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A bibliometric comparative study on global oil shale research: hotspots, trends and regional focus

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Abstract. *The world energy mix has been confronted with significant challenges since the international circumstances became increasingly complicated. Oil shale is a typical alternative resource to traditional oil, therefore, it is of great significance to re-evaluate its exploitation and utilization status and research trend under the new background. Through the bibliometric analysis of 944 articles on oil shale published between 2012 and 2022 collected from the Web of Science (WoS) database, this research has carried out a review on the global publication and research trend in oil shale relevant studies. It then investigated and compared the research characteristics in three major countries that carry out oil shale related research, to identify the opportunities of oil shale development in different nations under the restriction of diversified factors. The results show that during the last ten years, research on oil shale has experienced a continuous growth in publication quantity and greatly contributed to the oil shale development with the production of highest cited studies. As for the regional characteristics, Estonia focuses on the comprehensive utilization of oil shale and stands out in its engagement in the environment protection, while China and the United States are still accumulating the applied technological research and fundamental science knowledge and conservatively develop the utilization of oil shale. Although different regions have developed different*

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research priorities and strategies due to the differentiated resource reserve, technical condition and environmental pressure, the environment-friendly and efficient utilization of oil shale resource will be the future emphasis of the oil shale development.

Keywords: *oil shale, bibliometric analysis, research trends, unconventional energy, review.*

1. Introduction

Oil shale is a type of fine-grained sedimentary rock that is rich in organic matter, has subtle lamination, and is flammable. It is also widely recognized as an important alternative resource to traditional oil resources, and has gained global attention as conventional oil and gas resources are depleted at an alarming rate, and the unstable factors in the international energy security situation worsen [1, 2]. Oil shale reserves are abundant in the world. These can be converted into approximately 4,110 × 108 t shale oil, which is equivalent to 3.5 times the world's current conventional oil and gas resources. Today, the majority of the proven reserves are distributed in the United States, Estonia, China, Brazil, Russia, and Australia [3–7]. Oil shale enjoys a wide range of applications. It can be used to generate energy through the dry distillation preparation of shale oil and related chemical products, and as the fuel for power generation. Besides, it is also the raw material for construction, and cement and chemical fertilizers production. Currently, the research on oil shale mainly focuses on its comprehensive utilization and geological exploration [8–12]. Despite its abundant reserves and versatility of applications, oil shale exploration and utilization face a number of challenges, including high costs and environmental pollution. The availability, economic benefits, and environmental effects must all be considered in the choice of alternative energy sources [13, 14]. In 2002, the World Energy Council pointed out at the international symposium on the prospects of global oil shale development and utilization held in Estonia that the global oil shale resources were huge, but the utilization rate was very low [15]. However, as related research and new approaches to exploration, exploitation, and utilization of various oil shale resources have advanced, the utilization rate and the green employment degree of oil shale resources have improved.

Nowadays, the world's energy is confronted with a series of new challenges, including the climate change and unbalanced relationship between supply and demand [16]. These bring about changes in oil shale research topics and direction. Against this background, it is of great significance to take a further up-to-date look at the international oil shale research trend. Over the past decade, a large body of work has been dedicated to oil shale-related science and technology research, while the object and content of these studies have been very complex. Some investigations have reviewed the oil shale research

status from a certain technical aspect or a certain country's perspective [17–21]. However, the changing world energy situation requires a more systematic characterization of progress, hotspots and trends in oil shale research. In addition, very few researches investigate the differences in oil shale related studies between regions. To fill these gaps, the overall research trends and hotspots, as well as the regional research features were investigated using bibliometric approaches in this research, respectively. This paper collects all related scientific publications from the Web of Science (WoS) database, and analyzes them by CiteSpace software to give a clear picture of the overall research domain and trend of oil shale research.

To achieve the objective of this study, the following research questions are addressed: 1) What are the general publication output trend and the main hotspots of oil shale research worldwide from 2012 to 2022? How does the research trend evolve over the time? 2) How do different countries and regions feature different oil shale research topics, and what information can be generated from the differences? 3) What are the trends and opportunities of oil shale research restricted by different influencing factors in different regions?

2. Methodology and data

To answer the aforementioned questions, this research adopted bibliometric methodology to quantitatively analyze the oil shale literature. CiteSpace 6.1.R2, a visual analysis tool, is employed to process the data and draw knowledge maps and spectrum to help to identify hotspots and research trends. The bibliometric analysis of science and technology related to oil shale was conducted based on data collected from the Web of Science Core Collection database on 26th July 2022.

2.1. Data source and extraction

Web of Science is considered as the largest and one of the most reliable databases for academic journals. Covering the most significant peer-reviewed publications on geology, mining, and energy, it is chosen as the data source for this research. The search was "AK = (Oil shale)", and the retrieval time was from 2012 up to July 2022. The source databases are Web of Science Core Collection, including Science Citation Index Expanded and Conference Proceedings Citation Index. From the research, a total of 1,060 publications were generated. After removing less relevant and academically rigorous documents such as review articles, editorial materials, book chapters, and duplications, the bibliometric information of the 944 publications was exported as a plain text file and downloaded for visual analysis in CiteSpace. "Full record" was chosen as the export content, which encompasses the information on authors, affiliations of the authors, titles, publication year, citations, author keywords, keywords plus, countries, institutions, journals, and so on.

2.2. Data analysis and visualization

The analysis was separated into three parts on the basis of research questions. How the bibliometric information functions in every part of analysis is demonstrated as follows. The publication year records are used in the statistics of the annual number of articles to identify its development stages from 2012 to 2022. The author keywords, keywords plus, publication titles, years, and citations are used to identify the main hot topics in oil shale research worldwide, their evolution over the time, and the future direction of the research. By combining keywords with countries, institutions and authors, the research characteristics of oil shale in different regions will be analyzed.

