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Article

How does environmental regulation matter? An analysis of the current research hotspots and future direction

Yang Liu[1,2,*], Roshazlizawati Mohd Nor[1], Ma Kalthum Ishak[1], Xuan Li[1,2]

[1] Faculty of Management, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
[2] School of Economics and Management, Ningxia University, Yinchuan 750021, China
*** Corresponding author:** Yang Liu, liuyang@graduate.utm.my

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Abstract: Environmental regulation is globally recognized for its crucial role in mitigating environmental pollution and is vital for achieving the Paris Agreement and the United Nations Sustainable Development Goals. There is a current gap in the comprehensive overview of the significance of environmental regulation research, necessitating high-level insights. This paper aims to bridge this gap through an exhaustive bibliometric review of existing environmental regulation research. Employing bibliometric analysis, this study delineates publication trends, identifies leading journals, countries, institutions, and scholars. Utilizing VOSviewer software, we conducted a frequency and centrality analysis of keywords and visualized keyword co-occurrences. This research highlights current hotspots and central themes in the field, including "innovation", "performance", "economic growth", and "pollution". Further analysis of research trends underscores existing knowledge gaps and potential future research directions. Emerging topics for future investigation in environmental regulation include "financial constraints", "green finance", "green credit", "ESG", "circular economy", "labor market", "political uncertainty", "digital transformation", "exports" and "mediating effects". Additionally, "quasi-natural experiments" and "machine learning" have emerged as cutting-edge research methodologies in this domain. The focus of research is shifting from analyzing the impact of environmental regulation on "innovation" to "green innovation" and from "emissions" to "carbon emissions". This study provides a comprehensive and structured understanding, thereby guiding subsequent research in this field.

Keywords: environmental regulation; environmental policy; research hotspots; future direction; bibliometric; VOSviewer

1. Introduction

Environmental regulation plays a crucial role in shaping global sustainable development practices and is essential for achieving the Paris Agreement and the United Nations Sustainable Development Goals. Environmental regulation helps balance the complex interactions between economic growth and environmental management (Aziman et al., 2023), influencing key areas such as exports, trade, foreign direct investment, research and development, innovation, corporate sustainability, and ecological conservation (Hu and Liu, 2019; Lăzăroiu et al., 2020; Mahajan and Majumdar, 2023c, 2023b). As the global community faces escalating challenges like climate change, resource depletion, and environmental degradation, understanding the impacts and effectiveness of environmental regulations has become imperative.

Despite the extensive literature on environmental regulation, there remains a gap in providing a comprehensive overview of its significance. The exponential growth of

publications has made it challenging to identify clear hotspots, trends, influential works, and future directions. This complexity impedes policymakers, researchers, and practitioners from effectively utilizing these insights. In this context, bibliometric analysis emerges as a crucial method. It offers a quantitative way to assess and synthesize large volumes of research data, particularly revealing the accumulated knowledge structure and connections within specific fields or disciplines (Qin et al., 2022). By relying on computer programs, this approach overcomes the subjective biases of traditional literature reviews (Bretas and Alon, 2021). It maps the landscape of environmental regulation research, identifies seminal works, and traces the evolution of themes over time. Past bibliometric studies often focused on the impact of environmental regulations in specific areas, such as the labor market (Zhao and Zhang, 2023), green innovation (Li et al., 2022), and foreign direct investment (Santos and Forte, 2021), yet lacked a broader perspective to thoroughly understand the multifaceted impacts and the evolution of hot topics in environmental regulation on economic, social, and environmental aspects.

Therefore, this study aims to provide a comprehensive overview of the field of environmental regulation using bibliometric analysis. The specific objectives are: (1) to identify the main countries, institutions, and authors contributing to this field; (2) to explore various hot topics within environmental regulation research and their interconnections through keyword frequency and co-occurrence analysis; (3) to analyze the distribution and evolution of literature on environmental regulation over the years, to determine the main trends and shifts in research focus. By achieving these goals, this study will clarify the core areas of focus in environmental regulation research, illustrate the global contributions to this field, and highlight emerging trends that could influence future research agendas.

The significance of this research lies in its ability to elucidate the complex body of knowledge surrounding environmental regulation, making it accessible and actionable for stakeholders. The bibliometric method not only provides a macroscopic view of the academic field but also delves into the nuances of research collaborations and thematic developments. The innovative contribution of this study is its comprehensive bibliometric review, which deepens understanding of environmental regulation research and offers insights that can inform policy-making and strategic decisions in environmental management, as well as inspire scholars to identify future research directions.

2. Materials and methods

Bibliometric analysis is a common and precise approach for examining extensive scientific data. This methodology enables the detailed examination and understanding of the hotspots and trends in a particular academic field (Feng et al., 2024). Commonly utilized tools for bibliometric analysis include Bibliometrix, VOSviewer, CiteSpace, and HistCite (Qin et al., 2022). Among these, VOSviewer is particularly noted for its robust data visualization capabilities, efficient data processing, and broad academic recognition. It is highly effective for examining collaborations between countries/regions, keyword co-occurrence networks, and temporal trends (Jin and Chang, 2023). This study employs the VOSviewer software to conduct a visual

bibliometric analysis of 3944 articles in the field of environmental regulation. It offers a comprehensive review, detailing the distribution of publications across years, countries/regions, journals, institutions, and authorship. The analysis spans from 1 January 2010 to 31 December 2023. The time frame for the analysis is set from 1 January 2010 to 31 December 2023. The reason for selecting the start year as 2010 is because of the noticeable increase in the number of publications related to the topic post-2010, as opposed to the slower growth before that year. This study is based on the PRISMA guidelines for data screening, and the process is shown in **Figure 1**.

