the decade and the very first years of the 1980s were characterized by a relatively stable output averaging 61 publications per year. However, this first phase of interest can be said to have come to an end by 1983 when only 27 journal papers could be found.

From 1983 to 2010, a total of 438 journal papers were produced, averaging 16 papers per year. This 28-year period of low scientific production constitutes the second distinct phase.

The third phase represents the renewed interest in deep-sea mining that became evident in scientific production in 2011 when the number of journal publications nearly doubled from the previous year (40 against 23) and reached a level not seen since 1982. When evaluated as a moving two-year average, the publication numbers have increased continuously since 2014. The stable level of the second half of the 1970s was reached by 2017 and the previous 1975-peak was surpassed the following year. Scientific output has been particularly high over the last two years, resulting in an all-time high of exactly 200 journal publications in 2021.

Of the 1935 publications returned by the Scopus search, 903 (46.7%) have been published since the start of 2011, including the 652 (33.7%) papers published over the five-year period from 2017 to 2021.

3.2.3. Publications by Subject Area (1968–2021)

The Scopus database classifies each publication as belonging to one or several defined subject areas depending on the formal classification of the source journal. A description of each subject area can be found on the Scopus website.

The publications in the original 1968–2021 dataset are distributed amongst 21 different subject areas, which can be seen as a testament to the multidisciplinary challenges of deep-sea mining. 'Engineering' represents the largest subject area with a total of 986 publications (51.0%) since 1968, followed by 'Earth and planetary science' (723), 'Environmental science' (569), 'Agricultural and biological science' (373) and 'Social sciences' (268).

The same five subject areas have remained on top of the list since the mid-1980s, but their relative prominence has changed over time. Figure 2 shows the development of the three largest subject areas from 1968 to 2021. Until 1980, the 'Engineering' category was more than twice as large as the next four categories combined, whereas 'Environmental science' comprised less than 10% of the publications. In contrast, an analysis of the 2017–2021 period shows that the latter category now holds 42% of the publications, whereas 'Engineering' has dropped to third position (fourth in the corrected 2017–2021 dataset).

Care should be taken when interpreting the date presented in the previous paragraphs. The sample size is relatively low, and the publications are classified based on the subject area classification of the journal and not on their actual content. Both these aspects are illustrated by the prominent peak in 2001 observed for 'Earth and planetary sciences'. Of the 26 publications constituting this peak, 15 can be attributed to a Special Issue of 'Deep-Sea Research Part II: Topical Studies in Oceanography' entitled 'Environmental Impact Studies for the Mining of Polymetallic Nodules from the Deep Sea' (volume 48, issue 17 and 18). Despite their obvious relevance, these publications do not contribute to the 'Environmental science' category, since this subject area was not among those attributed to that particular journal.

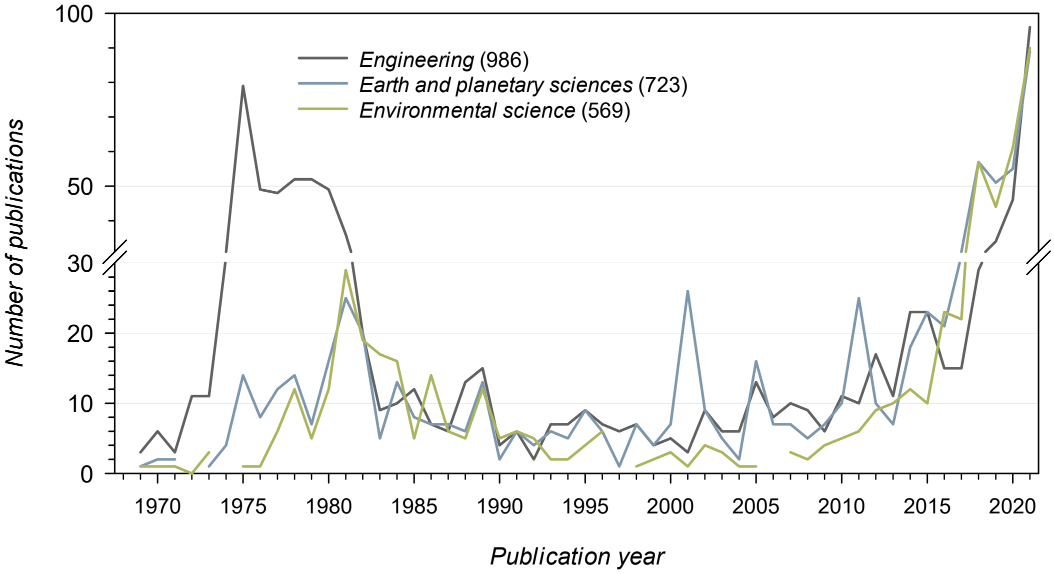

Figure 2. Annual number of publications for the top three subject areas from 1968 to 2021. Note the break in the y-axis.

A more comprehensive analysis of publications by subject area is given in Section 3.3.1 based on the corrected 2017–2021 dataset. The quality of these data also allows for the results to be broken down by country, and the extent of overlap between subject areas is addressed.

3.2.4. Publications by Country Affiliation (1968–2021)

The 'analyze results' functionality of the Scopus database allows for the search result to be broken down into country affiliation or, to be precise, the registered country affiliation of the individual authors. Hence, a single publication could produce hits for several countries. However, the quality of these data varies, as earlier publications tend not to have a separate registration of country affiliation, and thus return a hit in the 'undefined' category.

In 2021, only 3 of the 200 publications had an undefined country affiliation, whereas this was the case for all but one of the 93 1975-publications. Of the 1935 publications, 678 (35.0%) are not attributed to any country. The vast majority of these papers are published prior to the mid-1990s, from which point the affiliation data in the Scopus database begin to become more complete. Starting from 2013, the fraction of publications with an undefined country affiliation has never been higher than 4%.

