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Review

Understanding Climate Change and Heavy Metals in Coastal Areas: A Macroanalysis Assessment

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Abstract: Increasing human-induced climate issues, such as water pollution, have triggered rapid physiochemical changes, especially in coastal regions. These changes have directly impacted aquatic animals that live near coastal areas, such as bivalves and crustaceans (e.g., clams, crabs), as well as those that live in the lower areas of the habitat (i.e., sediment). Heavy metal pollution (e.g., mercury) is one of the most concerning physiochemical changes in these areas. The effects of heavy metals on coastal environments and organisms can be substantial, in spite of restoration efforts. Thus, more studies are needed to analyze the current situation of the impacts of climate-change-related issues on heavy metal concentrations in coastal areas. In this paper, we provide a scientometrics analysis of the interactions between climate change and heavy metal concentrations in coastal regions around the world. Scientometrics is the quantitative analysis of the available literature, with a focus on research patterns, using continuous and systematic methods. Our results showed that there was a total of 7922 related studies from 1979 to 2021. Heavy metal contamination, ecological quality status and ocean acidification are among the most influential keywords in this field. We concluded that among climate change issues, heavy metals are becoming a popular topic within research associated with climate change.

Keywords: climate change; pollution; brackish water; marine environment; trends and hotspot; anthropogenic stressors; sediment; acidification

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1. Introduction

Climate change is a global phenomenon in which the climate changes more than expected due to human activities, including changes in temperature, precipitation and wind. The increase in temperature due to human activities, such as the large-scale burning of fossil fuels to operate power plants, automobiles and deforestation, has occurred because

urban development requires the release of greenhouse gases, such as carbon dioxide, methane and other gases, into the atmosphere at unprecedented rates, which triggers climate change [1]. Greenhouse gas emissions include the following: carbon dioxide (CO_2) from fossil fuel combustion and industrial processes; CO_2 from forestry and other land use (FOLU); methane (CH_4); nitrous oxide (N_2O); fluorinated gases covered under the Kyoto Protocol (F-gases), which increases annually with a growth rate of 1.3% from 1970 to 2000 [2]. Globally, CO_2 emissions from fossil fuel combustion have increased from 55% of total greenhouse gas emissions in 1970 to 65% in 2010, signifying that it has become the main contributor to climate change [2]. Economic development and population growth continue to be the most important drivers of the increases in CO_2 emissions from fossil fuel combustion [2]. Additionally, the global average surface air temperature increased by 0.85 °C between 1880 and 2012, while the global mean sea level rose by 0.11 m between 1901 and 2010 [2,3]. Climate change also causes ocean acidification, in which increasing atmospheric CO_2 levels lead to increases in the partial pressure of CO_2 (pCO_2), which decreases pH and carbonate concentrations [4]. Although climate change is the most widely occurring threat to coastal ecosystems, excessive nutrients, heavy metals and other forms of land-derived pollutants also cause contamination in coastal areas.

Coastal area refers to land that is next to a sea, where the boundary of the land meets the water. Coastal areas contain a variety of marine and terrestrial ecosystems, including mangroves, salt marshes, coral reefs and beaches [5]. Coastal areas also include areas that are transitional regions between land and oceans, which provide critical ecosystem services to human societies, such as biodiversity maintenance, fishery nurseries, climate regulation, carbon sequestration and coastal flood and storm protection [6,7]. These areas are also where major human activities are carried out, such as agriculture, aquaculture, mining, fossil fuel burning and sewage discharge; therefore, they have become some of the world's most intensely populated regions [8–10]. Thus, coastal areas are significantly threatened by climate change and the other impacts of human activities.

Heavy metals are a group of elements that are found in the Earth's crust and can be used in a variety of industrial, domestic and agricultural processes [11]. Due to the massive increase in these activities, the production and usage of heavy metals are also increasing [11]. Heavy metals, such as mercury, arsenic, cadmium, lead, zinc, copper, etc., are often analyzed to examine pollution conditions in coastal areas [7,11]. As mentioned previously, climate change leads to ocean acidification, and heavy metal contamination can exacerbate acidification in coastal waters, as heavy metals decrease the rate of photosynthesis and the efficiency of CO_2 that is available for absorption by seawater [4]. Ocean acidification also causes reductions in OH^- and $CO_3{}^{2-}$, which is expected to change the speciation of heavy metal ions in seawater into a speciation that is more toxic to biota [4]. For example, copper, cadmium and lead are toxic to marine environments and small increases in the amounts of these elements often lead to toxic effects on organisms that are unaccustomed to these changes [12]. Thus, the impacts of climate change on heavy metal concentrations can be seen in coastal areas. More studies are needed to analyze the current situation of the impacts of climate-change-related issues on heavy metal concentrations in coastal areas. In this paper, we provide a scientometrics analysis of the interactions between climate change and heavy metal concentrations in coastal regions around the world.

Briefly, scientometrics refers to the analysis of the available scientific literature using various visualizations and comprehensive text. Scientometrics is a quantitative analysis of the available literature, with a focus on study patterns, using systematic, continuous and comprehensive methods [13]. These methods help us to quantify the impacts of academia and publications in terms of the published literature, the types of publication sources (e.g., journals), institutional hot spots and the countries that are involved in the selected thematic issues or subject areas. Data for scientometric assessments are available from Web of Science, Scopus, Google Scholar, Microsoft Academic, PubMed and Dimensions. CiteSpace, BiblioMaps and VOSviewer are a few of the tools (i.e., software) that can be used to analyze text-mining activities [13,14]. Nodes, centrality, citation bursts, cluster analysis, modularity

and silhouette scores are some of the key terms used in such software. Essentially, a node is a structure from which "leaves" and "buds" emerge, as well as "branches." Nodes in scientometrics usually refer to the connections between various elements of the analysis, such as the authors, countries or available references [15]. The nodes in most scientometrics analysis software are critical for the basic foundations of the chosen research field [16]. In most cases, centrality refers to "turning points" in the selected issue, which are usually represented by different colors based on the software used and the significance of the nodes in the literature. Modularity and silhouette scores are linked to each other, with the latter being referred to as indicators of the overall structure of the research [15].

The present study aimed to identify interactions between climate change and heavy metal concentrations in coastal areas using a visualized graph of scientometrics analysis. Specifically, we identified the current literature trends in terms of the total number of publications, main contributors (as well as the most influential author), affiliations, journals and top countries within the field. Additionally, document cluster and keyword analyses were also conducted using CiteSpace. Heavy metal contamination, ecological quality status and ocean acidification are among the most influential keywords in this field. We concluded that along with field and climate change issues, heavy metals are becoming a popular topic within research associated with climate change. Our results could contribute to the further exploration of the nature of collaborative partnerships, which we are confident would be of general interest to institutions, funding agencies and researchers alike.