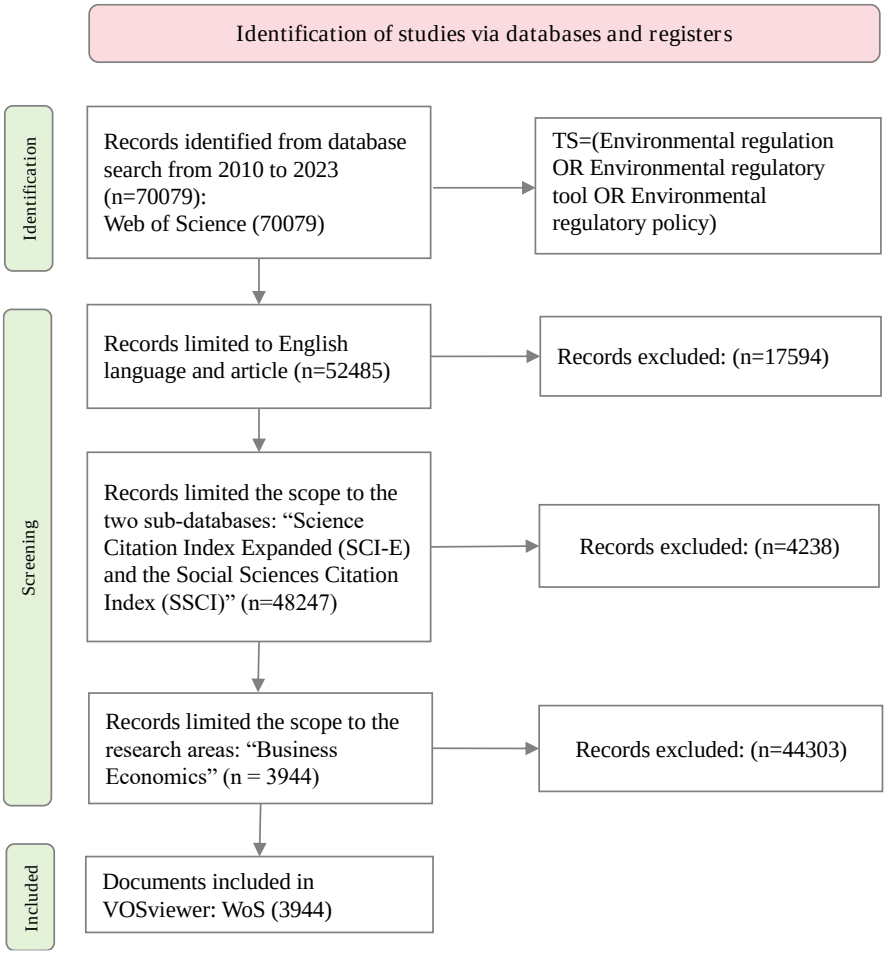

Figure 1. The process of searching the literature.

The sample for this study was derived from the Web of Science (WoS) Core Collection, widely recognized as the most extensive and frequently utilized database for bibliometric analyses (Chen et al., 2023). The initial search was conducted using the following string: "TS = Environmental regulation OR Environmental regulatory tool OR Environmental regulatory policy", spanning from 2010 to 2023. This initial query yielded a total of 70,079 documents. To ensure the manageability and relevance of the study, the first step in the screening process involved language and document type restrictions. Only English-language documents classified as academic articles were retained. This criteria led to the exclusion of 17,594 documents, leaving 52,485 for further consideration. Subsequently, to ensure the quality of the literature, further screening was applied based on inclusion in two sub-databases: the Science Citation

Index Expanded (SCI-E) and the Social Sciences Citation Index (SSCI). This step resulted in the exclusion of an additional 4238 documents not indexed within these databases, reducing the pool to 48,247 documents. In the final phase of screening, the focus was narrowed to the field of business economics to align closely with the thematic thrust of the study. This refinement resulted in the exclusion of 44,303 documents that did not meet the thematic criteria, culminating in a corpus of 3944 documents deemed suitable for the subsequent bibliometric analysis.

3. Results and discussion

3.1. Distributions of the literature

3.1.1. Publication years

Figure 2 shows the distribution of the environmental regulation literature by year of publication from 2010 to 2023, which helps to examine the progress of literature publication. According to **Figure 2**, an upward trend can be easily observed, except for a few specific years. This upward trend became more pronounced after 2016, likely due to the signing of the Paris Agreement, which set clear targets for global environmental governance.

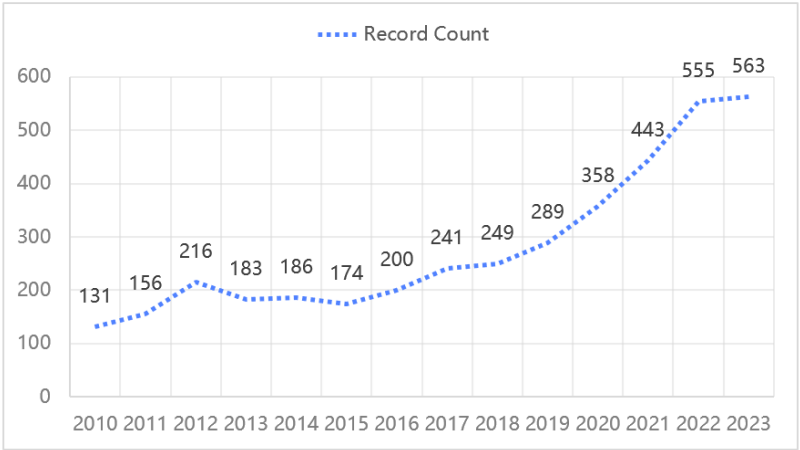

Figure 2. Annual publication output of the environmental regulation.

3.1.2. Productive journals

A total of 507 journals have collectively published 3944 articles on environmental regulation. Remarkably, the top 50 journals contribute to over 60% of these publications. **Table 1** presents the top 25 journals, representing approximately half of the total publications. Notably, these journals predominantly fall within the WoS categories of Economics, Management, and Environmental Sciences, and tend to publish more articles than other journals. The most prolific journal, Energy Policy, has published 330 articles, representing 8.4% of the total. The second most productive journal is Energy Economics, with 207 articles, accounting for 5.2% of the total. Additionally, Business Strategy and the Environment (164; 4.2%), Ecological Economics (154; 3.9%), and the Journal of Environmental Economics and Management (133; 3.4%) are the next three highest-yielding journals.

Table 1. Top 25 productive journals.