Since 1968, a total of (at least) 77 countries have contributed to the total output. China produces the highest number of hits, with 307 publications, followed by the United States (284), Germany (190) and United Kingdom (185). Note that these figures do not include contributions from the 678 undefined publications. The annual output from each of the four major contributing countries is shown in Figure 3. A more detailed analysis of country affiliation and the extent of bilateral cooperation is given in Section 3.3.3 based on the corrected 2017–2021 dataset.

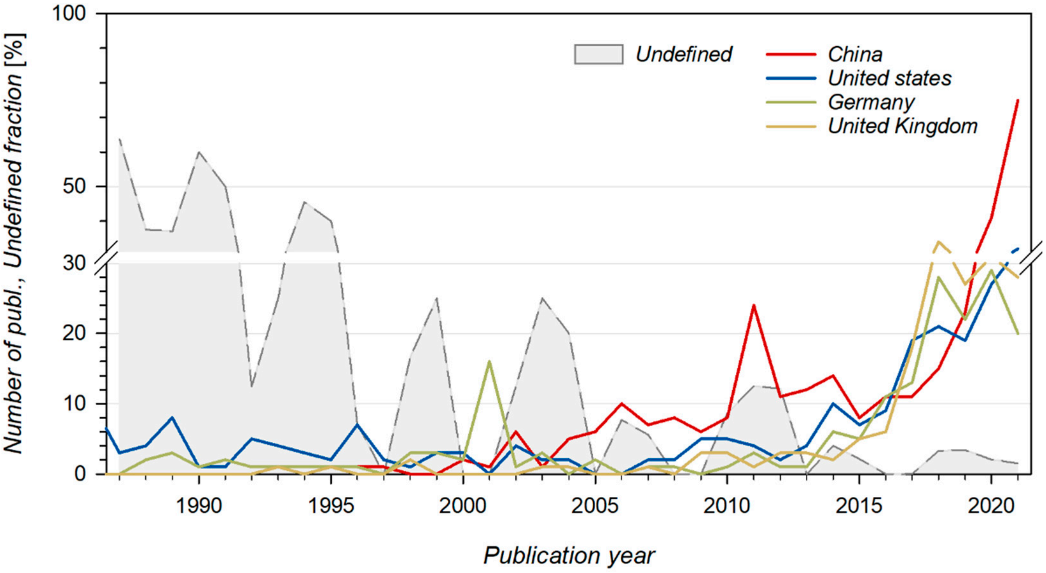

Figure 3. Annual number of publications for the four major contributing countries for 1987 to 2021. The fraction of papers with undefined affiliation is also indicated. Note the break in the y-axis.

3.3. A Comprehensive Analysis of the Corrected 2017–2021 Dataset

3.3.1. Publications by Subject Area (2017–2021)

The annual and aggregated numbers of relevant publications for each of the top five subject areas over the 2017–2021 period are shown in Table 3. 'Earth and planetary science' is now the largest subject area, with 261 publications (43.1%), slightly ahead of 'Environmental science' with 251. The top five subject areas combined include 90.9% of the 606 relevant publications. 'Economics, econometrics and finance' (62) represents the largest of the 16 remaining subject areas (not shown in the table), followed by 'Physics and astronomy' (33) and 'Materials science' (32). Combined, these 16 subject areas include 33.0% of the publications.

Table 3. Publication numbers and pairwise intersection for the top five subject areas (2017–2021).

Subject Area	**Total** (basis)	**Publication Year** 2017	2018	2019	2020	2021	**Pairwise Intersections [%]** Eart	Envi	Agri	Engi	Soci
Earth and planetary sci.	261	28	50	50	49	84	100.0	36.4	48.3	34.9	5.7
Environmental science	251	18	50	43	57	83	37.8	100.0	59.4	34.3	36.3
Agricult. And biolog. Sci.	233	24	52	38	59	60	54.1	63.9	100.0	21.9	25.3
Engineering	203	14	25	33	40	91	44.8	42.4	25.1	100.0	1.0
Social sciences	119	8	27	18	40	26	12.6	76.5	49.6	1.7	100.0
Remain. 16 subject areas	204	19	47	34	49	55	11.8	35.3	38.7	33.3	72.1

It is evident from the previous paragraph that there is a substantial degree of overlap between subject areas. Hence, the pairwise intersections of the top five subject areas are also shown in Table 3. The highest degree of overlap in absolute terms is found between 'Environmental science' and 'Agricultural and biological sciences', with 149 publications in common. As discussed in Section 3.4, many of these publications represent ecosystem studies and biological site descriptions of areas targeted for deep-sea mining, most notably the abyssal nodule fields of the Clarion-Clipperton Zone.

It is also worth noting that the subject area 'Social sciences' shares 91 of its 119 publications (76.5%) with 'Environmental engineering'. These are, to a large extent, publications addressing the political or legal aspects of environmental management. In contrast, 'Social sciences' has only two publications in common with 'Engineering'.

3.3.2. Subject Area by Main Country

When each country's output is broken down into subject areas, an interesting picture emerges. Figure 4 presents the subject area distributions for the four main contributing countries based on the corrected 2017–2021 dataset. While the United Kingdom, the United States and Germany share a relatively similar pattern, the results show that China has a comparatively stronger focus on engineering and a lesser focus on environmental science.