2. Materials and Methods

The metadata collected in this research were based on the online version of the Web of Science Core Collection (WOSCC), which was accessed via the Thomson Reuters Web of Science website. We found 7922 articles in the online version of the SCI-Expanded website that were related to the topic of the impacts of climate change on heavy metals in coastal areas. The search activities were based on the literature that was published between 1979 and 2021.

The keywords (i.e., the "Topic" on the WOS) that we searched for were climate change, along with the following terms, synonyms and related keywords: ("climat* chang*") OR ("climat* risk*") OR ("climat* effect*") OR ("climat* variab*") OR ("climat* variat*") OR ("climat* extrem*") OR ("climat* uncertaint*") OR ("climat* hazard*") OR ("climat* disaster*") OR ("climat* shock*") OR ("climat* stressor*") OR ("climat* impact*") OR ("climat* condition*") OR ("global warm*") OR ("global climat*") OR ("global chang*") OR ("seasonal* variat*") OR ("weather* variab*") OR ("extreme* event*") OR ("environment* variab*") OR ("environment* impact*") OR ("environment* chang*") OR ("environment* factor*") OR ("anthropogenic effect*") OR ("temperature ris*") OR ("temperature effect*") OR ("sea level chang*") OR ("sea level ris*") OR ("el-nino") OR ("la$nina") OR (drought*) OR (precipit*) OR (rainfall*) OR ("carbon dioxide") OR ("greenhouse gas") OR ("greenhouse effect*") OR ("air temperat*") OR ("atmospheric temperat*") OR ("sea surface* temperat*") OR (runoff). The heavy metal-related search terms were as follows: ("heavy metal*") OR ("toxic element*") OR ("element* contaminant") OR ("element" pollution") OR (element* residue*") OR ("chemical pollutant*") OR ("trace element*") OR ("trace metal*") OR ("inorganic element*") OR ("inorganic metal*) OR ("organic element*") OR ("organic metal*"). These keywords were used to compile a bibliography of all articles related to the impacts of climate change on heavy metal concentrations. Additionally, the keywords related to coastal areas were as follows: ("coast*") OR ("coast* area*") OR (coastal zones, estuary, wetland, coastline, shore, intertidal, littoral, lagoon, mangrove, mudflats, seagrass beds, brackish water, marine aquatic).

The data that were downloaded from the WOSCC were then exported into a text file (.txt), with the full records and cited references presented as in the record content selection. The data were then converted into a few different text files and incorporated into the subsequent analysis. For our scientometrics analysis of the co-citation data, we used CiteSpace software. The basic version of the software was developed by Prof. Dr. Chaomei Chen,

a researcher at the College of Computing and Informatics, Drexel University, USA, and was freely available from the CiteSpace website (https://citespace.podia.com/download) (accessed on 3 October 2022). The 5.8.R4 version was applied using the integrated installers in msi/dmg form, without Java separately installed. There are two types of data presented in this study: descriptive and co-cited data. For the co-cited data, we conducted an analysis of co-citation authors, countries, formats (i.e., articles), institutions and journals and identified the related clusters and keywords. We also used CiteSpace to determine the variable qualities of the selected articles using degree (i.e., the total number of citations from author to another), centrality and citation bursts. In the analysis graphs shown in the results, we used network analysis to assess the relationship (based on citation) among key documents in climate change, heavy metal and coastal areas. Network analysis analyzes the relationship pattern of actor (document, author, journal, etc.) inside the network. A network is a string of nodes (a document, author, affiliation and country of published article) that are intercorrelated with one another via ties (lines that link two or more nodes with each other, where the link represents the citation that an article gives or obtains from other articles) [17–19].

3. Results and Discussion

3.1. Demographics of the Published Articles

3.1.1. Publication Trends

Figure 1 indicates the total number of documents related to the impacts of climate change on heavy metal contamination in coastal areas that were published between 1979 and 2021, according to the WOSCC database. The total number of publications was 7922, with the number of publications increasing over the years. Publications on this topic first emerged in 1979 (with only one article) but remained scarce until 1990 (in the range of 1–7 articles). Due to the noticeable increase in awareness of the impacts of climate change on heavy metal contamination in coastal areas in the early 1990s, the number of publications started to increase from 1991 (55 articles) and continued to steadily increase over the years until recently. From 1998 to 2006, the number of publications averaged 136 articles per year, while from 2007 to 2009, it averaged 236 articles per year. From 2010 to 2019, the number of publications increased steadily, ranging from 305 to 564 articles per year. In 2020, the number of published articles was at its highest (701 articles), but the number reduced in 2021 (510 articles).

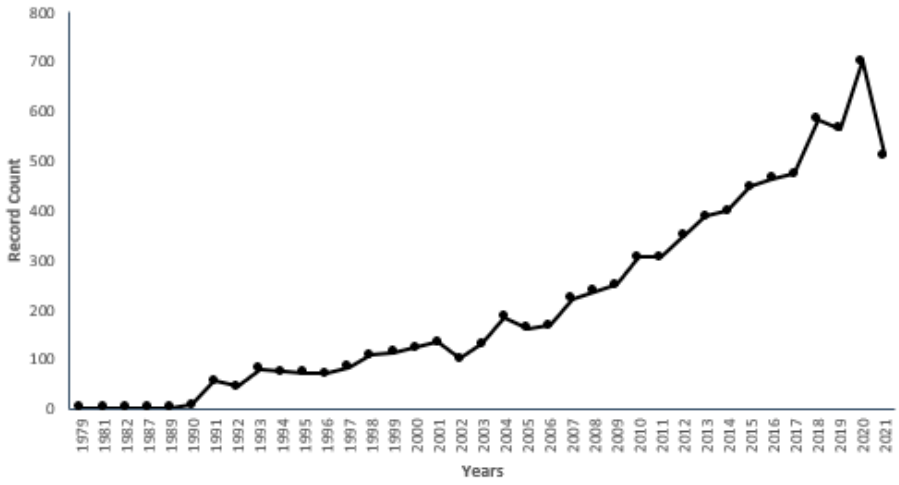

Figure 1. The annual number of publications related to the impacts of climate change on heavy metal contamination in coastal areas, based on the Web of Science Core Collection database (1979–2021).

According to the publication trends between 1979 and 2021, climate change significantly impacted heavy metal concentrations, mostly in coastal areas. Research on heavy metals has increased due to the fact that climate change increases the toxicity of sea water,

which could in turn impact human activities. The number of publications related to the impacts of climate change on heavy metal concentrations in coastal areas has gradually increased over the years since 1979, but drastically dropped in 2021, most probably due to the COVID-19 pandemic, during which some research was put on hold between 2020 and 2021. Additionally, as the WOSCC database was generated and is lagging behind a few months with at least final complete data will be available in early quartile of 2022 compared with the primary journal. Wolowiec et al. (2022) stated that during the COVID-19 pandemic, studies on climate change and environmental pollution were still being conducted but in the direction of the impacts of COVID-19 on environmental pollution.