Ranking	Source Title	Number of articles	Percentage
1	Energy Policy	330	8.4%
2	Energy Economics	207	5.2%
3	Business Strategy and The Environment	164	4.2%
4	Ecological Economics	154	3.9%
5	Journal of Environmental Economics and Management	133	3.4%
6	Environmental & Resource Economics	116	2.9%
7	Technological Forecasting and Social Change	95	2.4%
8	Corporate Social Responsibility and Environmental Management	63	1.6%
9	Journal of Business Ethics	57	1.4%
10	Applied Economics	56	1.4%
11	Economic Analysis and Policy	55	1.4%
12	Forest Policy and Economics	52	1.3%
13	Resource and Energy Economics	46	1.2%
14	Journal of Regulatory Economics	45	1.1%
15	Sustainability Accounting Management and Policy Journal	41	1.0%
16	Economic Modelling	39	1.0%
17	World Development	39	1.0%
18	Review of Environmental Economics and Policy	35	0.9%
19	European Journal of Operational Research	33	0.8%
20	Economic Research-Ekonomska Istrazivanja	31	0.8%
21	International Environmental Agreements-Politics Law and Economics	30	0.8%
22	Journal of the Association of Environmental and Resource Economists	29	0.7%
23	Transportation Research Part A-Policy and Practice	29	0.7%
24	Environment and Development Economics	28	0.7%
25	Finance Research Letters	27	0.7%
Total number of articles		1934	-

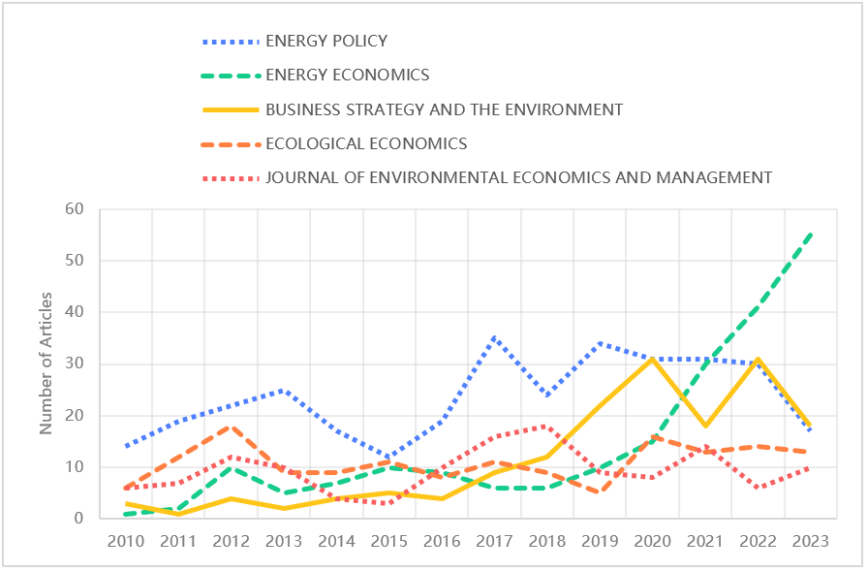

Figure 3. Annual publication output of the top 5 most productive journals.

Figure 3 illustrates the annual publication volume of the top five journals with the highest output. Over the years, Energy Policy and Energy Economics have published a significant number of articles on environmental regulation. The publication volumes of Energy Policy, Energy Economics, and Business Strategy and the Environment overall show an increasing trend. Notably, Energy Economics has demonstrated robust growth in annual publication volume since 2019. Based on time-series predictive analysis, Energy Economics is anticipated to become the most productive journal in this field within a few years. In contrast, the publication trends for Ecological Economics and the Journal of Environmental Economics and Management have been relatively stable.

3.2. Countries and regions

3.2.1. Productive countries and regions

Table 2 presents the top 25 countries/regions with the highest number of publications on environmental regulation. These countries and regions, in other words, have done more research on this issue than others. As the largest carbon emitter, China leads in publication productivity with 1214 documents, accounting for 30.78% of the total. The United States ranks second with 1136 publications, comprising 28.8% of the total, lower than China but significantly higher than other countries and regions. The United Kingdom, Germany, and France follow as the third, fourth, and fifth countries, respectively, with 394 (10%), 238 (6%), and 234 (5.9%) documents. Apart from China, the United States, Australia, and Canada, six of the top ten most productive countries are European countries. It is noteworthy that the same article may include collaborators from multiple countries. Each co-authored article is counted once for each contributing country. Consequently, the total number of articles in the top 25 countries/regions exceeds the initial sample size of 3944 articles.

Table 2. Top 20 productive countries and regions.

Ranking	Countries/Regions	Number of Articles	Percentage
1	China	1214	30.8%
2	USA	1136	28.8%
3	England	394	10.0%
4	Germany	238	6.0%
5	France	234	5.9%
6	Australia	212	5.4%
7	Canada	211	5.4%
8	Italy	202	5.1%
9	Spain	169	4.3%
10	Netherlands	116	2.9%
11	Sweden	92	2.3%
12	Japan	91	2.3%
13	Switzerland	77	2.0%
14	India	74	1.9%
15	South Korea	69	1.7%

Table 2. (*Continued*).

Ranking	Countries/Regions	Number of Articles	Percentage
16	Taiwan	69	1.7%
17	Norway	62	1.6%
18	Belgium	48	1.2%
19	Singapore	46	1.2%
20	New Zealand	45	1.1%
21	Scotland	44	1.1%
22	Denmark	42	1.1%
23	Brazil	40	1.0%
24	Finland	35	0.9%
25	South Africa	33	0.8%
Total number of articles		4993	

Figure 4 displays the annual publication output from 2010 to 2023 of the top 5 countries/regions in terms of productivity. The United States has consistently published a stable and slightly increasing number of articles on environmental regulation each year, maintaining the position of the highest producer until 2019. The United Kingdom, Germany, and France also show modest growth trends. In contrast, China's early output was minimal. However, a significant surge began in 2017, likely due to China's formal accession to the Paris Climate Agreement in September 2016. Subsequently, energy conservation, emission reduction, and energy structure adjustment became focal points in China's environmental protection efforts, making environmental regulation a central topic in both academic and business circles in China. From 2020 onwards, China surpassed the United States to become the most prolific country in this field.

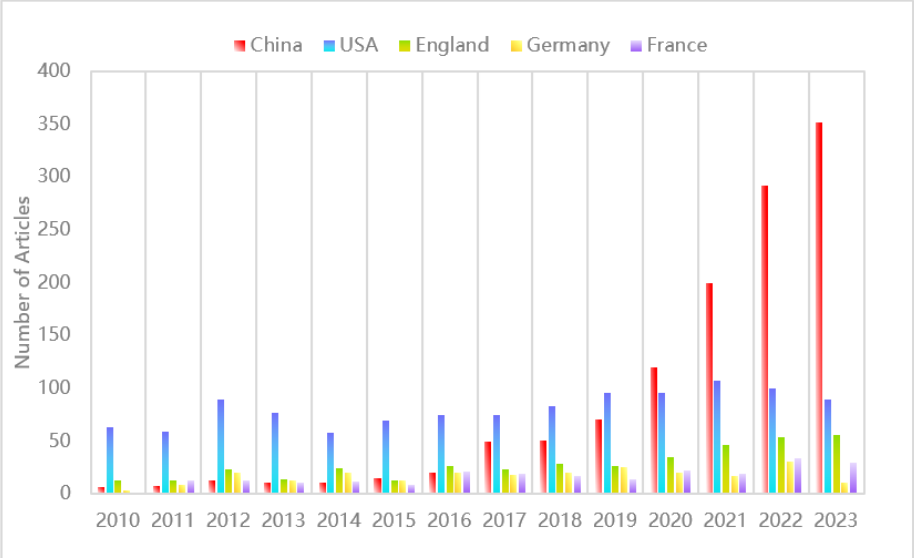

Figure 4. Annual publication output of the top 6 most productive countries and regions.