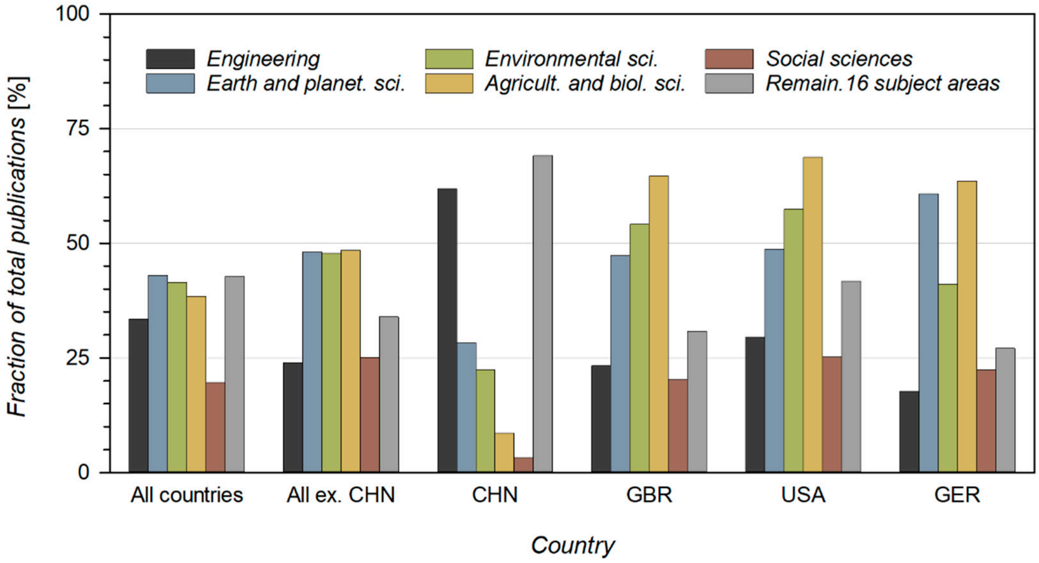

Figure 4. Relative distribution of publications by subject area for each of the main contributing countries, for all countries combined and for all countries excluding China.

As shown in Sections 3.3.3 and 3.3.4, China is the country with the highest publication numbers and has an output characterised by limited international co-authorship. Hence, it is both useful and feasible to look at the total distribution when excluding publications with a Chinese affiliation. This operation results in the exclusion of 152 papers (of which 15 have international co-authorship). The total distribution with and without Chinese publications is shown in Figure 4.

The dataset can also be presented as subject area by country; however, as much of this information can be inferred from the previous data, it is not presented in a separate table or figure. However, it is worth noting that 94 (46.3%) of the 203 'Engineering' publications are affiliated with China. The United States can claim (co-)authorship of 34 publications, whereas the United Kingdom (31), Germany (19), France (14) and the Netherlands (14) follow next. At the top of the corresponding list for 'Environmental science', we find the United Kingdom (72), the United States (66), Germany (44), China (34) and Belgium (30).

3.3.3. Country Output and International Cooperation

Of the 606 relevant publications in the corrected 2017–2021 dataset, only 14 have an undefined country affiliation, and contributions from (at least) 59 countries are identified. The total and annual output for all countries with a total of at least 10 publications is listed in Table 4. For these countries, the table also indicates all international cooperation (i.e., pairwise intersections) representing at least three shared publications.

Table 4. Publications by country and extent of bilateral cooperation (2017–2021). Only countries with at least 10 publications are included, along with all respective pairwise (bilateral) intersections representing at least 3 publications.

Country	Total	Publication Year					CHN	GBR	USA	GER	NED	BEL	NOR	AUS	JAP	POR	FRA	RUS	CAN	POL	SWE	NZL	ESP	KOR	IND	SUI	BRA
		'17	'18	'19	'20	'21																					
CHN	152	10	15	22	34	71	152	4	3	3					4	3			3	4							
GBR	133	18	31	27	31	26	4	133	47	34	14	12	18	12	10	19	19	13	12	13	13	12	10		3	10	
USA	115	19	19	18	27	32	3	47	115	25	14	10	18	14	13	9	16	11	16	9	11	8	9	4	3	7	
GER	107	13	24	22	29	19	3	34	25	107	17	14	12	7	6	15	16	9	9	7	4	5	7		4	4	
NED	48	9	9	5	13	12		14	14	17	48	4	3	7	4	6	9	6	4		4						
BEL	44	6	5	7	10	16		12	10	14	4	44	5			5	8			4			4			3	
NOR	44	4	12	10	9	9		18	18	12	3	5	44	4	4	5	9	3	9	6	10		4			5	
AUS	41	5	11	6	9	10		12	14	7	7		4	41		4	5		3	3		3					
JAP	41	3	6	8	9	15	4	10	13	6	4		4		41	3	6	5	6	4				4			
POR	39	5	5	9	12	8	3	19	9	15	6	5	5	4	3	39	8	6	5				4				
FRA	37	9	5	4	8	11		19	16	16	9	8	9	5	6	8	37	8	7	6	3		8		3	7	
RUS	28	6	6	3	5	8		13	11	9	6		3		5	6	8	28	4		3		3			5	
CAN	27	1	5	4	9	8	3	12	16	9	4		9	3	6	5	7	4	27				3				
POL	21	3	2	3	3	10	4	13	9	7		4	6	3	4		6			21						4	
SWE	20	2	4	5	2	7		13	11	4	4		10				3	3			20		5				
NZL	19	2	2	2	6	7		12	8	5				3								19					
ESP	17	3	2	4	1	7		10	9	7		4	4			4	8	3	3		5		17				
KOR	16	1	4	4	2	5			4						4									16			
IND	13	1	0	5	2	5		3	3	4							3								13		
SUI	13	2	4	0	3	4		10	7	4		3	5				7	5		4						13	
BRA	10	0	2	3	2	3																					10
ITA																							3				
HKG								4	4	4						3	5	3	3	4							
RSA									3																		
SGP									3																		
CHI										3																	
IRL									5	5				3			3	3		3							
JAM										4																	
AUT										3	3																
MEX									3	3					3												
Publ. with only national authors [%]							90	23	23	36	31	30	23	27	49	23	8	32	19	14	5	16	6	69	69	8	30

Legend

🟧	> 20
🟧	11-20
🟧	6-10
🟧	3-5
☐	< 3

The exclusion of irrelevant publications does not change the overall picture presented in Section 3.2.4. China is the main contributor, with a total of 152 relevant publications over the last five years, followed by the United Kingdom (133), the United States (115) and Germany (107). It is also interesting to that the Chinese output doubled from 2020 to 2021, a relative increase matched only by countries with far lower production. This may or may not be the start of a trend. Historically, there have been significant annual fluctuations in output (Figure 3) even for the main contributors (and especially for China). Hence, the observed increase must be interpreted with caution.