3.1.2. Top 10 Contributors (Authors, Affiliations, Journals and Countries)

The top 10 authors of studies on the impacts of climate change on heavy metal contamination in coastal areas are shown in Figure 2a. Out of the total of 7922 related studies, the top 10 authors published a total of 260 publications, ranging between 20 and 41 articles each. The top three authors were as follows: Jörg Rinklebe from Bergische Universität Wuppertal, Germany, who is internationally recognized for his research on the biogeochemistry of trace elements in soils and groundwater management, with a total of 41 publications in the WOSCC database [20]; Jing Zhang from the Ocean University of China, China, whose main research focuses on the interface chemistry of oceans, dissolved organic carbon, colored dissolved organic matter and marine environmental impact assessments, with 32 publications; and Carlos Vale from the National Institute of Biological Resources, Portugal, whose research focuses on sediments, trace elements and environmental pollution, with 30 publications in the WOSCC database [21]. The rest of the authors in the top-10 list were as follows: Jörg Schäfer and Gérard Blanc from Université Bordeaux 1, France, with 26 and 25 research articles, respectively; Yang Liu from Tsinghua University, China, and Yi Qiang Zhang from the University of Montana, United States, with 22 publications; Isabel Cacador and Mario Caetano from the Universidade de Lisboa, Portugal, with 21 publications; and Edward D. Burton from Southern Cross University, Australia, with 20 publications.

Figure 2b shows the top 10 affiliations involved in studies on the impacts of climate change on heavy metal contamination in coastal areas. The French National Center for Scientific Research (also known as the Centre National de la Recherche Scientifique, CNRS) was the affiliation with the highest number of publications, with 461 articles. The CNRS is a publicly funded institution that covers all scientific disciplines. It has international joint units and offices around the world and it ranked second in the world in 2019, according to the Scopus SCImago Institutions Rankings. The Chinese Academy of Sciences, China was the second largest contributor, with 303 publications. It also has many branches in many cities but in this analysis, all articles were pooled under one heading. The Institut de Recherche Pour le Development (IRD), France, is another French public research institute that operates under the joint authority of the French Ministry for Higher Education and the French Ministry for Europe and Foreign Affairs [22]. The IRD was the third largest contributor, with 204 publications out of the 7922 related publications that have been published since 1979.

Meanwhile, Figure 2c shows the top 10 journals that published articles related to the impacts of climate change on heavy metal contamination in coastal areas. The Science of the Total Environment, Elsevier, was the top journal publishing studies about the impacts of climate change on heavy metal contamination in coastal areas, with 360 publications in the Web of Science Core Collection database. The Marine Pollution Bulletin was the second largest contributor, with 255 related articles, followed by the Estuarine Coastal and Shelf Science, with 176 articles. Both the Environmental Pollution and the Environmental Science and Pollution Research journals published 130 articles, while the Chemosphere and the Paleogeography, Paleoclimatology, Paleoecology journals published 114 articles. All of these journals cover studies related to the impacts of climate change on heavy metal contamination in coastal areas.

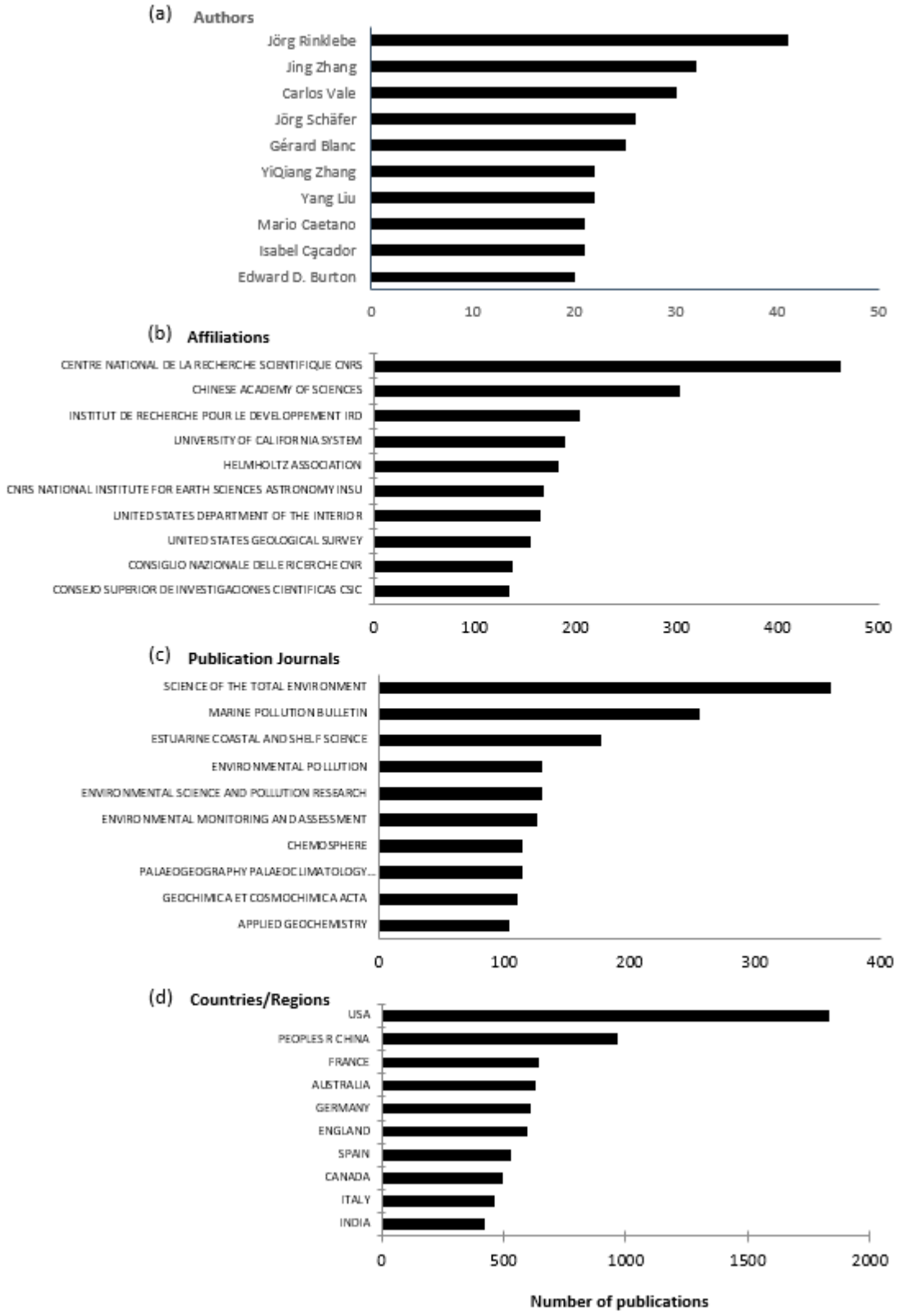

Figure 2. The top 10 contributors of studies related to the impacts of climate change on heavy metal contamination in coastal areas, based on the Web of Science Core Collection database (1979–2021): (**a**) authors; (**b**) affiliations; (**c**) publication journals; (**d**) countries.