3.2.2. Cooperation among countries and regions

Figure 5 illustrates the collaboration network among the top 25 countries/regions in terms of publication output. The colors of the labels indicate clustering by continent: red for Asia, green for Europe, blue for the Americas, yellow for Africa, and purple for Oceania. The size of each label reflects the volume of publications from that country/region. The links represent collaborative publications between scholars from two countries/regions at the endpoints of a line, with thicker lines indicating a higher number of joint publications. Among the top 25 countries/regions, China, the United States, and the United Kingdom are positioned centrally in **Figure 5**, indicating extensive academic exchanges with other nations. The United States shows closer collaboration with other countries, with the strongest connection intensity. Interestingly, while the United States and Canada are geographically closer, the United States has the most international co-publications with China. Additionally, China's collaborative publications with the United States, the United Kingdom, and Australia far exceed those with other Asian countries and regions. Among Asian countries and regions, mainland China and Taiwan exhibit the closest cooperation in terms of collaborative publications.

Of the top 25 countries/regions, 13 are European, accounting for over half, and 6 are Asian. Among these, only one African country (South Africa) and one South American country (Brazil) are included, both of which occupy more peripheral positions in the collaboration network. This may be related to the lower levels of technological advancement in African and South American countries.

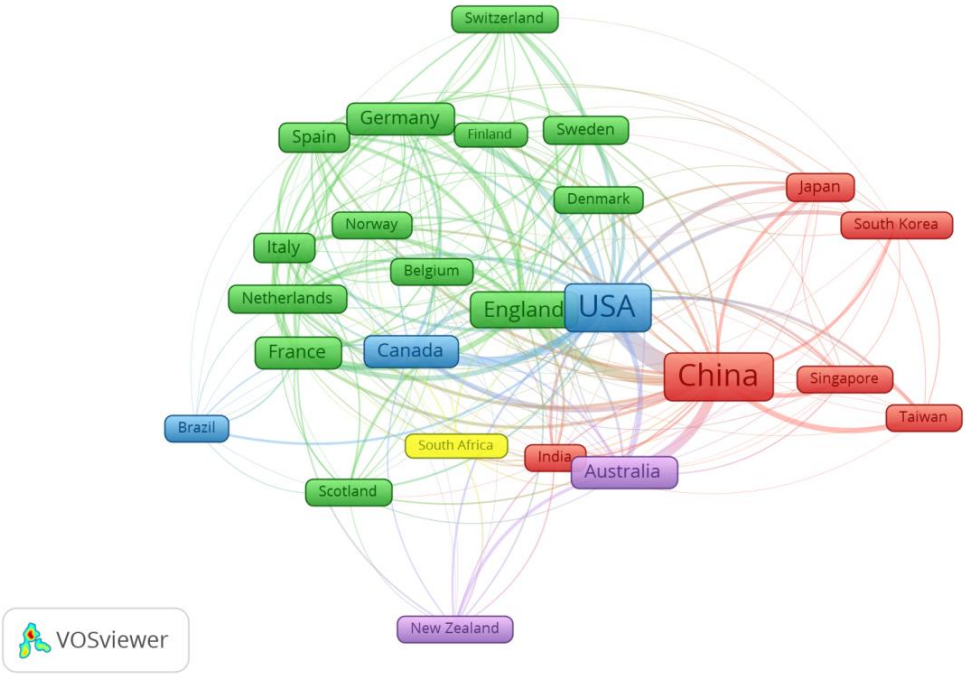

Figure 5. Cooperations among the top 25 countries and regions.

3.3. Productive institutes

Table 3 lists the top 25 research institutions and their respective countries in terms of publication output on environmental regulation. The University of California

system leads with 87 publications, making it the most productive institution in this area. The second highest is the National Bureau of Economic Research, with 67 publications. Close behind are Xiamen University with 65 publications, Centre National De La Recherche Scientifique (CNRS) with 52 publications, and both the University of London and Shanghai University of Finance and Economics with 52 and 51 publications respectively, ranking them jointly in fifth place.

Moreover, over half of the top 25 institutions with the highest output on environmental regulation issues are located in China. This indicates that China is currently the most active country in researching environmental regulation issues.

Table 3. Top 25 productive institutes.

Ranking	Affiliations	Country	Number of Articles
1	University of California System	USA	87
2	National Bureau of Economic Research	USA	67
3	Xiamen University	China	65
4	Centre National De La Recherche Scientifique CNRS	France	52
5	University of London	England	52
6	Shanghai University of Finance Economics	China	51
7	Zhongnan University of Economics Law	China	49
8	Central South University	China	44
9	Harvard University	USA	41
10	Resources for The Future	USA	41
11	University of International Business Economics	China	41
12	Wuhan University	China	41
13	Beijing Institute of Technology	China	40
14	Southwestern University of Finance Economics China	China	40
15	Hunan University	China	39
16	Renmin University of China	China	38
17	Chinese Academy of Sciences	China	37
18	Inrae	France	37
19	University of California Berkeley	USA	37
20	Peking University	China	36
21	State University System of Florida	USA	36
22	University System of Maryland	USA	35
23	Xi'an Jiaotong University	China	35
24	Shanghai Jiao Tong University	China	34
25	Anhui University of Finance Economics	China	33

3.4. Productive and influential scholars

In this study, we aim to identify leading scholars who have significantly influenced the development of this research area through their contributions within a specific dataset of 3944 documents. Specifically, high-production scholars are defined as those who have published a notably higher number of articles compared to their peers within this dataset. Similarly, highly-cited scholars are those whose works have

been cited more frequently than those of their counterparts in the same dataset. The data for both high-production and highly-cited scholars were obtained from the WoS and processed and presented using VOSviewer software. This analysis allowed us to present a detailed overview of these scholars' affiliations and countries, underscoring the geographical and institutional contexts of their research contributions. High-output scholars and highly-cited scholars are listed in **Tables 4** and **5**, respectively.