The pairwise intersection matrix in Table 4 is offered in an attempt to illustrate the degree of international cooperation or, to be precise, bilateral co-authorship. Even though only pairwise intersections are shown and not intersections of a higher order, this is sufficient to produce a relatively clear pattern. In absolute terms, it is reasonable to expect the larger contributors to produce a larger number of pairwise intersections (i.e., shared publications). This is also the case, with the very notable exception of China, for which less than 10% of the total output has international co-authorship and no more than four publications are shared with any other country. In comparison, the United Kingdom and the United States mutually share authorship of 47 publications and have extensive cooperation with most of the top-listed countries. As a result, more than 3 out of 4 publications have international co-authorship.

International cooperation is governed by many factors, including political, cultural and practical aspects. Countries with extensive national research activity on deep-sea mining may not need to cooperate internationally, but make very attractive research partners by virtue of the competence, facilities and economic capability of their research institutions. Public funding mechanisms, e.g., most of the funding from the European Union, may also promote (or require) international cooperation.

With respect to practical aspects, language could also be a barrier for international cooperation. As evident from Table 4, countries with writing systems that differ significantly from English (i.e., China, Japan and South Korea) have a high proportion of publications without international co-authorship.

The COVID-19 pandemic is also likely to have had a negative effect on both the degree of international cooperation and the total scientific output for 2020 and 2021, but the underlaying growth trend makes quantification difficult. However, due to the time lag between research activities and publication of the results, the effect of the pandemic on publication numbers might be more pronounced for 2022.

It is important to remember that research cooperation, as a rule, originates between individual research institutions and not between countries. Mapping specific inter-institutional cooperation would be preferable, but represents a far more complex task due to the high number of research institutions involved (see Section 3.3.4). The analysis of research cooperation between countries is still valuable, since the output for a single country is usually dominated by a limited number of research institutions and the governance of seabed minerals is conducted at national or international levels.

3.3.4. Institutions, Journals and Authorship Structures

A total of (at least) 160 research institutions (i.e., author affiliations) contributed to the corrected 2017–2021 dataset. The top 25 institutions with respect to publication numbers are listed in Table 5, using the names as they appear in the Scopus database. Note that institutional mergers, reorganizations or name changes makes it challenging to track organization affiliations over longer time periods.

Table 5. Top 25 institutions with respect to publication numbers (2017–2021).

Rank	Publ.	Institution	Country
1.	70	National Oceanography Centre Southampton	GBR
2.	57	Central South University	CHN
3.	53	University of Southampton	GBR
4.	40	University of Hawaii at Manoa	USA
5.	35	Universiteit Gent	BEL
6.	33	GEOMAR – Helmholtz-Zentrum für Ozeanforschung Kiel	GER
7.	31	Senckenberg Gesellschaft für Naturforschung	GER
8.	27	Shanghai Jiao Tong University	CHN
9.	25	Royal Netherlands Institute for Sea Research – NIOZ	NED
10.	25	The Natural History Museum, London	GBR
11.	22	Universiteit Utrecht	NED
12.	22	Universität Bremen	GER
13.	21	IFREMER Institut Français de Recherch' pour l'Exploitation de la Mer	FRA
14.	19	Bundesanstalt für Geowissenschaften und Rohstoffe	GER
15.	18	MARUM – Zentrum für Marine Umweltwissenschaften	GER
16.	18	State Key Laboratory of Ocean Engineering	CHN
17.	17	Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung	GER
18.	17	P.P.Shirshov Institute of Oceanology, Russian Academy of Sciences	RUS
19.	16	Japan Agency for Marine-Earth Science and Technology	JAP
20.	16	Duke University	USA
21.	16	Norges Teknisk-Naturvitenskapelige Universitet	NOR
22.	16	University of California, San Diego	USA
23.	13	Jacobs University Bremen	GER

24.	13	Scripps Institution of Oceanography	USA
25.	13	Universidade dos Açores	POR

The National Oceanography Centre in Southampton (NOC) is heading the list with 70 publications, in front of Central South University in Changsha, with 57. The NOC is an independent, self-governing organization, but is closely linked with the University of Southampton, which is third on the list (50).

Several of the institutions in Table 5 have formal ties, e.g., Center for Marine Environmental Sciences (MARUM) is part of the University of Bremen, whereas Scripps Institution of Oceanography is part of the University of California, San Diego. These links are also apparent in Table 6, where all pairwise inter-institutional joint authorships, representing more than 10 publications, are listed in descending order. The first international pair (NOC and the University of Hawaii) is third on the list.

On average (arithmetic mean), a publication in the corrected 2017-2021 dataset has 4.91 authors, representing 3.27 institutions and 1.81 countries. The respective corresponding median/mode values were found to be 4/3, 2/1 and 1/1. As is typical for scientific publishing, the distributions are right-skewed, with a small number of publications with a large number of different affiliations.

As shown in Table 4, China has a very high proportion of publications with only national authors (89.5% compared to 58.5% for the entire dataset), but although the 152 papers that can be attributed to China have an average of only 1.49 country affiliations and 3.04 institution affiliations, the average number of authors (4.87) differs less from the corresponding total figure. This indicates a higher degree of intra-institutional cooperation.