The top 10 countries that were involved in studies on the impacts of climate change on heavy metal contamination in coastal areas were the USA, the People's of Republic

China, France, Australia, Germany, England, Spain, Canada, Italy and India (Figure 2d). From 1979 until recently, the USA was the top country in the world for publishing studies on the theme of climate change and heavy metals, with a total of 1832 publications, followed by the People's of Republic China, with 961 publications. Meanwhile France, Australia and Germany published about 609–641 articles. England and Spain contributed 594 and 526 publications, respectively, while Canada, Italy and India contributed over 416–494 publications. Although most of the top authors and institutions were not from the USA, the USA remained the top contributor in selected study areas. The main publications on climate change issues related with heavy metals according to the top two countries were mercury and lead studies (the USA and the People's Republic of China [7], sea level rise (the USA [23]) and cadmium studies (the People's Republic of China [7]).

3.2. Scientometrics Analysis

According to our scientometrics analysis, the top three most cited authors with the highest centrality were S. R. Taylor (0.18), W. Stumm (0.10) and E. D. Goldberg (0.10) (Figure 3). S. R. Taylor is a geochemist and planetary scientist who has worked on a wide variety of topics within trace element geochemistry, including the composition and evolution of the moon, the continental crust, tektites, impact glasses and island arc rocks [24]. He has 200 publications listed in the WOSCC database, with 22,073 citations in 17,890 documents [25]. Taylor [24] also stated that he has published 10 books and 240 papers in scientific journals. W. Stumm is also a geochemist and he has published 202 documents, with 15,905 citations in 11,760 documents in the WOSCC database. His most citated publication was published 1970, with the title "Acidic Mine Drainage: The Rate-Determining Step", which had 1248 citations recorded in the WOSCC database. This article stated that the rate-determining step in the oxidation of iron pyrite and the formation of acidity in streams is associated with coal and copper mines [26]. E. D. Goldberg is a marine chemist who is known for his studies on pollution in the oceans, including trace elements and heavy metals. He has 250 publications recorded in the WOSCC database, with 5340 citations in 4494 articles, excluding self-citation [27]. The top three authors mainly published articles on the impacts of trace elements or heavy metals on marine and/or sediment habitats rather than articles that were directly related to climate change.

Additionally, the publications that referenced studies related to the impacts of climate change on heavy metal contamination in coastal areas are shown in Figure 4. Audry et al. [28] studied Cd, Cu, Co Ni, U, Mo and V diagenesis in a macrotidal estuary, which appeared to be the most cited article in the related studies, with a centrality of 0.20. Adelson et al. [29] studied Mo in coastal sediments, which appeared to be the second most cited article in the related studies, with a centrality of 0.12. The study of the composition of the continental crust by Wedepohl [30] revealed the heavy metal/elemental composition or levels in the Earth's crust, and had a centrality of 0.10. Meanwhile, the publication of Simpson et al. [31] regarding the effects of short-term resuspension events on the oxidation of Cd, Pb and Zn sulfide estuarine sediment was also highly cited in the related studies, with a centrality of 0.10.

Although these countries had the highest numbers of citations in 1979–2021, the two most cited affiliations were the Chinese Academy of Sciences, China and the US Geological Survey (USGS), USA (Figure 5). The countries with the highest numbers of citations were the USA in 1981, France in 2006 and Canada in 1991 (Figure 6). The USGS is a water, earth, biological science and civilian-mapping agency that collects, monitors, analyzes and provides a scientific understanding of natural resource conditions, issues and problems in the region. The US Geological Survey published 475 articles on topics related to climate change, according to the records in the WOSCC database. Meanwhile, as mentioned above, the Chinese Academy of Sciences has many branches in many cities but was pooled under one heading in this study, so the analysis results could be different if the different branches were analyzed separately.

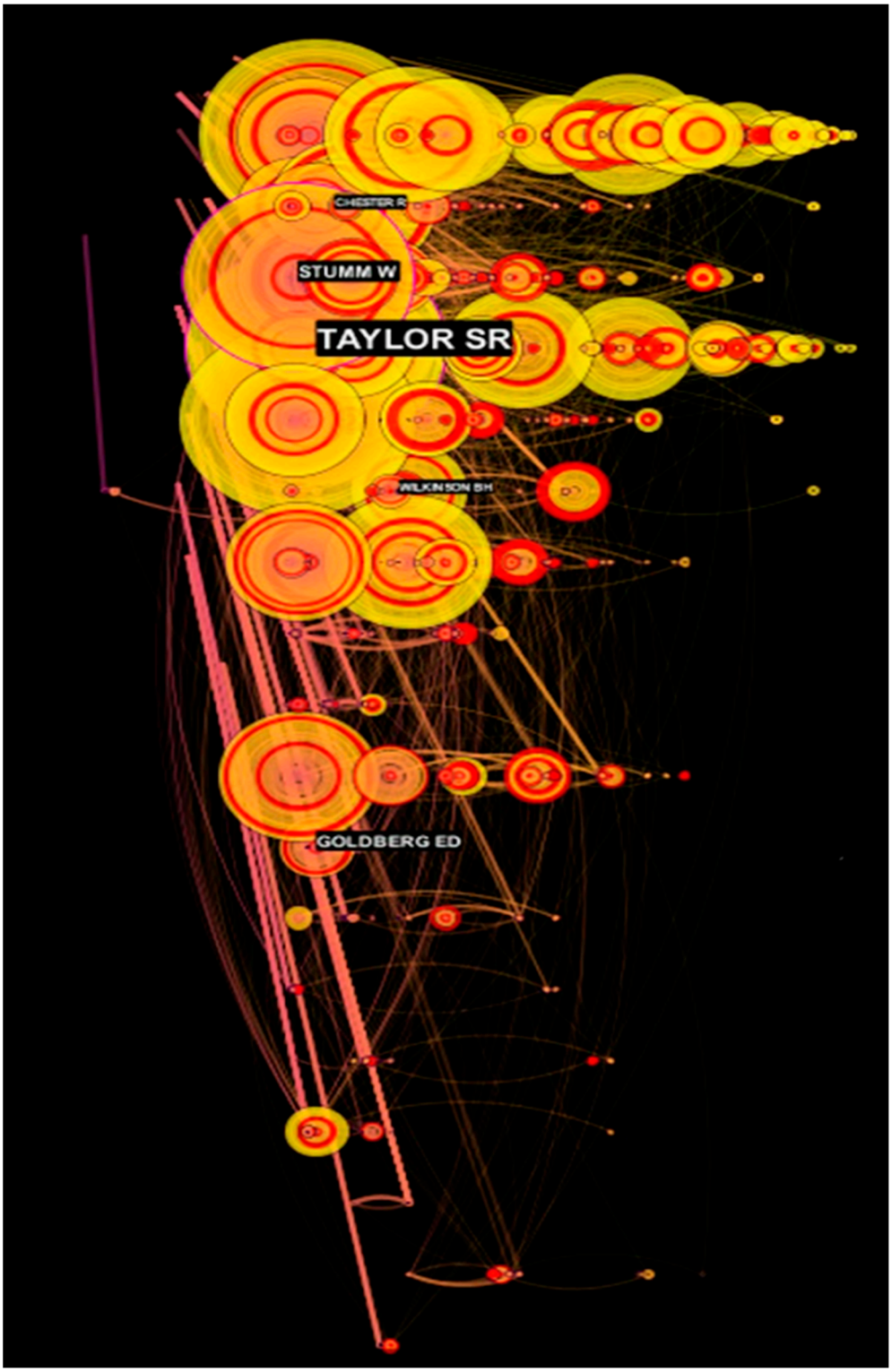

Figure 3. The most cited authors in studies related to the impacts of climate change on heavy metal contamination in coastal areas, based on the Web of Science Core Collection database (1979–2021).