3.4.1. High-production scholars

The affiliation of a scholar with multiple research institutions is a common phenomenon. In such cases, we identify the scholar's most recent article as the first author and select the first listed institution as their primary affiliation. Consequently, the country of this institution is considered the scholar's country.

According to **Table 4**, between 2010 and 2023, Song, Malin, and Sueyoshi, Toshiyuki are the scholars with the highest production, having published 19 and 16 articles respectively, with citation counts of 1035 and 1320 each. Earnhart, Dietrich; Espinola-Arredondo, Ana; Goto, Mika; Munoz-Garcia, Felix; Sun, Chuanwang; Zhang, Bing each published 13 articles, tying for third place. **Table 4** reveals that over half of the top 20 high-production scholars come from China, accounting for more than half of the total. The United States follows closely behind. Japan, Sweden, and Italy each have only one scholar listed in the top 20 for productivity.

Table 4. Top 20 high-production scholars.

Ranking	Author	Documents	Citations	Institute	Country
1	Song, Malin	19	1035	Anhui University of Finance & Economics	China
2	Sueyoshi, Toshiyuki	16	1320	New Mexico Institute of Mining Technology	USA
3	Earnhart, Dietrich	13	304	University of Kansas	USA
3	Espinola-Arredondo, Ana	13	60	Washington State University	USA
3	Goto, Mika	13	1102	Tokyo Institute of Technology	Japan
3	Munoz-Garcia, Felix	13	49	Washington State University	USA
3	Sun, Chuanwang	13	457	Xiamen University	China
3	Zhang, Bing	13	1204	Nanjing University	China
9	Coria, Jessica	12	177	University of Gothenburg	Sweden
9	Hao, Yu	12	1242	Beijing Institute of Technology	China
9	Shao, Shuai	12	752	East China University of Science & Technology	China
12	Kong, Dongmin	11	214	Huazhong University of Science & Technology	China
12	Zhang, Dongyang	11	285	Capital University of Economics & Business	China
14	Blackman, Allen	10	503	Inter-American Development Bank	USA
14	Du, Kerui	10	790	Xiamen University	China
14	Zeng, Huixiang	10	162	Central South University	China
17	Chen, Xiaohong	9	559	Central South University	China
17	Lee, Chien-Chiang	9	838	Nanchang University	China
17	Lin, Boqiang	9	312	Xiamen University	China
17	Marin, Giovanni	9	395	University of Urbino	Italy
17	Ren, Shenggang	9	605	Central South University	China
17	Zeng, Juying	9	105	Hangzhou City University	China

3.4.2. High-cited scholars

If a scholar has multiple name abbreviations, the information for the same scholar will be merged. According to **Table 5**, the most cited scholar is Rammer, Christian from Germany, whose publications have been cited 1443 times. Ranked second is Shahbaz, Muhammad from Pakistan, with 1333 citations. In third place is Ambec, Stefan from France, with 1323 citations. Notably, the top three high-cited scholars from 2010 to 2023 do not have a high output volume, but their works are highly cited, reflecting the early publication dates and significant contributions of these scholars. Among the top 20 high-cited scholars, 9 are from China and 5 are from the United States.

Table 5. Top 20 high-cited scholars.

Ranking	Author	Citations	Documents	Institute	Country
1	Rammer, Christian	1443	6	Centre for European Economic Research	Germany
2	Shahbaz, Muhammad	1333	6	COMSATS University Islamabad	Pakistan
3	Ambec, Stefan	1323	6	University of Toulouse	France
4	Sueyoshi, Toshiyuki	1320	16	New Mexico Institute of Mining Technology	USA
5	Hao, Yu	1242	12	Beijing Institute of Technology	China
6	Zhang, Bing	1204	13	Nanjing University	China
7	Kesidou, Effie	1126	7	University of Nottingham	England
8	Goto, Mika	1102	13	Tokyo Institute of Technology	Japan
9	Song, Malin	1035	18	Anhui University of Finance & Economics	China
10	Mazzanti, Massimiliano	1021	5	University of Ferrara	Italy
11	Wu, Haitao	962	7	Beijing Institute of Technology	China
12	Ren, Siyu	894	5	Nankai University	China
13	Toffel, Michael W.	894	7	Harvard University	USA
14	Kahn, Matthew E.	884	8	University of Southern California	USA
15	Zhang, Yue-Jun	871	7	Beijing Institute of Technology	China
16	Greenstone, Michael	869	5	Massachusetts Institute of Technology	USA
17	Lee, Chien-Chiang	838	9	Nanchang University	China
18	Du, Kerui	790	10	Xiamen University	China
19	Shao, Shuai	752	12	East China University of Science & Technology	China
20	Popp, David	657	6	Syracuse University	USA

3.5. Research hotspots

The 3944 sample articles in this study encompass a total of 13,053 keywords. We conducted a keyword analysis using VOSviewer. Employing the full counting method, we set the minimum occurrence frequency for keywords at 10 and merged duplicate keywords, resulting in 590 keywords that met the criteria. This study focuses on analyzing these keywords more precisely.

3.5.1. Keyword frequencies and centralities

Table 6 presents the frequency, links, and strength of link for the top 25 high-frequency keywords. During the analysis, many keywords, though differently expressed, had the same meaning and were thus merged in this study. For example,

"carbon emissions," "carbon-dioxide emissions" and "CO_2 emissions" were consolidated into one term.

Table 6. Top 20 high-frequency keywords.