3. Results and discussion

3.1. Publication output and growth

The analysis of oil shale research publication output covers 11 years spanning from 2012 to 2022. Considering that 2022 is not a complete year when the last retrieval is conducted, the data from this year will not be shown in the trend figure (Fig. 1) for academic strictness (Note. Up to 30th July 2022, 51 publications on oil shale research have been published in 2022). Generally speaking, there has been an uptrend in the number of publications on oil shale research worldwide during the period from 2012 to 2021 and the number of articles published annually has doubled from 57 at the beginning of the period to 106 at the end of it. The development can be divided into two phases. Between 2012 and 2015, the share of articles on oil research increased by 66.7%, and it can be regarded as a rapid growth stage due to the prompt expansion in the number of annual publications. From 2016 to 2021, the number of articles published per year did not experience huge growth and fluctuated between 98 and 111. This period can be seen as the stable development stage with minor fluctuations. According to the existing data, this phase will keep going in 2022. The output growth tendency of oil shale research indicates the scholars' continuous interest and attention in this field.

The increase in oil shale research output from 2012 to 2022 has made a considerable contribution to extending hotspots and producing highly influenced publications. The characteristics of the 944 articles are presented in Table 1. During these ten years, 2,303 authors have contributed to oil shale research and published the respective scientific papers in 211 journals. The average number of citations per article is 12.05, and the most influential article has been cited 178 times. As seen from Table 2, amongst the top 10 articles with the most citations, those published between 2012 and 2022 account for 50% [22–31]. The H-index is 46, indicating the substantial impact of publications during the time span on the overall oil shale research.

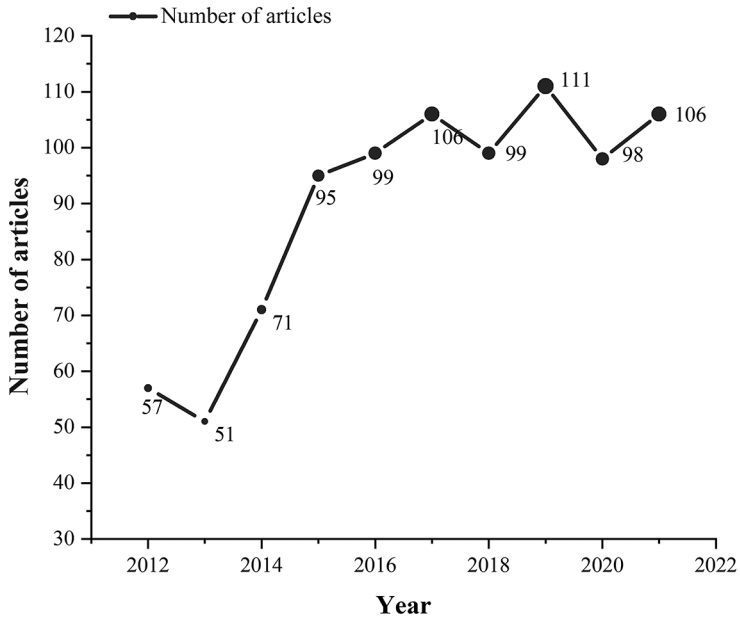

Fig. 1. Publication trend over time from 2012 to 2022.

Table 1. Characteristics of the articles published between 2012 and 2022

Description	Results
Sources	211
Authors	2303
Average article citations	12.05
Highest article citations	178
H-index	46

Table 2. Top 10 articles with the most citations

Title	Source	Publication year	Citations
Characterization of oil shale pore structure before and after pyrolysis by using X-ray micro CT	Fuel	2013	178
New technology for the comprehensive utilization of Chinese oil shale resources	Energy	2007	148
Oxygen groups in coals and alginite-rich kerogen revisited	International Journal of Coal Geology	2008	144
A TG-FTIR investigation to the catalytic effect of mineral matrix in oil shale on the pyrolysis and combustion of kerogen	Fuel	2013	140
The preparation of a green shape-stabilized composite phase change material of polyethylene glycol/SiO_2 with enhanced thermal performance based on oil shale ash via temperature-assisted sol-gel method	Solar Energy Materials and Solar Cells	2015	138
Multi-scale multi-dimensional microstructure imaging of oil shale pyrolysis using X-ray micro-tomography, automated ultra-high resolution SEM, MAPS Mineralogy and FIB-SEM	Applied Energy	2017	132
Conversion of oil shale ash into zeolite for cadmium and lead removal from wastewater	Fuel	2004	123
Investigation of oil-shale pyrolysis processing conditions using thermogravimetric analysis	Applied Energy	2000	123
Non-isothermal thermogravimetry and decomposition kinetics of two Jordanian oil shales under different processing conditions	Fuel Processing Technology	2000	119
Formation and development of the pore structure in Chang 7 member oil-shale from Ordos Basin during organic matter evolution induced by hydrous pyrolysis	Fuel	2015	111

Fuel is the most frequent source of the top 10 articles with the most citations. In addition, through the analysis of the literature, it is revealed that few journals specialize mainly in the research on oil shale except for Oil Shale. Some comprehensive or cross-disciplinary journals also report progress in oil shale research, such as Journal of Thermal Analysis and Calorimetry, Energy, et al. The leading journals that report oil shale related research are shown in Figure 2 with the number of published literature indicated in the area.