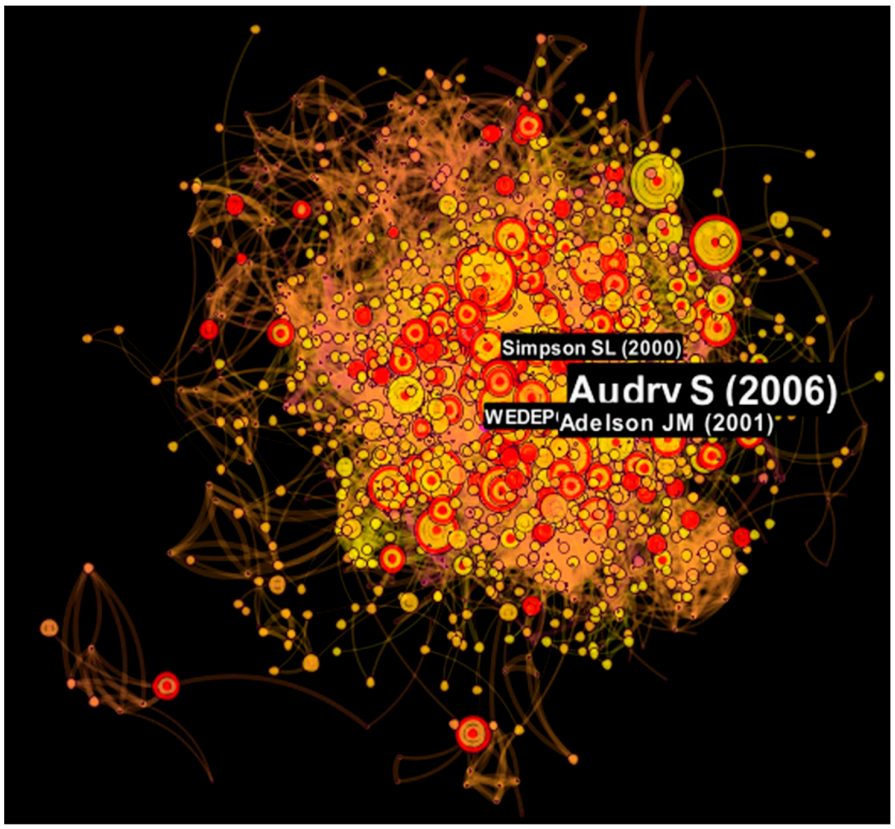

Figure 4. The top article citations in studies related to the impacts of climate change on heavy metal contamination in coastal areas, based on the Web of Science Core Collection database (1979–2021).

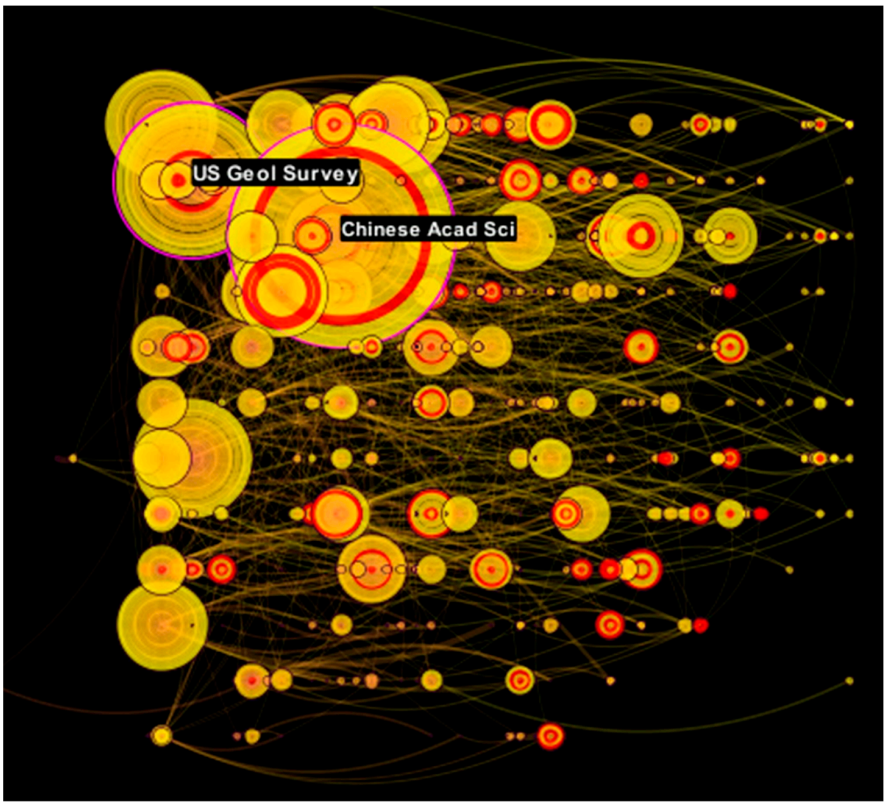

Figure 5. The top cited affiliations in studies related to the impacts of climate change on heavy metal contamination in coastal areas, based on the Web of Science Core Collection database (1979–2021).