Ranking	Keyword	Occurrences	Keyword	Links	Keyword	Total link strength
1	Environmental regulation	1540	Environmental regulation	1714	Environmental regulation	9481
2	Environmental policy	803	Innovation	1447	Innovation	5609
3	Innovation	799	Environmental policy	1086	Environmental policy	4856
4	Impact	701	Economic growth	1006	Impact	4563
5	Performance	636	Corporate social responsibility	726	Performance	4229
6	Economic growth	603	Pollution	709	Economic growth	3915
9	Pollution	560	Energy	650	Pollution	3609
7	Corporate social responsibility	425	Trade	609	Corporate social responsibility	2844
8	China	380	Impact	582	China	2594
10	Management	336	Climate change	529	Productivity	2313
11	Trade	330	Performance	464	Management	2157
12	Productivity	325	Model	461	Trade	2106
13	Energy	308	Firm	458	Determinants	2071
14	Determinants	281	Foreign direct investment	454	Energy	1868
15	Foreign direct investment	253	Carbon emissions	432	Foreign direct investment	1766
16	Model	246	Productivity	422	Firm	1657
17	Firm	238	Cost	413	Carbon emissions	1587
18	Sustainability	237	Market	412	Empirical-analysis	1527
19	Carbon emissions	236	Empirical-analysis	400	Sustainability	1431
20	Climate change	234	Management	376	Climate change	1318

Keyword frequency refers to the count of specific keywords within a set of 3944 sample articles. A higher frequency indicates more research interest and significance within the sample, highlighting research hotspots in the field (Chen et al., 2023). Evidently, "environmental regulation", "environmental policy", "innovation", "impact," and "performance" are the top 5 most frequent keywords. Other terms also feature as high-frequency keywords in the top 20. Topics such as "economic growth," "pollution", "corporate social responsibility", "China", "management", "trade", "productivity", "energy", "determinants", "foreign direct investment", "sustainability", "carbon emissions", "climate change" have also garnered significant scholarly attention. In recent years, the issue of environmental regulation in China has increasingly become a focal point for scholars around the world, with "China" appearing 340 times in the 3944 articles.

The links and link strength of keywords reflect their centrality in a specific research field (Chen et al., 2023). When two keywords appear together in the same article, a link is formed between them. Therefore, links can be seen as the number of other keywords that appear in the same article as a specific keyword. The strength of the link indicates the frequency of co-occurrence of two keywords. The higher the link

strength, the more frequently these two keywords appear together in the article. Thus, if a specific keyword has more links and link strength it indicates greater centrality. It is important to note that the links and strength of link for a specific keyword are not always consistent. Based on the number of links, the number of keywords appearing together with "environmental regulation," "innovation," "environmental policy," "economic growth," and "corporate social responsibility" is the highest, suggesting they hold a central position in the field of environmental regulation research. Furthermore, the strength of link highlights "impact" and "performance" as additional focal points, suggesting their importance as current hot topics within this field.

3.5.2. Keyword co-occurrence network

This study utilized VOSviewer software to create a co-occurrence network map of keywords. In the network, the size of a node represents the frequency of occurrence of a keyword, while the thickness of the connecting lines indicates the frequency (link strength) with which two keywords appear together in the same document. To enhance the clarity and comprehensibility of the visual representation, the study set a minimum frequency threshold for keyword occurrences, ultimately selecting the top 30 high-frequency keywords for the co-occurrence network analysis.

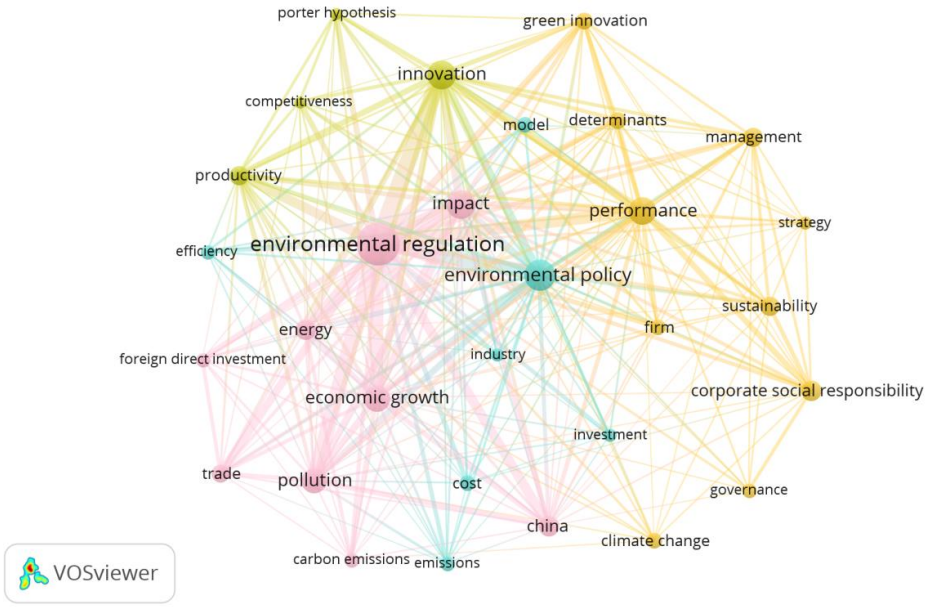

Figure 6. Keyword co-occurrence network.

From **Figure 6**, it is clear that the keyword "environmental regulation" not only appears most frequently but also has the highest number of links and the strongest total link strength. Additionally, the keywords "impact," "environmental policy," "innovation," "performance," "economic growth" and "pollution" have larger nodes and are centrally located in the visualization, indicating that they are hot and central topics within the theme of environmental regulation. This aligns with the findings presented in **Table 6**. In terms of link strength, "innovation" is most strongly connected to "environmental regulation," indicating frequent co-occurrence. This is followed by "impact," "pollution," "economic growth," "performance," "China," "Productivity," and "energy." These findings suggest the significant role of

environmental regulation in areas such as innovation, economic development, productivity, and environmental performance. Additionally, the prominence of "China" indicates a specific geographical focus in the research field, while "pollution" and "energy" underscore the environmental and resource concerns associated with regulatory impacts.

"Environmental policy", as the second most frequent keyword, is often used interchangeably with "environmental regulation" in the existing literature. In empirical studies, these terms frequently employ the same proxy variables for quantification. For example, Martínez-Zarzoso et al. (2019) employed the OECD Environmental Policy Stringency Index, which amalgamates various quantitative and qualitative measures related to laws and regulations, serving as a composite index for environmental policy assessment. Similarly, Wang et al. (2019) applied the same index for assessing the stringency of environmental regulation. Additionally, in certain studies, "environmental policy" may refer to specific measures like carbon emission trading schemes (Fu et al., 2023) or sewage charges policies (Tang et al., 2020). Meanwhile, the term "Environmental regulation" can sometimes lead authors to use singular policy (Tang et al., 2020), or they might employ composite indexes composed of multiple policies (Wang et al., 2019) or comprehensive pollution indicators for a broader assessment (Shao et al., 2022). This variability indicates that in past research, "environmental regulation" and "environmental policy" are often used interchangeably without a strict distinction in their definitions.