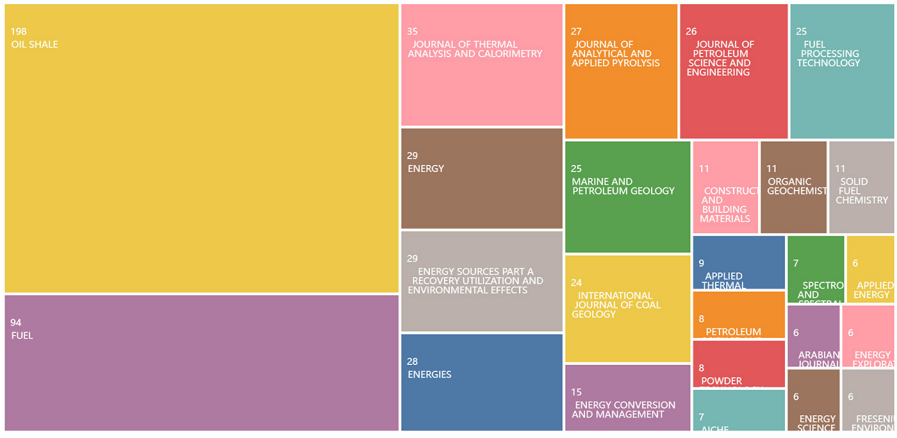

Fig. 2. The leading journals of oil shale related research.

3.2. General hotspots and research trend

If a problem is intensively discussed in many studies, it can be regarded as a hotspot. Considering that keywords are the concentrations of an article, research hotspots can be inferred through their analysis. Process and cluster keywords data in CiteSpace 6.1.R2, and the keyword co-occurrence network of oil shale research are obtained and displayed in Figure 3. The total number of nodes is 422, and the number of connections is 1511. The values of modularity Q (MQ) and mean silhouette (MS) are 0.5143 and 0.7697, respectively. Therefore, the clustering effect is in line with the requirements. The size of the node represents the counts of the keyword. The color in the node equals its occurrence time with deep red for the first year of existence and yellow for the latest. It can be deduced that the highest counted keyword falls into the cluster #2 oil shale. A different area color represents different clusters, and the link represents the strength of relationship among keywords. The links and overlaps between clusters show that hotspots of oil shale research share close relationships. Nine important hotspots are identified through the analysis, including “pyrolysis”, “oil shale”, “oil shale ash”, “gc-ms”, “pore structure”, “flame propagation”, “maastrichtian”, “trace elements”, “atomic force microscopy”, and “hcl-hf isolation method”. The main concerns in oil shale

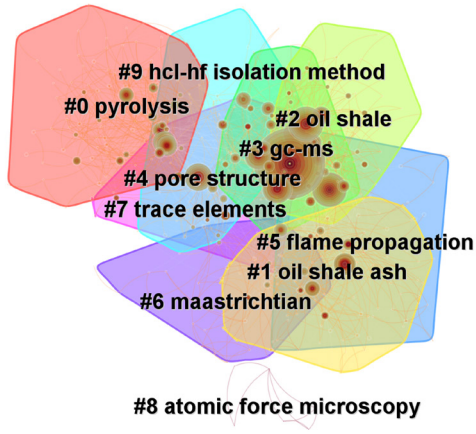

Fig. 3. The keyword co-occurrence network of oil shale related research.

research involve the technologies of extracting shale oil and gas, the geology and chemical characteristics of oil shale, the utilization of by-products from its processing, and the safe production of oil shale mixed with other resources.

Figure 4 presents the timeline view of the aforementioned hotspots, from which the development of every cluster and the significant relevant publications can be seen. Topics related to pyrolysis, oil shale ash, and GC-MS are the most enduring ones with the most influential achievements and their relevant research lasted for the whole time span retrieved. Topics related to flame propagation, Maastrichtian, trace elements, atomic force microscopy, and hcl-hf isolation method encompass fewer achievements and their research is greatly influenced by the study of the former.

Keywords bursts visualize the distribution of the strongest oil shale research hotspots in the time span. As demonstrated in Figure 5, “oil shale ash”, “trace element”, “shale oil”, “emission”, “thermogravimetry”, and “estonian kukersite” are the earliest hotspots in oil shale research beginning in 2012 and ending in 2016. From 2015 to 2020, the topics “green river formation”, “oil shale pyrolysis”, “lignite”, and “co-combustion” became more and more valuable for scholars. And recently, “numerical stimulation”, “gasification”, “permeability”, “recovery”, and “thermal cracking” turned out to be the most prominent ones.

In a word, from 2012 to 2022, the oil shale research worldwide features various hotspots, with the focus on the extract processes and utilization approaches of the by-products. Keywords with the strongest citation bursts appear continuously in the ten-year time span, indicating the vitality of and trend in oil shale research. The new emergences of keyword burstiness are also mainly related to the pyrolysis of oil shale, suggesting that pyrolysis will continue to be one of the main topics in oil shale research and utilization, stimulating the development of new technologies and related theoretical approaches.