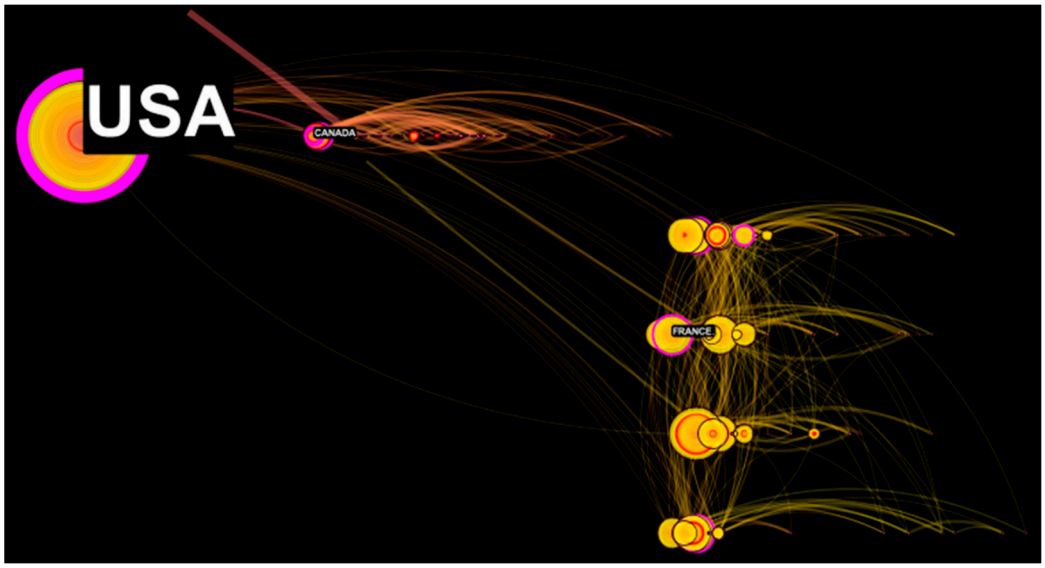

Figure 6. The most cited countries in studies related to the impacts of climate change on heavy metal contamination in coastal areas, based on the Web of Science Core Collection database (1979–2021).

The top 10 most cited journals are shown in Figure 7. Ecology, Geochimica et Cosmochimica Acta and Science of the Total Environment were the top three most cited journals in studies related to climate change and heavy metals in coastal areas, with centrality scores of 0.18, 0.16 and 0.15, respectively. Ecology is a journal that reports research on all aspects of ecology, while Geochimica et Cosmochimica Acta publishes research on the subjects of terrestrial geochemistry, meteoritics and planetary geochemistry. Science of the Total Environment publishes research on the environment as a total, including the atmosphere, lithosphere, hydrosphere, biosphere and anthroposphere. The articles by Audry et al. [28], Adelson et al. [29] and Wedepohl [30] (which were the three most cited articles) were all published in Geochimica et Cosmochimica Acta, which is why it was one of the most cited journals.

Among the most cited journals, there were 33 co-citation clusters, from which we identified the 13 largest clusters (Figure 8). Out of those 13 clusters, the most important cluster was heavy metal contamination (Figure 8), followed by the ecological quality status, ocean acidification, floodplain soil, Port Jackson, saltwater intrusion, the Gironde estuary, ecological status, aquatic plants, the Iberian pyrite belt, organic carbon budgets, eastern Siberia and atmospheric inputs (Figure 8). Although heavy metal contamination was the most cited topic, the majority of the studies in this cluster were published around 2007–2017. Ecological status was the eighth most cited topic, the majority of the citations occurred around 2017–2020, indicating that this was a recent research topic. Moreover, ecological quality status was also a popular topic around 2004–2020, although this cluster reached its peak number of citations around 2013–2016. These top clusters, i.e., heavy metal contamination, ecological quality status, ocean acidification, etc., were also the main topics studied by the top authors and the main topics of the most cited articles, as mentioned previously. There were few studies (almost none) on aquatic plants, the Iberian pyrite belt, organic carbon budgets and atmospheric inputs after 2008.

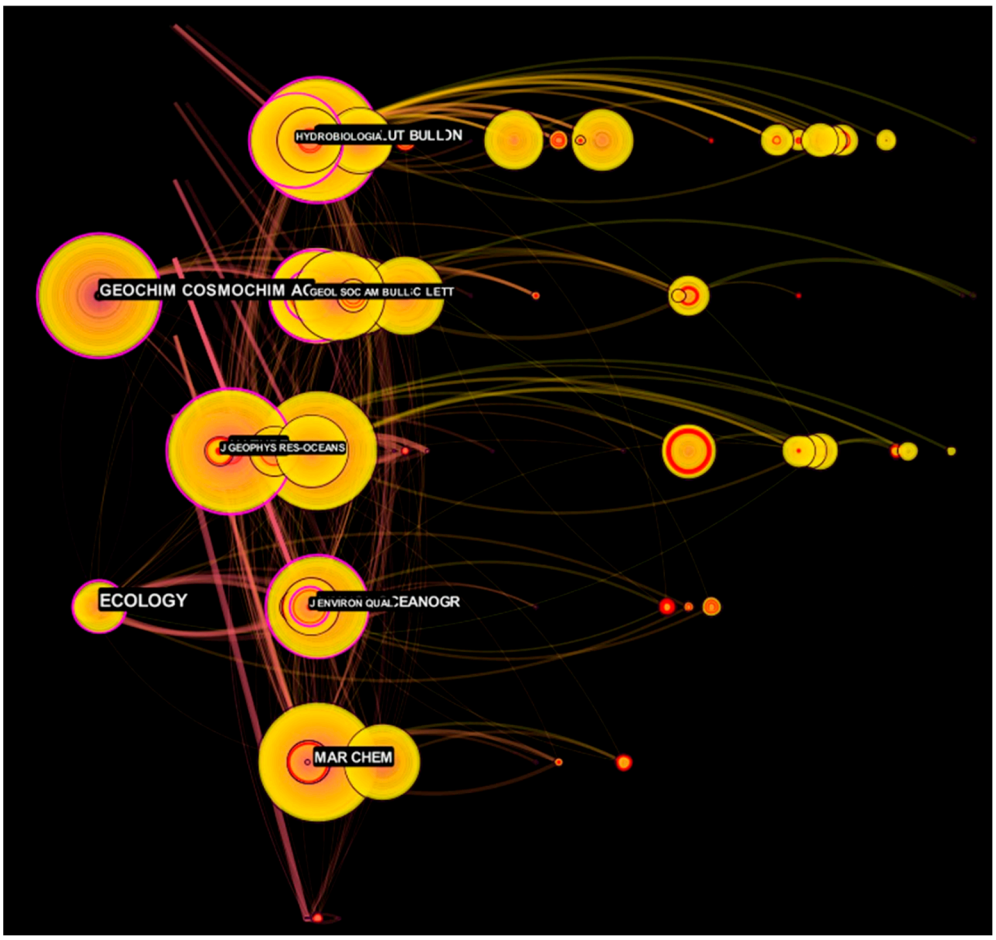

Figure 7. The most cited journals in studies related to the impacts of climate change on heavy metal contamination in coastal areas, based on the Web of Science Core Collection database (1979–2021).

Figure 9 shows the distributions of the major keywords in studies related to the impacts of climate change on heavy metal contamination in coastal areas from 1979 to 2022. Though our analysis was only from 1979 to 2021, some articles were published in 2022 and their results are also shown. The major keywords included water, sea, marine, sediment, metal, element, coastal, community, ocean, pyrite, isotope, surface, north, sulfur, carbon and ocean. The characteristics of the top 10 keywords from 1979–2022 are shown in Table 1. They were climate change, surface change, surface sediment, lead, copper, management, cadmium, diversity, coastal, ecosystem and ocean acidification. Among these keywords, climate change, surface sediment and management were the three most frequently used keywords over recent years (2014–2022) in studies related to the impacts of climate change on heavy metals in coastal areas. The most frequently used keywords in studies on this topic in 2015–2020 were diversity, coastal, ecosystem and ocean acidification, while the most frequently used keywords in 1993–2010 were lead, copper and cadmium.