Previous studies have commonly focused on a set of environmental policies and regulatory tools including environmental protection laws (Lin and Zhang, 2023), environmental target (Tang et al., 2020), pollution control regulations (Johnston Edwards and Walker, 2020), emission fees (Zhang et al., 2023), environmental taxes (Mahajan and Majumdar, 2021; Tan et al., 2022), carbon emission trading schemes (Calel and Dechezleprêtre, 2016), environmental disclosure (Galani et al., 2012), and renewable energy incentives (Jacobs, 2016; Smith and Urpelainen, 2014).

The third most frequent keyword in the field of environmental regulation is "innovation," which, aside from environmental regulation, has the most links and the strongest total link strength with other keywords, indicating its significant position in this research area. The top 5 keywords most strongly associated with innovation are "environmental regulation", "impact", "performance", "Porter hypothesis", and "productivity". In the literature on environmental regulation, the impact of environmental regulation on innovation has always been a crucial research area in environmental economics and innovation economics. Past studies, often based on the Porter hypothesis theory and neoclassical economic theory, have theoretically analyzed and empirically tested this relationship, yet empirical conclusions remain inconclusive. The prevailing views can be categorized into four main conclusions. The first conclusion supports the Porter hypothesis theory, suggesting that environmental regulation can generate an innovation offset effect, positively influencing innovation (Calel, 2020; Liu et al., 2022; Mahmood et al., 2022). The second conclusion aligns with neoclassicism, arguing that the costs associated with environmental regulation crowd out innovation resources and inhibit innovation (Ramanathan et al., 2010; Tang et al., 2020). The third conclusion posits that the impact of environmental regulation on innovation is nonlinear (Li and Du, 2021; Shao et al., 2022). The fourth highlights

heterogeneity in impacts, indicating that the effects on innovation vary depending on the specificity of the research subject and the diversity of environmental regulatory tools (Guo and Bai, 2019; Luo et al., 2021; Qu et al., 2022).

The keyword "impact" is the fourth highest frequency. The strongest strength of the link with "impact" is "performance". This indicates a strong co-occurrence and relevance between the two keywords in environmental regulation literature. Studies typically explore the effects of environmental regulation on various aspects of performance, including environmental performance (Li and Ramanathan, 2018; Wu and Lin, 2022), corporate performance (Fu et al., 2020; Zhou et al., 2021), innovation performance (Tang et al., 2020), and economic performance (Ramanathan et al., 2010). Subsequently, "impact" strongly correlates with "innovation", "economic growth" and "pollution." Past research on "pollution" primarily focuses on evaluating environmental regulation's role in areas such as air pollution (Feng et al., 2020; Liu et al., 2021), pollution control and reduction (Bao et al., 2021; Neves et al., 2020; Yang et al., 2021), and pollution transfer (Li et al., 2021). Notably, the term "impact" is strongly associated with China, indicating the significant attention to the effects of environmental regulation in China, especially on "economic growth" and high-quality economic development (Liu et al., 2021; Wang and Lee, 2022), and "carbon emissions" (Wu et al., 2020). This interest aligns with China's commitment to the Paris Agreement and its carbon neutrality goals. Consequently, China's increasing focus on environmental protection has significantly influenced its socio-economic and ecological landscape.

3.5.3. Theme analysis

As shown in **Figure 6**, the keyword co-occurrence network reveals four clusters (green, pink, yellow, and blue), identifying four hot theme clusters that demonstrate the multifaceted impacts of environmental regulation. Each theme encapsulates a range of interconnected topics that collectively reveal the complex interactions between environmental regulation and various economic, industrial, and social.

Theme 1: Innovation and Competitiveness (Green Cluster). This theme explores how environmental regulation stimulates innovation, often discussed in the context of the Porter Hypothesis. Some studies support the notion that environmental regulation can foster an innovation offset effect, thereby enhancing innovation and competitiveness. For instance, Zhang et al. (2022) analyzed the impact of environmental regulation on innovation and green total factor productivity (GTFP) using urban data from China, finding that environmental legislation increases patent numbers, which supports the weaker version of the Porter Hypothesis. Conversely, Tang et al. (2020) observed that command-and-control environmental regulations in China hinder corporate innovation performance. Mahajan and Majumdar (2021) found that the impact of environmental taxes on the comparative advantage of G20 countries is negative, it is necessary to stimulate the innovation effects produced by environmental policy stringency (Mahajan and Majumdar, 2021a). This theme underscores the varied empirical outcomes and theoretical discussions within the field, highlighting how environmental regulation can act both as a catalyst for and an obstacle to innovation.

Theme 2: Corporate Environmental Behavior (Yellow Cluster). This theme

examines the impact of environmental policies on corporate behavior, particularly in areas of corporate social responsibility, sustainability strategies, and climate change mitigation (Lăzăroiu et al., 2020; Mahajan and Majumdar, 2023a; Teng et al., 2023). The research discusses how companies incorporate environmental policies into their strategic planning to meet stakeholder expectations and regulatory demands. Topics such as sustainable development, corporate governance, and strategic responses to climate change are prevalent, reflecting a comprehensive view of how businesses adapt to and lead in environmental management.

Theme 3: Industry (Blue Cluster): This theme delves into the specific impacts of environmental regulation on industry sectors, highlighting aspects such as emissions control, cost impacts, investments, and efficiency (Chen et al., 2022; Fan et al., 2022; Huang and Lei, 2021; Liu et al., 2021). The studies examine the direct effects of regulatory policies on operational practices, with a special focus on how industries address the challenges of reducing pollution and enhancing resource efficiency. This cluster provides insights into the specific challenges and responses within different industrial sectors, emphasizing the varied impacts across diverse industrial landscapes.

Theme 4: Economic Growth and Structural Effects (Pink Cluster): This theme addresses the broader economic impacts of environmental regulation, exploring how it influences economic growth, energy structures, pollution levels, trade, and foreign direct investment (Aziman et al., 2023; Du et al., 2021; Fahad et al., 2022; Mahajan and Majumdar, 2023b). This cluster focuses on the macroeconomic outcomes of environmental policies, examining how environmental regulations affect national economic performance, industrial and energy structures, trade competitiveness, and foreign investments. The role of environmental regulation in shaping economic policies and influencing global economic trends is a key focus, with particular attention to the transition towards low-carbon and sustainable economic models.