Table 6. Number of shared authorship publications between pairs of institutions (2017-2021). The table shows all pairs representing more than 10 publications.

Shared Authorship (Institution 1 ǀ Institution 2)	**Publ.**
National Oceanography Centre Southampton ǀ University of Southampton	45
Royal Netherlands Institute for Sea Research - NIOZ ǀ Universiteit Utrecht	21
National Oceanography Centre Southampton ǀ University of Hawaii at Manoa	18
Shanghai Jiao Tong University ǀ State Key Laboratory of Ocean Engineering	18
Universität Bremen ǀ MARUM – Zentrum für Marine Umweltwissenschaften	15
University of Hawaii at Manoa ǀ The Natural History Museum, London	13
National Oceanography Centre Southampton ǀ The Natural History Museum, London	12
University of California, San Diego ǀ Scripps Institution of Oceanography	12
Nat. Oceanography Centre South. ǀ P.P.Shirshov Inst. of Oceanology, Russian Academy of Sciences	11
National Oceanography Centre South. ǀ GEOMAR - Helmholtz-Zentrum für Ozeanforschung Kiel	11
University of Southampton ǀ University of Hawaii at Manoa	11
Heriot-Watt University ǀ The Lyell Centre	11

The interdisciplinary nature of deep-sea mining is also evident from the large number of different journals that have been used to publish the research. A total of 160 journals is found in the corrected 2017–2021 dataset, although 82 of them are only credited with a single publication. A total of 22 journals is necessary to include at least half (306) the publications.

The top 13 journals are shown in Table 7. The list is headed by 'Marine Policy' followed by 'Frontiers in Marine Science' which, together, account for 17.7%. If the results are broken down by subject area (not shown), the same order is found for 'Environmental science' and 'Agricultural and biological sciences'. 'Marine Policy' is also the top journal for 'Social sciences', followed here by 'International Journal of Marine and Coastal Law'. 'Frontiers in Marine Science' is the main outlet for both 'Engineering' and 'Earth and planetary sciences'. Here, the second place is held by 'Ocean Engineering' for the former subject area and 'Minerals' for the latter.

Table 7. Publication numbers and degree of OA publication for the top 13 journals (2017–2021).

Rank	**Publ.**	**Journal**	**OA[1] [%]**

1.	57	Marine Policy	42.1
2.	50	Frontiers in Marine Science	100
3.	22	Minerals	100
4.	18	Ocean Engineering	22.2
5.	16	Biogeosciences	100
6.	16	Marine Georesources and Geotechnology	6.3
7.	12	Deep Sea Research Part I Oceanographic Research Papers	41.7
8.	11	International Journal of Marine and Coastal Law	18.2
9.	11	Zhongguo Youse Jinshu Xuebao Chinese Journal of Nonferrous Metals	100
10.	10	Scientific Reports	100
11.	9	Journal of Marine Science and Engineering	100
12.	9	Marine Biodiversity	33.3
13.	9	Marine Technology Society Journal	11.1

[1] Relative amount of open access publications.

In total, 54.1% of the publications are available in some form of open access. This ratio has changed little over the five-year period. In comparison, only 23.3% of the original 1968-2021 dataset is offered as open access. Table 7 shows the relative amount of open access publications for each of the top journals.

3.4. Contents Analysis 2017–2021

3.4.1. Aggregated Results: Quality and Relevance

By examination of the 652 publications in the original 2017–2021 dataset, it was found that 46 publications (7.1%) had to be classified as irrelevant. The overall results from the classification of content in the remaining 606 publications are presented in Table 8. Note that a single publication can be placed in several categories when it comes to geography, type of resource and content, and that the sum of these categories (or subcategories) can exceed 100%. A closer look at geography and resource type is given in Section 3.4.2, whereas each content category is analysed in Sections 3.4.3–6. Note that the citations given in these sections serve as examples of scope and illustrate the definition of the (sub)category. They state the focus of the research, not the findings or conclusions.

Table 8. Publication numbers by geog. location, resource type and content category (2017-2021).

	Publication Year					**Total**	**Rel. Distr. [%]**	
	2017	2018	2019	2020	2021		of total	of cat.
Number of Relevant Publ.	60	112	113	134	187	606	100	
Geographical Location								
Clarion-Clipperton Zone	12	20	21	17	32	102	16.8	
Other Pacific Ocean	5	25	14	15	28	87	14.4	
Atlantic Ocean	5	9	11	12	7	44	7.3	
Indian Ocean	2	1	4	2	7	16	2.6	
Other specified location	1	1	1	2	0	5	0.8	
General or non-specified	35	59	66	89	120	369	60.9	
Resource Type								
Nodules	16	30	30	27	53	156	25.7	
Massive seafloor sulphides	8	18	15	13	18	72	11.9	
Polymetallic crusts	0	3	5	3	10	21	3.5	
Other specified resource	1	0	1	2	5	9	1.5	
General or non-specified	35	64	65	90	110	364	60.1	
Content Categories								
A. Engineering aspects	17	26	33	44	73	193	31.8	100
a1. Mining process	*3*	*7*	*12*	*12*	*28*	*62*	*10.2*	*32.1*
a2. Vertical transport	*9*	*9*	*14*	*27*	*38*	*97*	*16.0*	*50.3*

a3. Other aspects	*5*	*12*	*9*	*9*	*11*	*46*	*7.6*	*23.8*
B. Environmental aspects	34	50	58	58	79	279	46.0	100
b1. Environmental status	*18*	*20*	*25*	*25*	*43*	*131*	*21.6*	*47.0*
b2. Impact and impact assessment	*12*	*25*	*26*	*19*	*21*	*103*	*17.0*	*36.9*
b3. Other aspect	*7*	*16*	*18*	*25*	*26*	*92*	*15.2*	*33.0*
C. Political and legal aspects	8	32	22	41	42	145	23.9	
D. Strategic and econ. aspect	3	18	9	4	16	50	8.3	
E. Other	1	4	1	2	3	11	1.8	

The degree of overlap between content categories is limited with 88.8% of the publications belonging to a single category. Furthermore, only 1.8% of the publications require the use of the 'Other aspects' category. These figures suggest that the classification system is appropriate and fairly robust.