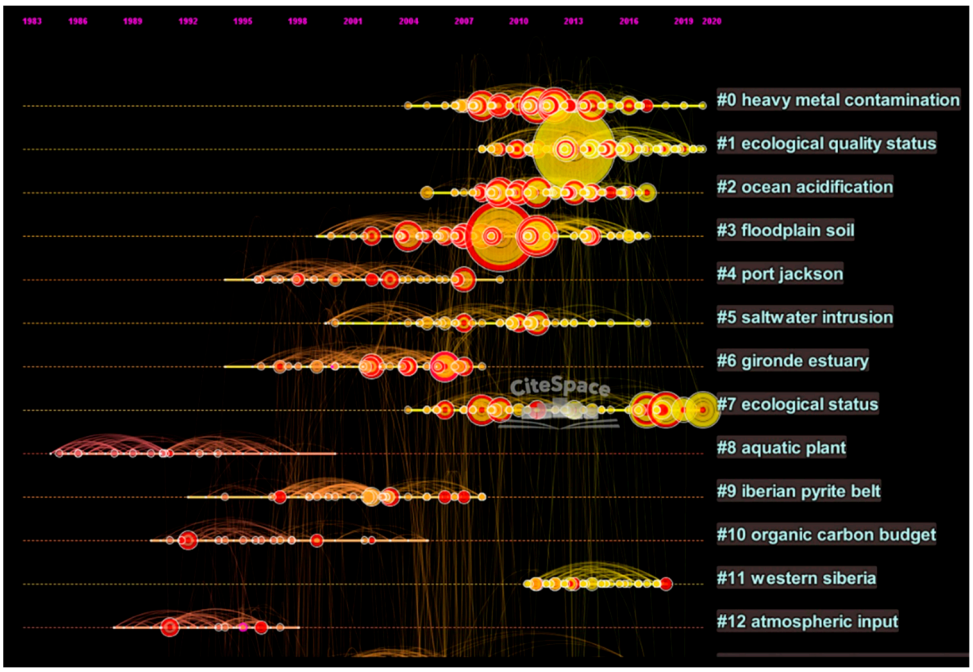

Figure 8. The most cited clusters in studies related to the impacts of climate change on heavy metal contamination in coastal areas, based on the Web of Science Core Collection database (1979–2021).

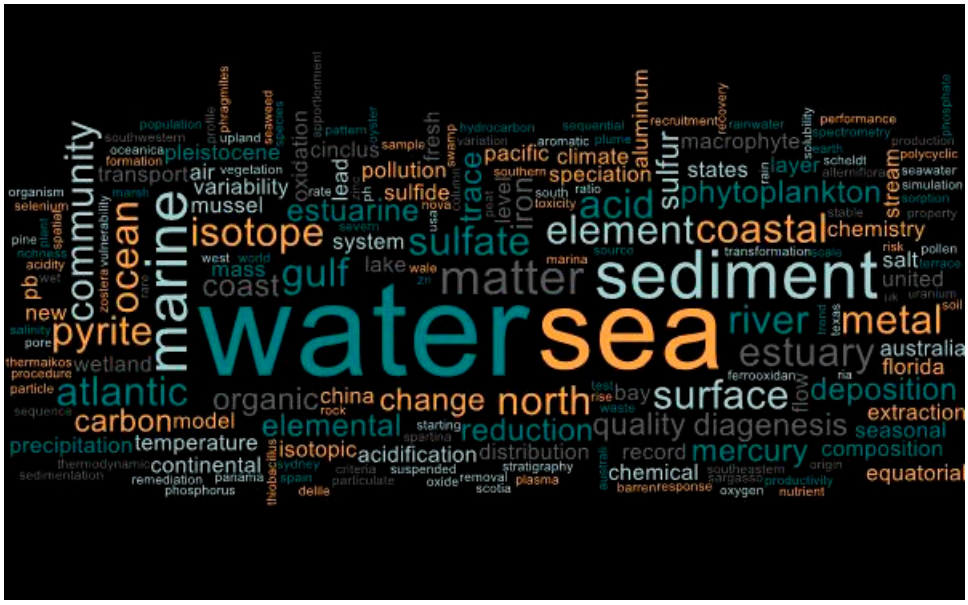

Figure 9. The most cited keywords in publications related to the impacts of climate change on heavy metal contamination in coastal areas, based on the Web of Science Core Collection database (1979–2021).

Table 1. The top citation bursts of the selected keywords in publications about the impacts of climate change on heavy metal contamination in coastal areas, based on the Web of Science Core Collection database (1979–2021).

Keywords	Year	Strength	Beginning	End	1979–2022
Climate Change	1979	32.77	2017	2022	*
Surface Sediment	1979	28.7	2014	2022	
Lead	1979	20.54	1993	2010	
Copper	1979	19.44	1995	2006	
Management	1979	19.08	2016	2022	
Cadmium	1979	17.82	1993	2009	
Diversity	1979	16.59	2017	2019	
Coastal	1979	15.72	2015	2019	
Ecosystem	1979	15.7	2017	2019	
Ocean Acidification	1979	15.66	2016	2020	

Note: * The blue dot line indicated the time frame of analysis, which is from 1979 until 2022. The red dot line indicates the peak of the strength on the keywords used from 1979 until 2022, which are described in columns "Beginning" and "End".

3.3. Characteristics of Publication Outputs

Most studies on heavy metals in coastal areas have been involved with sediment studies due to the outbreak of the Itai-itai disease (which is caused by cadmium) and Minamata disease (which is caused by mercury) in Japan in the 1950s [32]. The majority of related studies have been connected to the anthropogenic sources of heavy metals that are discharged into marine environments, such as acid mines, ores, plant manufacturing, steel industry, antifouling paints, steel industry, industrial/domestic sewage, oil spills, metal refineries/production, coal burning, etc. [6,7,33]. The bioaccumulation and biomagnification of marine organisms through the food chain has caused concerns regarding toxicity. The persistence and non-degradability of this toxicity have also become major topics in studies on heavy metals in coastal areas. The main heavy metals in coastal sediment are zinc, copper, chromium, lead, nickel, arsenic, mercury and cadmium, which have also been noted in the published literature [7,33]. Thus, the citation bursts of keywords related to lead, copper and cadmium were the largest between 1993 and 2010.

Since 2014, studies on climate change related to heavy metals in coastal areas have started to receive increased attention. The IPCC was established by the United Nations in 1988 for the comprehensive review and recommendation of the scientific, social and economic impacts of climate change, as well as potential response strategies [34]. Since then, studies on climate change in coastal areas have been related to storm-induced coastal floods, ocean acidification, sea level rise and anthropogenic stresses, such as eutrophication, hypoxia and pollution [33]. Insights into the pollution related to climate change in coastal areas include atmospheric CO_2 resulting from ocean acidification, eutrophication caused by acidification and increased precipitation and runoff that results in more nutrients and pollutants caused by biogeochemical processes [33]. The bioavailability and activity of contaminants are promoted by climate change and increase the potential risks of toxins to coastal organisms.