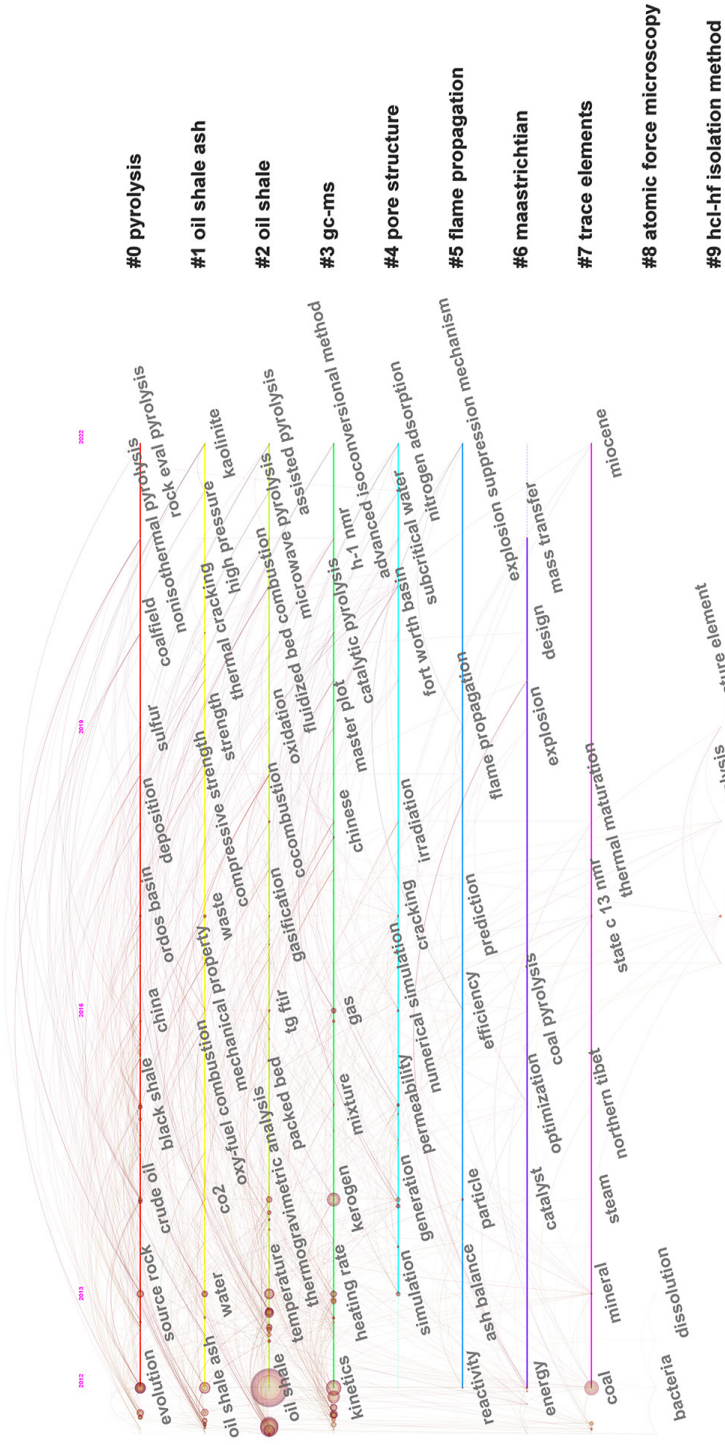

Fig. 4. The timeline view of the aforementioned hotspots.

Top 15 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2012-2022
oil shale ash	2012	4.74	**2012**	2014	
trace element	2012	4.63	**2012**	2015	
shale oil	2012	3.79	**2012**	2015	
emission	2012	3.63	**2012**	2015	
thermogravimetry	2012	3.71	**2013**	2016	
estonian kukersite	2012	3.6	**2014**	2015	
green river formation	2012	3.68	**2015**	2017	
oil shale pyrolysis	2012	5.73	**2016**	2018	
lignite	2012	3.86	**2017**	2019	
co-combustion	2012	4.32	**2018**	2020	
numerical simulation	2012	4.93	**2019**	2022	
gasification	2012	4.19	**2019**	2020	
permeability	2012	3.63	**2020**	2022	
recovery	2012	3.62	**2020**	2022	
thermal cracking	2012	3.34	**2020**	2022	

Fig. 5. Top 15 keywords with the strongest citation bursts.

3.3. Research features in countries and regions

This section is aimed to identify the characteristics of oil shale research in different countries and regions, including the main authors, institutions, and research focuses.

Processing the collected data in CiteSpace 6.1.R2 and setting the node type as country, the network of countries with citations more than 46 is obtained, including the People's Republic of China, Estonia, the United States of America, and Jordan (Fig. 6). Contributing to more than 50% of the total articles (Table 3), China holds the leading position in terms of publication quantity, followed by Estonia, USA, and Jordan. However, USA ranks first in the average number of citations, indicating that its publications are more frequently consulted and enjoy great influence. The distribution of the countries in oil shale research is consistent with the world oil shale reserve. From Table 4 it can be seen that USA ranks first after converting oil shale reserves to shale oil, while China, Jordan, and Estonia rank second, sixth, and eighth, respectively. This research will analyze and compare the research features of the top 3 countries with the most oil shale related publications, which are China, Estonia, and USA, respectively.

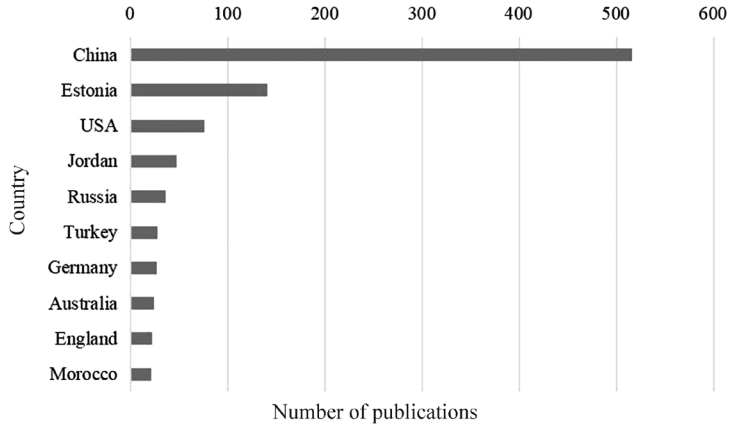

Fig. 6. Publication distribution per country.