3.6. Research trends

This section reviews the research from a longitudinal perspective to provide guidance for future research directions. In analyzing the research frontier, to avoid excluding newer but less frequent keywords in VOSviewer, we lowered the minimum frequency threshold for keyword occurrence to capture a broader range of keywords. For instance, “financial constraints,” “green finance,” “green credit,” “ESG,” “circular economy,” “labor market,” “political uncertainty,” “digital transformation,” “exports,” and “mediation effect” are among the latest research topics to emerge, with an average publication year of 2022. Additionally, “difference-in-differences”, “quasi-natural experiments”, and “machine learning” have become cutting-edge methodologies in the field of environmental regulation recently. The above keywords appear relatively infrequently and are insignificant in the visualization picture. This implies that there are emerging trends and research gaps in environmental regulation concerning these keywords.

To enhance the observability in visualization, **Figure 7** displays the top 30 frequent keywords, where the color transition represents the temporal change from darker blue for older to lighter yellow for more recent years. In this visualization, lighter node colors indicate more recent research topics, and smaller circles suggest

less frequent research activity. For instance, "impact," "green innovation," and "carbon emissions" have become new focal points in the discourse on environmental regulation post-2021. Their depiction through lighter yellow hues and smaller nodes in visual analyses indicates that, although they are in the top 30 frequent keywords reflecting current research interests, their recent emergence and substantial research potential require further investigation.

Figure 7 clearly illustrates that the color of "carbon emissions" is lighter than the color of "emissions". This suggests a shift in recent research focus from a broad concern with various pollutant emissions to a more specific emphasis on carbon emissions. Additionally, it should be noted that recent trends in innovation studies have shifted from traditional technological innovation to green innovation. This shift is represented in **Figure 7**, where "innovation" appears as larger, darker nodes, while "green innovation" appears as smaller, lighter nodes. Before conducting the bibliometric analysis, we consolidated terms such as "eco-innovation", "environmental innovation", "sustainable technology", "renewable energy innovation", "green technology", "low-carbon innovation", "solar technology innovation", "green product innovation", and "green process innovation" under "green innovation". This indicates that future research focusing on environmental regulation could delve deeper into the technological categories of green innovation.

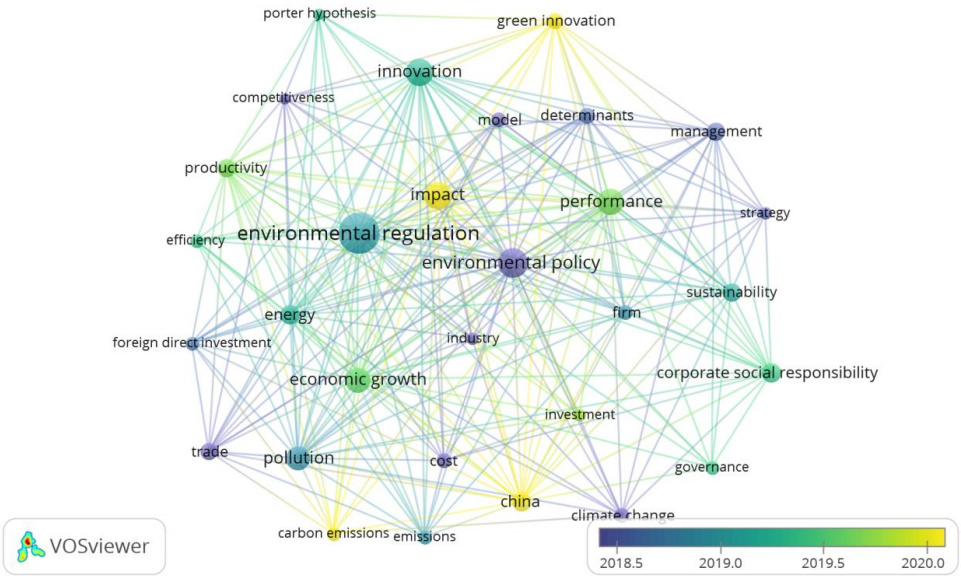

Figure 7. Keyword co-occurrence network temporal trends.

4. Conclusion

Contrary to previous studies which primarily focused on the impact of environmental regulation on specific, isolated domains such as the labor market, green innovation, and foreign direct investment, this study adopts a more comprehensive perspective, analyzing the multifaceted impacts of environmental regulation on industry, society, economy sustainability. Employing bibliometric methods, we have not only identified hot topics within the field of environmental regulation but also unveiled potential emerging topics and trends for future research. These findings offer a more holistic and detailed framework for understanding.

The impacts of environmental regulation have been a focal point of considerable interest over the years, particularly after the signing of the Paris Agreement. This paper has analyzed the distribution, hotspots, and future research directions in the literature on environmental regulation from 2010–2023 through a bibliometric analysis of the literature. Through the WoS database, 3944 articles were selected as the research sample for this paper. The VOSviewer was used to obtain information on these 3944 articles. Our findings indicate a significant evolution in the focus of environmental regulation research, especially post-2016, coinciding with global policy shifts like the Paris Agreement. Unlike earlier studies that concentrated on specific aspects like pollution control, our analysis reveals a broader spectrum of research themes, including innovation, corporate environmental behavior, industry, and economic growth. This shift highlights a growing scholarly interest in integrating environmental policies within broader economic and technological strategies. Notably, while China leads in publication output, it lags behind the United States in terms of international collaboration and citation impact, suggesting an area for potential improvement in global research integration.

Keyword analysis and co-occurrence networks are instrumental in identifying hotspots in environmental regulation research. The frequency and link strength of keywords such as "impact," "innovation," "performance," "economic growth," and "pollution" highlight their central and hot-topic status within this field. Main themes such as innovation and competitiveness, corporate environmental behavior, industry impacts, economic growth and structural effects have emerged as significant. Through an analysis of keyword trends, we have identified emerging research topics including "financial constraints", "green finance", "ESG", "circular economy" and "digital transformation". These emerging areas, coupled with cutting-edge methodologies like "machine learning" and "quasi-natural experiments," signify new directions for environmental regulation studies. The observed shift in focus towards "green innovation" and "carbon emissions" reflects a global concern for climate change and sustainable development. Future research could delve deeper into these areas.

Despite the contributions of this study to understanding environmental regulation, it is not without limitations. Primarily, the reliance on the WoS database might limit the global perspective that could be attained by integrating more comprehensive databases such as Scopus. Future studies could enhance conclusions by incorporating these databases, thereby mitigating the risk of overlooking relevant research due to database constraints. Furthermore, while bibliometric analysis provides robust statistical data and impressive visual mappings, it inherently offers a broad rather than deep view of the landscape of environmental regulation research. It is recommended that future analyses include more profound text analytics to delve deeper into theoretical underpinnings and specific research trajectories within the field.

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