In recent years, although heavy metal contamination and ecological quality status have still been the most frequently cited topics in studies related to the impacts of climate change on heavy metals in coastal areas, ecological status seems to have become the main cluster being studied that is strongly related to microbial communities and ontogenetic migration. According to the citation bursts of the related keywords, the issues of climate change, surface sediment and management have also become popular topics of research. Many recent studies have focused on how climate change has increased flooding frequency and heavy metal pollution, in turn causing global land degradation [35]. These studies have not only involved redox activities but have also examined heavy metal ontogeny migration in microbial communities [35–39]. Additionally, many recent studies have also investigated the impacts of human and environmental management on climate change and heavy metal contamination in coastal areas [37,40]. Thus, according to the most cited clusters and keywords, the recent study trends have focused on the impacts of climate change on heavy metal or elemental ontogeny migration in microbial communities and abiotic activity in the

surface sediment around coastal areas. Heavy metals affect various factors of biotic and abiotic such as dissolved organic matter transformation and transport, which contributed to their roles as toxicants and nutrients for microorganisms [41]. Microorganism dynamics are particularly good indicators of climate change in the environment largely because of the tight coupling between microorganisms dynamics and environmental changes [42].

3.4. Factors and Management

Heavy metal contaminant pathways that will be altered by climate change included volatilization, adsorption, hydrolysis, biodegradation, photodegradation, photo-enhanced toxicity, uptake and metabolism [43–45]. The impact of climate change on heavy metal contamination regarding marine ecosystems has been discussed for the past three decades [7], such as temperature dependence of arsenic release from flooded contaminated soils [46,47]. Studies also showed that certain trace elements/heavy metals, such as copper, cadmium and zinc, play crucial biological roles in the ecosystem and their supply controls the structure and possibly productivity of marine ecosystems [7,12], which is, however, due to the increasing CO_2 in the marine systems that may cause a change in metal speciation due to acidification [44,47,48]. In addition to these, mercury cycle has been overloaded by human activities, causing fluxes and burdens of mercury in the air and surface water rises due to the increase in temperature around coastal areas [43,47]. UNEP [49] suggested that different trends in the emissions of mercury in Asia, North America and Europe could change the bioavailability of mercury or ecosystem functioning due to climate change. Figure 10 showed the relationship and pathways of climate change and heavy metals at coastal areas caused by various anthropogenic stressors.

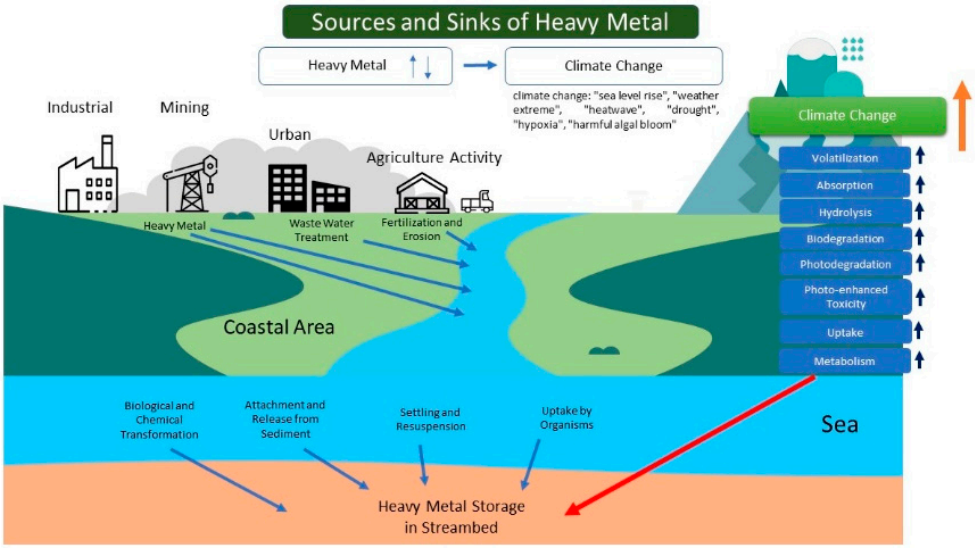

Figure 10. Anthropogenic stressors, such as industrialization, mining, urbanization and agriculture farming, that caused climate change and heavy metal contaminant pathways, while climate change also altered the heavy metals cycle at the coastal areas.

In addition to these, there are international organizations that in particular monitor and manage the heavy metal pollution at coastal areas or the environment, such as UNEP and IPCC. UNEP, which were developed as part of the 2030 Agenda for Sustainable Development: SDG Targets 3.9 and 12.4 hoped to achieve the environmentally sound management of chemicals and all wastes and substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination [50]. The sound management of chemicals and waste could also help to achieve many other SDGs by halting biodiversity loss, clean water and sanitation, facilitating access to clean energy, climate action, ensuring quality education and gender equality [50]. IPCC [34] suggested that biochar, a light-weight black residue that is made out of carbon and ashes,

has the ability to mitigate climate change when it increases, particularly in sandy and acidic soils with low cation exchange capacity, as it increased soil water-holding capacity, nitrogen-use efficiency, biological nitrogen fixation, as well as the absorption of organic pollutants and heavy metals. Pyrolysis, a thermal decomposition process of materials that produce biochar, can reduce organic wastes, including heavy metals [34,42,51]. Although most of the research frameworks and policies are promoted globally, the impact of these works may be limited in developing countries because these are strongly linked to sustainable development, vulnerability and climate risks, limited economic and social and institutional resources [9,34,42,50].

3.5. Strengths and Limitations

To our knowledge, this is one of the first studies to systematically analyze the available research on issues related to the impacts of climate change on heavy metals in coastal environments, especially using a scientometrics analysis. This study provided insights into the relationship between climate change and pollution, especially heavy metal contamination, as well as valuable information that could help academics to identify new possibilities for future collaborations, research directions and institutional cooperation. However, this study also had some limitations. It is noticeable that some of the cited documents were not directly involved with all of the selected issues, i.e., climate change, heavy metals and coastal areas. Some of the cited documents just referred to heavy metals and coastal areas or climate change and coastal areas.

4. Conclusions

This unique overview allowed us to conclude that along with field and climate change issues, heavy metals are becoming a popular topic within research associated with climate change. Collaborative studies among researchers, institutions and countries are vital in encouraging further work and development around the issue of the impacts of climate change on heavy metal concentrations. The studies of climate change over heavy metal concentration at the coastal areas, especially on heavy metal or elemental ontogeny migration in microorganism dynamic, which relates to surface sediments and ecology management, is currently the topic that is looked into the most. However other studies, such as studies on ocean acidification, flood level, seafood security and safety and heavy metals due to climate change, should be continuously monitored.

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