A total of 35 publications have been classified as belonging to both 'Environmental aspects' and 'Political and legal aspects', representing the largest overlap between two categories. This constitutes 5.8% of the total dataset and 12.5% and 24.1% of the publications in each respective category. Of the four defined categories, 'Strategic and economic aspects' is the one with the highest degree of overlap, with a respective 9, 10, and 10 publications in common in the 'Engineering aspects', 'Environmental aspects' and 'Political and legal aspects' categories. Only 49.0% of the publications in this category do not overlap. In contrast, 94.7% of the 'Engineering aspects' publications belong to a single category.

Table 8 also shows the development in production volume for each of the content categories over the 2017–2021 period. These results indicate a rapid growth in the 'Engineering aspects' category, which is consistent with (and partly explained by) the observed growth in the Chinese output and the country's strong focus on engineering. However, the limited size of the dataset (especially for 2017) means that apparent trends must be interpreted with caution. This is illustrated by the 2018 peak in the 'Strategic and economic aspects' and 'Political and legal aspects' categories, which is mainly due to a single volume (no 95) of Marine Policy.

3.4.2. Resource Type and Geographical Location

The majority (60.9%) of the publications can be classified as general or non-specific (GNS) with respect to resource type. This also applies to the geographical classification, where 60.1% of the publications refer to no specific location. Typical exponents for such publications are contributions addressing the political and legal aspects of seabed resources in general, environmental publications on management protocols or monitoring systems and engineering publications focusing on various aspects of vertical transport (or transportation).

Of the 252 publications pertaining to one (or more) specific resource(s), nodules have received the most attention, with a total of 156 publications. In contrast, seafloor massive sulphides are covered by 72 publications, and ferromanganese crusts by 21. This pattern is also mirrored in the distribution of geographical locations. Of the 255 location-specific papers, 102 can be attributed to the abyssal nodule fields of the Clarion-Clipperton Zone in the Pacific Ocean. Hence, the correlation between the CCZ location and nodules as a specific resource type is strong, with 94 publications belonging to both categories.

The Pacific Ocean accounts for 162 publications, whereas the respective counts for the Atlantic Ocean and Indian Ocean are 44 and 16. In the Atlantic the main focus has been on seafloor massive sulphides, with a total of 19 publications.

3.4.3. Engineering Aspects

As shown in Table 8, more than half (52.7%) of the 'Engineering aspects' publications fall into the subcategory 'Vertical transport'. Although both bucket systems [22,24,40] and airlift systems [41,42] are studied, the vast majority of these papers address various aspects of hydraulic transport.

Many of the hydraulic transport studies make use of coupled Computational Fluid Dynamics/Discrete Element Method (CFD-DEM) modelling to simulate and analyse the complex simultaneous transport of fluids and solid particles [43–50]. This also includes more fundamental studies on multiphase flow, with an explicitly expressed relevance for deep-sea mining. In some of these studies, the numerical analysis is supported and verified by experiments. This approach was used by Dai et al. [49], who investigated the transportation characteristics and wall shear stress at different particle concentrations and flow rates, and Hu et al. [48], who studied the distribution and motion characteristics of the particles in the Y-shaped connecting pipe between the buffer and the lift pipe.

Various aspects of lifting pump performance have also been subject to study, including pump design [51], cavitation [52,53] and wear [50,54,55]. The reciprocal wear (erosion) of particles during hydraulic transport has been experimentally tested by van Wijk at al. [56] and de Hoog et al. [57], both utilising polymetallic nodules from the Clarion-Clipperton Zone.

The 'Vertical transport' subcategory also contains a number of publications addressing the integration of the hydraulic riser pipe with the support vessel and the mining unit [58,59] and the stress, vibration and dynamic response induced by internal or external forces [58–62] This includes the work by Thorsen et al. focusing on the effect of time-varying internal slurry flows on vortex induced vibrations and the study by Wu et al. [61] on the of the effect of heave motion.

The subcategory 'Mining process' contains 57 publications (30.3%) which predominantly focus on design, operation and performance characteristics of mining vehicles [20,63–67] and nodule collecting systems [68–72]. An overview of the latter category is given by Kang and Liu [72].

The 'Mining process' subcategory also includes studies on the mechanical properties of the seabed and the breakage characteristics of the ore [73–77]. Zhu et al. [76] investigated the stability of heterogeneous sediments when exposed to the load and vibration of the mining vehicle, whereas Dai et al. [73] determined the uniaxial and triaxial strengths of seafloor massive sulphide samples to obtain their key mechanical properties in order to simulate the cutting process. Hu [77] studied the use of pulse plasma discharge and experimentally determined the breakdown voltage of artificial crust and bedrock samples.

The subcategory 'Other aspects' consists of 45 publications (23.9%) and comprises technology for ore prospecting and production monitoring, communication, ore handling and processing. Many of these publications focus on the development and application of acoustic technology for seabed mapping and assessment of nodule abundance or crust composition [78–81], but the use of hyperspectral imaging [82,83] is also described. However, the subcategory extends beyond in situ exploration. Milinovic et al. [84] developed a method for XRD identification of ore minerals during cruises, thus enabling on-site modification of exploration strategies, whereas Teixeira et al. [85] studied height optimization in aerial networks for enhanced broadband communications at sea. Yang et al. [86] proposed and examined a novel design for an offshore agitated vessel.