Table 3. Top 4 countries with the highest number of publications on oil shale research

Country	Publication count	Percentage	Average article citation
China	516	54.66%	13.02
Estonia	141	14.94%	8.08
USA	76	8.05%	18.74
Jordan	47	4.98%	7.3

Table 4. Shale oil reserves converted by oil shale of the main countries

No.	Country	Shale oil reserves converted by oil shale, million tons
1	USA	303566
2	China	47644
3	Russia	38770
4	Brazil	11734
5	Canada	6300
6	Jordan	5233
7	Australia	4531
8	Estonia	2494

After analyzing and visualizing the keywords from 516 China's oil shale publications in CiteSpace 6.1.R2, the keyword co-occurrence network of oil shale research in China was obtained, as shown in Figure 7. After incorporating similar clusters, the identified hotspots and their ranking by size are namely #0 pyrolysis (119), #1 oil shale ash (83), #2 pore structure (58), #3 chemical composition (49), #4 co-combustion (36), #5 numerical stimulation (11), and #6 ignition sensitivity (8). It is demonstrated that China has focused primarily on the characteristics of oil shale, and the relevant clusters include "pyrolysis", "oil shale ash", "pore structure", "chemical composition", "co-combustion", and "ignition sensitivity". The research on the characteristics of oil shale can provide a theoretical basis for the exploitation and utilization of the rock. However, the hotspots show that China does not pay much attention to the oil shale exploitation and utilization practice [32]. Besides, the research related to technologies is also very limited and the only relevant cluster is "numerical stimulation" used in oil shale resource evaluation. It may be due to that in China coal has remained the main energy for a long time, and oil shale, as the minor energy resource structure, still does not receive enough attention concerning utilization, and the related industry is relatively immature in comparison with other main countries. However, with China's increasing focus on the unconventional oil and gas, its oil shale research needs to put more emphasis on efficient exploitation, comprehensive utilization, and the relevant technologies in the process. The key institutions include Jilin University (140 publications and 13.71 citations), China University of Petroleum (46 publications and 9.13 citations), and China University of Geosciences (40 publications and 15.05 citations). Jilin University ranks first in terms of publication quantity, while China University of Geosciences has the highest average number of citations. The three institutions account for 43.8% of the total publications on oil shale. The analysis shows that the research resources are concentrated in several strong institutions.

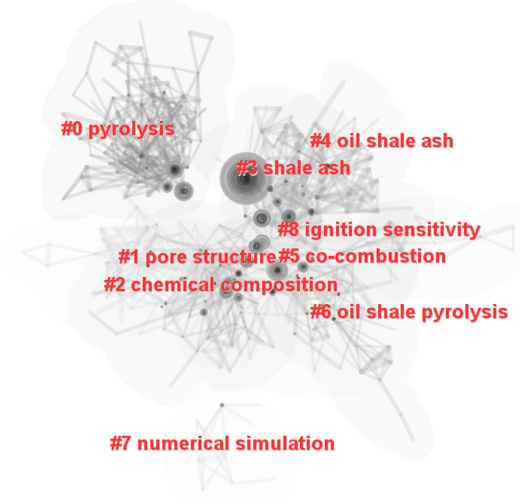

Fig. 7. The keyword co-occurrence network of China's oil shale research.

141 publications from Estonia were analyzed and the keyword co-occurrence network of its oil shale research is shown in Figure 8. After similar clusters were incorporated, the identified hotspots and their ranking by size are namely #0 oil shale (38), #1 oil shale ash (33), #2 co-combustion (32), #3 heavy metals (30), #4 constructed wetlands (30), #5 kukersite oil shale (27), #6 leaching (21), #7 CO_2 sequestration (20), and #9 carbon aerogel (8). Estonia shares a similar interest in the research of oil shale characteristics as China does, and the relevant clusters include "oil shale", "oil shale ash", and "kukersite oil shale". Besides, Estonia puts a high emphasis on the technologies of utilizing oil shale processing waste and by-products. The relevant clusters include "leaching", "CO_2 sequestration", "constructed wetlands", "granulation", and "carbon aerogel". "Leaching" concerns the treatment of oil shale ash such as landfill and its utilization in reducing soil pollution. "CO_2 sequestration" relates to the utilization of the burnt oil shale waste as the sorbent materials for carbon capture and sequestration through techniques such as mineral carbonation. "Constructed wetlands" concerns the utilization of oil shale ash in constructed wetland such as for wastewater treatment. "Granulation" embodies the treatment of oil shale ash to use it as a sorbent. "Carbon aerogel" is relevant to the production of carbon aerogels from oil shale processing by-products. Estonia's way of treating oil shale ash and other by-products demonstrates its efficient utilization of oil shale, and the country's high awareness of environment protection is re-verified by the cluster "heavy metal". Estonia is the only country in the world where oil shale represents the main source of energy. Therefore, its industrial chain is completer and more mature compared to other countries, and the urgent need to cut development costs has driven Estonia to pay attention to increasing the utilization efficiency of oil shale. The environmental impact of oil shale industry has also urged the country to ameliorate the pollution caused.

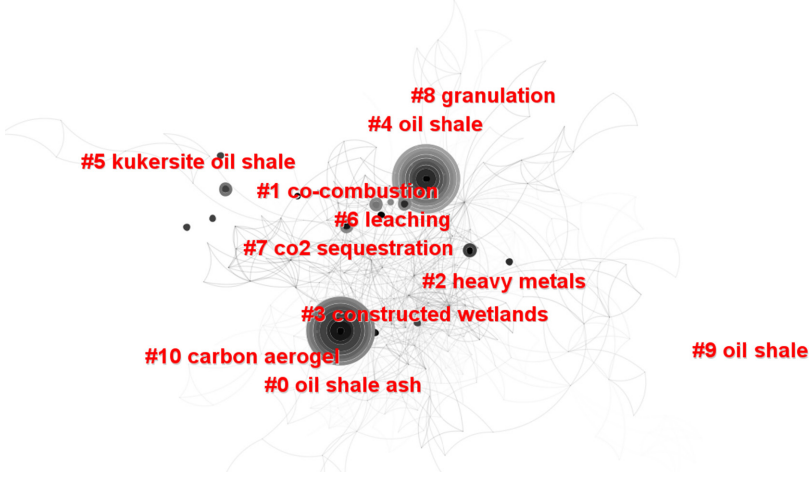

Fig. 8. The keyword co-occurrence network of Estonia's oil shale research.

After analyzing 76 publications from the United States, 11 hotspots were obtained and are shown in Figure 9. USA features multi-dimensional oil shale research. It keeps a balance between the theoretical and applied research, and embodies diverse technologies, including the most advanced artificial neural network. Specifically, the nation's research is concentrated on oil shale characteristics with relevant clusters including "organic geochemistry", "oil shale liquefaction", "lower carboniferous", and "reaction kinetics". Also the genesis and metallogenetic law of oil shale formation are investigated, while the most representative research object is the Green River Formation. Besides, the preservation conditions in the Qaidam Basin and the resource assessment in the Colorado Piceance Basin have also been studied. The technologies in hotspots include "hcl-hf isolation method", "artificial neural network", and "geothermic fuel cell", which can be applied to different oil shale-related areas from modelling its properties to extraction and in-situ exploitation. Last but not least, the hotspot "methylene blue" indicates USA's interest in the utilization of oil shale processing by-products. The United States' comprehensive research gives evidence of that it still takes advantage of other countries in capital and technology in the oil shale field.

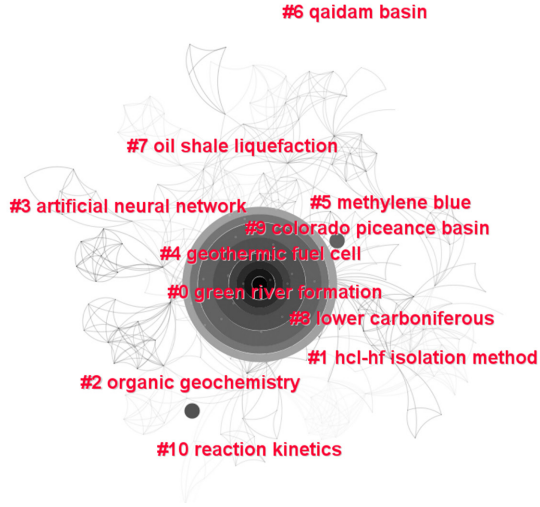

Fig. 9. The keyword co-occurrence network of USA's oil shale research.

3.4. Oil Shale's new role

Amongst the 944 relevant contributions, 198 have been published in Oil Shale. This journal exceeds Fuel (94), Journal of Thermal Analysis and Calorimetry (35), Energy (29) and other important journals in terms of article quantity, and ranks first with the total proportion of 20.02% out of all research. In addition, considering that the retrieval was conducted according to keywords, the actual

number of articles relevant to oil shale should be more than 198 in Oil Shale. Therefore, Oil Shale can be regarded as one of the most representative journals on oil shale research and it is of great significance to have a further detailed look at it. In 2011 and 2016, two reviews of the bibliometric analysis of Oil Shale were produced successively by Prof. Volli Kalm [33] and Kalmer Lauk [34]. Five years later, the global energy faces a number of fresh difficulties, such as the effects of climate change and an unbalanced supply and demand. Given this, it is essential to examine Oil Shale's new position in light of the opportunities and challenges presented by the current energy situation.

Impact factor is one of the data released in Journal Citation Reports by Clarivate. Calculated according to the ratio between citations and recent citable items in the previous two years, it reflects the overall research quality of a journal as well as its scientific impact in the relevant field. Figure 10 illustrates the rise and fall of Oil Shale's impact factor in the last ten years. Generally speaking, despite the minor fluctuation, its impact factor has experienced an upward trend and reached the summit in 2021, being 1.442. However, the impact factor is a relative indicator which cannot reflect the importance of a journal independently, and thus must be compared with impact factors of other journals in the same category. According to Figure 10, the journal impact factor (JIF) percentile of Oil Shale has experienced an overall downward trend in both categories of Energy, Petroleum and Energy & Fuels, indicating its weakening impact in the two categories in the last ten years. Specifically, the research quality of Oil Shale is higher than that of 64.58% journals in the Energy, Petroleum category in 2011. However, after the rapid increase in

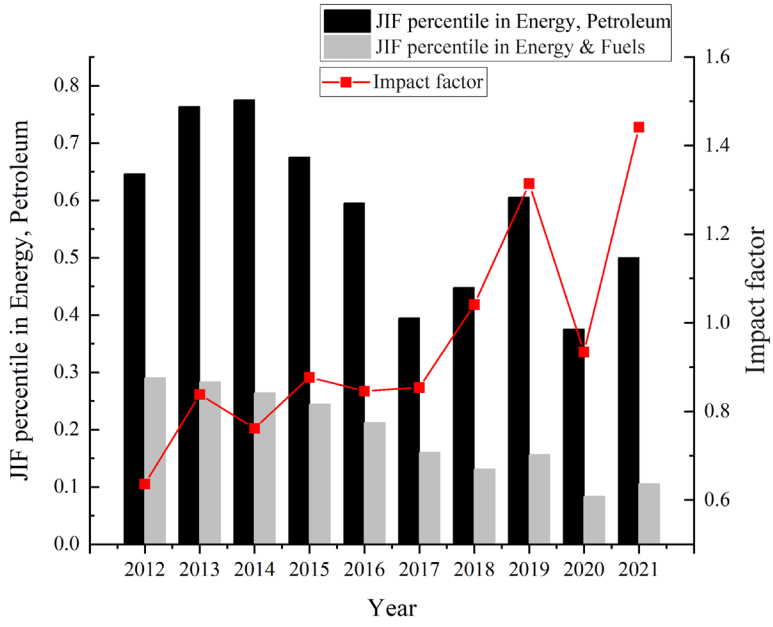

Fig. 10. Oil Shale's impact factor and JIF percentile in categories in 2012–2021.

the subsequent two years, its performance started to decline in 2015 and hit bottom in 2017. In the following years, Oil Shale has witnessed some rebound but its performance has not returned to the peak. The same trend can also be witnessed in the Energy & Fuels category. The change in Oil Shale's impact may result from the growing popularity of other unconventional energies and the weakening position of oil shale in energy and fuel, considering Oil Shale's particular specialization in oil shale research.