From a value chain (or production chain) perspective, it is worth noting that only a handful of publications investigate processing of the ore and that they mainly describe alternatives (or supplements) to physical particle separation. Wegorzewski et al. [87] studied thermal pre-treatment of polymetallic nodules to create metal-enriched particles for subsequent processing, whereas Kowalczuk et al. [88] considered the simultaneous leaching of polymetallic nodules and seafloor massive sulphides. Ochromowicz et al. [89] presents an overview of the recent advances in the metallurgical processing of deep-sea minerals.

3.4.4. Environmental Aspects

Almost half (47.0%) of the ‘Environmental aspects’ publications fall into the subcategory ‘Environmental status’, which includes environmental baseline studies, connectivity studies, spatial and temporal biodiversity mapping as well as chemical, physical and topographical site descriptions of areas targeted for deep-sea mining ([90–101]). Most of these publications explicitly state their relevance by emphasising the need for more knowledge prior to the commencement of mining operations, not only to establish the environmental baseline, but also to obtain a better understanding of the ecosystems and the ecological processes. As pointed out by Simon-Lledó et al. [94], ‘The environmental factors regulating seafloor ecology are still very poorly understood’. The biological mapping also includes reports of new species, including protists [90] sponges [95] and snails [96].

The vast majority of the ‘Environmental status’ publications pertain to the abyssal nodule fields of the Clarion-Clipperton Zone, but seafloor massive sulphides have also been addressed. Ramirez-Llodra et al. [97] studied the benthic communities on the Mohn’s Treasure mound on the Arctic Mid-Ocean Ridge, whereas Perez et al. [98] conducted connectivity studies on hydrothermal vent communities along the mid-ocean ridges in the West Indian Ocean. A review of inactive sulphide ecosystems is provided by Van Dover [99].

Although ‘Environmental status’ predominantly refers to biological or ecological status, the subcategory also includes descriptions of the physical and chemical environment. This can be illustrated by Niu et al. [100], who conducted a baseline assessment of ocean ambient noise in the western part of the Clarion-Clipperton Zone, or by the detailed study of the chemical composition of nodules and seafloor sediments in the eastern CCZ by Menendez et al. [101].

The ‘Impact and impact assessment’ subcategory comprises 103 publications (36.9%) and contains both assessment of observed or predicted environmental impact [102–107], as well as methodology, strategies and challenges for environmental impact assessment (EIA) [107–110]. The latter includes the work by Clark et al. [110], who summarises some of the key problems raised by previous EIA reviews and examines recent deep-sea mining EIAs.

In the absence of experience from actual seabed mining operations, several studies ([102–104]) seek to infer potential impacts from the large-scale disturbance and recolonization experiment (the DISCOL project) that was conducted in a ferromanganese nodule area in the South-East Pacific Ocean off Peru in 1989. Other experimental or evidence-based approaches include Spearmann et al. [105], who conducted plume experiments on the tropic seamount 300 nautical miles SSW of the Canary Islands, and Mestre et al. [106], who used the sulphide mine tailings deposit in Portmán Bay (Spain) as a shallow-water analogue to study the potential ecotoxicological impact of deep-sea mining.

The remaining 92 publications (33.0%) that make up the subcategory ‘Other aspects’ span a wide range of topics. This includes both strategies and framework for environmental governance [111–116] and technology, procedures and protocols for environmental sampling and monitoring [117–120]. The limited number of studies on solutions for mitigation and remediation [27,121,122], including the overview provided by Cuvelier et al. [121], also fall into this subcategory.

As shown in Section 3.4.1, there is a significant overlap between the ‘Political and legal’ and ‘Environmental’ categories. Typically, these are publications evaluating or proposing the integration of environmental management principles and assessment criteria in current or proposed legislation [113,114].

3.4.5. Political and Legal Aspects

The political and legislative governance of seabed resources [123–130] has been approached from several angles, with the intrinsic uncertainty and risk associated with deep-sea mining as the common denominator. Ginzky et al. [128] and Kung et al. [126] emphasised the need for more knowledge to enhance decision-making, Krutilla et al. [130] proposed an approach for addressing fundamental uncertainty in benefit–cost analysis, whereas Stabell and Steel [129] discussed how the cost of applying the precautionary principle should be distributed among the stakeholders. Kim [124] and Beaulieu et al. [125] asked if deep-sea mining should be allowed.

Several of the publications address the role of the International Seabed Authority (ISA) and discuss, or suggest modifications to, the legal framework at its disposal [32,128,131–136]. Here, any development in legislation or expressed policy will spur an immediate response in academic publishing, as illustrated by the publications [32,135] that address the Republic of Nauru's activation of the so-called 'two-year rule' at the International Seabed Authority in June 2021.

The public perception of deep-sea mining has also been subject to studies. Motoori and McLelland [137] conducted a survey in Japan to map society's awareness and understanding of deep-sea mining and its preferences for alternative sources of minerals, whereas Hallgren and Hansson [7] provided an overview of conflicting deep-sea mining narratives and structure of ongoing key discussions. Various aspects of activism against deep-sea mining have been discussed by Shewry [138] and Willaert [139].

As stated in Section 3.4.4., publications evaluating or proposing the integration of environmental management principles and assessment criteria in current or proposed legislation [113,114] contribute to the significant overlap between the 'Political and legal' and 'Environmental' categories.

3.4.6. Strategic and Economic Aspects

Most of the publications focusing on strategic and economic aspects could be classified as either resource estimates [140–145], mostly for nodules, or papers examining the strategic importance and/or economic feasibility of seabed resources from a critical raw materials point of view [2,6,146–150]. The latter frequently include comparisons with the supply from recycling and land-based mineral resources and overlap, to some extent, with the 'Political and legal' or 'Environmental' categories. To exemplify, Toro et al. [2] reviewed the role of seabed mineral resources in renewable energy production in both a strategic and political context, whereas Miller et al. [6] challenged the strategic need for these resources by addressing the social, economic and environmental uncertainty.