After removing reviews and editorial materials, 262 articles published in Oil Shale between 2012 and 2022 were subjected to keyword statistical analysis in CiteSpace 6.1.R2, and the keyword co-occurrence diagram indicating the hotspots was obtained. The 11 identified categories can be divided into three aspects. The first one is relevant to the oil shale mineral, chemical, and physical characteristics, including "oil shale pyrolysis", "characteristics", "co-combustion", "oil shale characteristics", and "minerals". These studies can provide a theoretical guidance to the resource evaluation and exploitation of oil shale. The second one is relevant to the efficient utilization of oil shale by-products and the significant clusters include "oil shale ash" and "carbon aerogel". The third one is related to the main study areas of oil shale and the clusters include "eastern china" and "estonia", which also highlights the main countries that contribute to the articles published in Oil Shale most. In the future, more attention can be paid to the topic of advanced evaluation, exploitation, and utilization technologies of oil shale against the background of climate change and carbon neutrality through the methods such as organizing special issues, by which more countries can also be involved in Oil Shale publications. The research hotspots in Oil Shale are displayed in Figure 11.

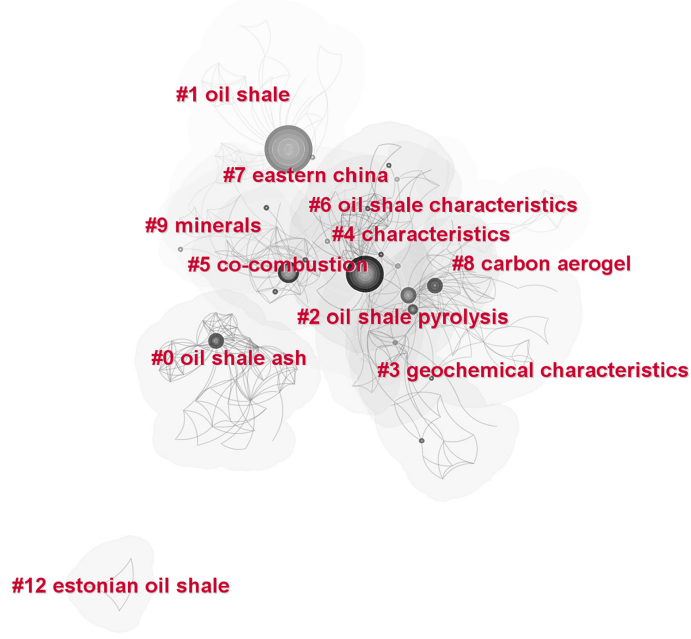

Fig. 11. Research hotspots in Oil Shale.

4. Discussion

The literature characteristics of the oil shale research conducted by different countries demonstrate similarities as well as differences in the main directions, which are closely related to the respective economic and technological development level, main utilization methods and energy resource shortage degree of the countries having major oil shale reserves. The research focuses of the United States, Estonia and China are indicated in Figure 12.

Taking the research in the United States, Estonia and China as an example (Fig. 12), these three countries all possess large literature, but feature different research emphases. Among them, the research hotspots in the Unites States can be mainly classified into the following categories: resource investigation, geological evaluation, resource prediction technology, and other novel technologies related to oil shale development and utilization. It can be concluded that USA attaches importance to both fundamental scientific and mechanism research and the application and practice research of technologies. According to the results of the U.S. Geological Survey (USGS) Energy Resources Program, the oil shale reserves in the United States are extremely rich, far exceeding those of other countries worldwide. For example, its Eocene Green River Formation of Colorado, Utah, and Wyoming are the largest oil shale deposits in the world [35]. However, the United States has not carried out many practices in the development and utilization of oil shale resources notwithstanding its rich research. This may be related to its favorable energy trade such as oil. In recent years, this can also result, on the one hand, from the progress made in the utilization of unconventional oil and gas resources such as shale gas, but, on the other, from concerns over environmental pollution. In addition, this is affected by the country's insufficient development and utilization technologies of oil shale. However, USA has a profound foundation of basic science and industrial technology, and its concern over fundamental

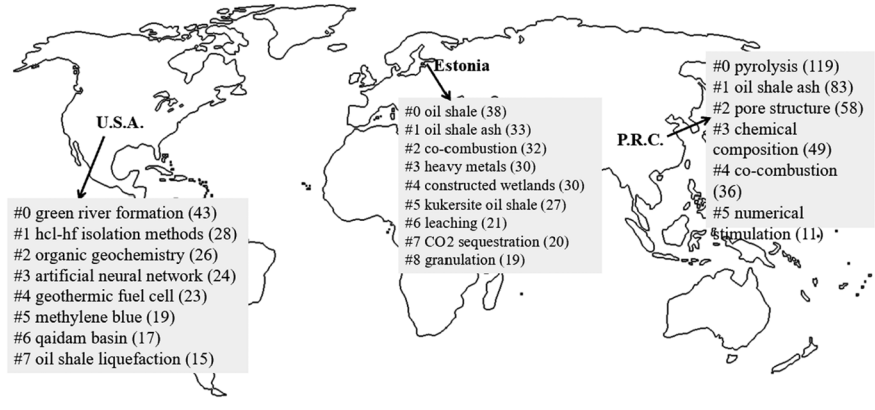

Fig. 12. Research focuses of the United States, Estonia and China.

scientific and mechanical research and application technologies is also demonstrated in the oil shale research. Therefore, it can be predicted that the country will be more likely to focus on novel green and economic exploitation and utilization technologies of oil shale research in the future.