The focus on resource estimation also extends to the development of methodology and tools for statistical interpretation. Yu and Parianos [151] studied the application of a generalized Rayleigh distribution for mineral resource estimation of seabed polymetallic nodules, whereas Lesage et al. [152] proposed a modular framework to produce economic block models for seafloor massive sulphides. Some of the resource estimate publications [80,81] describe or make use of novel technology and are also categorised as belonging to the 'Engineering aspects' category.

3.5. Relevance and Importance of the Findings

The search string was composed to catch all journal publications that explicitly express their relevance for deep-sea mining. Some of these will have a very specific focus with limited transfer value to other systems or situations. Others provide knowledge and insights that are valuable independent of their relevance for deep-sea mining. Publications pertaining to the design and operation of nodule collectors or mining vehicles generally belong to the former category, whereas biological mapping and ecological baseline studies are good examples of the latter.

Several of the biological mapping studies returned by the Scopus search could have been published in their own right, without a reference to deep-sea mining. This also applies to some of the engineering studies. At the same time, the search excludes the large number of publications that are missing an explicit reference, but could be equally relevant to those included. Hence, the datasets analysed in this study do not provide a balanced overview of the current sum of knowledge or technological state-of-art that is directly or potentially relevant for deep-sea mining. However, given the comprehensive search definition and the extent of the Scopus database, they probably constitute a fairly representative sample of the aspects that have been addressed in an explicit deep-sea mining context in peer-reviewed journals. As such, this study serves to highlight the foci of the academic community with respect to deep-sea mining.

The analysis of topic/content shows wide variation, but also clear patterns. Scientific publishing is subject to trends and two distinct publication scopes are particularly frequent; the CFD-DEM-analysis of vertical hydraulic transport and the ecological baseline study of the abyssal nodule fields in the Clarion-Clipperton Zone. It is also interesting to note how certain aspects of the deep-sea mining production process have received limited attention. As expected, studies on site remediation are rare, since no deposits have been mined to date. Studies on mineral processing of the ore are also scarce, which probably reflects the fact that mining and vertical transport are perceived as the major challenges. The concept of mineral separation of the ore prior to vertical transport is sometimes proposed as a measure to reduce the volumes that need to be brought to the surface. However, due to their less mature nature, it is difficult to find these solutions being described in peer-reviewed journal publications.

The analysis of author affiliations for the corrected 2017-2021 dataset where the quality of data facilitating such analyses revealed that at least 59 countries and at least 169 different institutions have contributed to the total scientific output, but also that a handful of institutions are responsible for a large proportion of the production. China has emerged as the largest contributor and doubled its publication output from 2020 to 2021. Compared to the remaining top-four countries, the United States, United Kingdom and Germany, China showed a comparatively stronger focus on engineering and a lesser focus on environmental science. Publications with Chinese affiliations also tend to have very limited international authorship. The bibliometric indicators employed in this study to describe these features are well-defined, reproducible, and easily determined. They do not explain the observations, but are well-suited to monitor development over time.

If the rapid growth in scientific production continues, an interval of no more than two or three years would be required to accumulate a sufficient number of publications to merit a new bibliometric study on deep-sea mining. Monitoring and interpreting the scope and patterns in scientific publishing could aid in the identification of knowledge gaps, research opportunities, potential inter-institutional cooperation and the need for strategic investment and policy development. The authors hope that this study will serve as a reference or baseline for future bibliometric analyses.

4. Conclusions

Elsevier's Scopus database was searched for publications containing an explicit reference to deep-sea mining (or an equivalent term) in their title, abstract or keywords. The resulting sample was subjected to a bibliometric analysis that produced the following main findings:

- Since the first relevant hit in 1968, a total of 1935 publications were found. A third of these were published between 2017 and 2021. Following the initial phase of interest in the 1970s, scientific production dropped in the early 1980s and remained low until the current phase of rapid growth, which began around 2010.
- While 'ocean mining' was the most common term of reference in the 1970s, it has now largely been replaced by 'deep-sea mining'.
- On inspection, 7.1% of the subset of papers published between 2017 and 2021 was found to represent irrelevant hits.
- Viewing the 2017-2021 period, 'Earth and planetary science' represents the largest Scopus subject area category, with 43.1% of the relevant publications. This is followed by 'Environmental science' (41.4%), 'Agricultural and biological science' (38.4%), 'Engineering' (33.5%) and 'Social sciences' (19.6%). These five subject areas combined include 90.9% of the 606 relevant publications.

- Until 1980 the ‘Engineering’ category was more than twice as large as the next four categories put together, whereas ‘Environmental science’ comprised less than 10% of the publications.
- At least 59 different countries have contributed to the 606 relevant papers published between 2017 and 2021. China (152 publ.), the United Kingdom (133), the United States (115) and Germany (107) are the top contributors.
- Of the top four contributing countries, China has had a comparatively stronger focus on ‘Engineering’ and contributed less to the ‘Environmental science’ category. While the United Kingdom and the United States have extensive international cooperation, Chinese research institutions produce very few publications with international co-authorship.

Manual review and classification of the 606 relevant 2017-2021 publications resulted in the following main findings:

- Almost half of the publications are focusing on environmental aspects, whereas engineering aspects are addressed by close to one third. Almost one in four focus on political or legal aspects.
- Of the environmental papers, almost half describe environmental status, e.g., environmental baseline studies, biodiversity mapping and site descriptions of areas targeted for deep-sea mining.
- More than half of the engineering aspects publications address aspects related to the vertical transport of the ore from the seabed to the surface.
- Very little is published on site remediation or ore processing.
- Of the publications focusing on a specific resource type, ferromanganese nodules feature more than twice as frequently as massive seafloor sulphides. Little is published specifically on ferromanganese crusts.

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