Estonia is a pioneer in the use and exploitation of oil shale as compared to the United States [36]. Its use of oil shale can be traced back to a century ago, and at one point, more than 60% of the world's oil shale was extracted there. Because of the long history of oil shale development and utilization, issues such as air pollution, solid waste disposal, water usage and pollution, land use, and greenhouse gas emissions have emerged. Estonia's keywords in its research literature reflect the country's uniqueness in the exploitation and utilization methods of oil shale and special attention to the ecological environment [37, 38]. This stems from Estonia's long-term oil shale resource development and the environmental issues it is experiencing. The most significant features of the nation's oil shale research can be viewed as the higher percentage of studies that are concerned with the environmental component. However, it is noteworthy that the EU is helping Estonia phase out oil shale in energy production because of environmental issues and potential effects on carbon neutral policies. But many researchers also believe that the continuous use of oil shale does not clash with environmental goals like carbon neutrality. In the future, Estonia should enhance the share of clean alternative energy in its energy system. In addition, research on environmentally friendly, effective and low-carbon uses of oil shale can be vigorously pursued to guarantee the security of the energy supply based on Estonia's abundant oil shale reserves.

China embodies the second largest oil shale reserves in the world. Additionally, oil and gas resources make up a small proportion of its energy system and the country's external dependence is relatively strong [39]. Despite that China has a large quantity of articles on oil shale research, the development of such resources is relatively static due to the high cost of exploitation and potential environmental damage, which in turn limits the publication of related articles. The country has been actively involved in evaluating oil shale reserves, conducting trials and developing cutting-edge technologies, including in-situ oil shale conversion. It can be stated that a "speed-up" phase is witnessed in China's development of oil shale resources. A series of technical innovation research programs are being implemented in the country, including comprehensive utilization of oil shale resource and exploration of deep earth resource [40]. Therefore, the potential of oil shale resources utilization has been greatly recognized in China. The keyword analysis of the nation's research literature also verifies the development status. It focuses on geological theory and chemical investigation of oil shale such as oil shale pyrolysis (chemical treatment), pore structure and components (geological characteristics), ash treatment, etc. Development technologies rank at the secondary place. At present, China's attitude toward oil shale is somewhat similar to that of the United States, and it is waiting for the maturation and

improvement of green and efficient resource utilization technologies.

The comparison shows that there are significant differences in the direction of oil shale research among the countries with rich oil shale resource due to disparities in exploitation history, resource features, and development technologies. To reduce environmental impact and increase green energy proportion in the energy system are top priorities for Estonia and other nations that use oil shale resources extensively. Countries with abundant oil and gas resources like USA should continue to make technological advances in the green and efficient utilization of oil shale resources. Only after resolving the two crucial problems of economic cost and environmental impact will substantial development and utilization of oil shale be taken into consideration. For countries like China where traditional fossil energy is rather rare, the breakthroughs in extraction technology may enable oil shale to be an important and convenient resource type that contributes to improving energy self-dependency, and serve as a realistic strategic reserve for oil and gas [41–43]. Specifically, China has less oil shale resources suitable for open-pit mining (burial depth less than about 100 m) and underground mining (burial depth between 100 m and 300 m), and the development of most oil shale resources will depend on breakthroughs in in-situ conversion mining technology.

Affected by the COVID-19 pandemic, climate change, and regional conflicts, the stability of the international energy system has been seriously threatened. In 2021, Europe became the first to bear the brunt from gas shortages and electricity supply crisis. Subsequently, energy supply tightness spread to other countries and regions, and the markets of other energies such as coal and oil have also been under pressure. The war between Russia and Ukraine is another serious hit on the energy market, revealing the vulnerability of the international energy supply chain and bringing about the spike of oil and gas prices worldwide. As a result, the energy security risk is compounded for continents and countries with a high external dependence such as Europe and China. Besides, with the rapid consumption of the conventional hydrocarbon resources and the difficulties in the exploitation and development of new sources, the world has experienced a turn in oil and gas exploitation, focusing the use of conventional oil and gas to combining it with unconventional oil and gas. The energy supply disorder caused by geopolitical conflicts can lead to high price in high season due to the short-term demand. In the medium term, with the alleviation of the supply-demand conflict the price may fall slightly. However, the low elasticity of supply determines that the room for decline is limited.

Oil shale, as one type of unconventional oil and gas resources, is increasingly difficult to develop as the stages move forward like tight oil (gas), shale oil and gas, coalbed methane, oil sands, and natural gas hydrate. Higher and higher technology is required, and the development cost is growingly correlated with resource abundance, technology level, and environmental protection problems. Despite the dual constraints of development cost and environmental

pressure, oil shale is widely distributed and has enormous reserves worldwide. Therefore, the prospect of the comprehensive utilization technology for sustainable, green, low-carbon, clean and efficient development of oil shale is still optimistic. In particular, recent geopolitical threats and the volatility of the global energy market have made it even more important to conduct basic scientific and utilization technology research on oil shale to increase the resilience of the global energy system. Therefore, it can be speculated through the systematic comparison and analysis that despite the regional differences in research directions and strategies, the oil shale resource utilization in the future needs to focus on the following problems: 1) the innovation of exploration and exploitation technology represented by underground in-situ conversion to further reduce the development costs; 2) the improvement of green and low-carbon comprehensive utilization technology; 3) resolving the existing or potential environmental impacts. The differences and trends in the general oil shale research focuses based on bibliometric analysis are displayed in Figure 13.

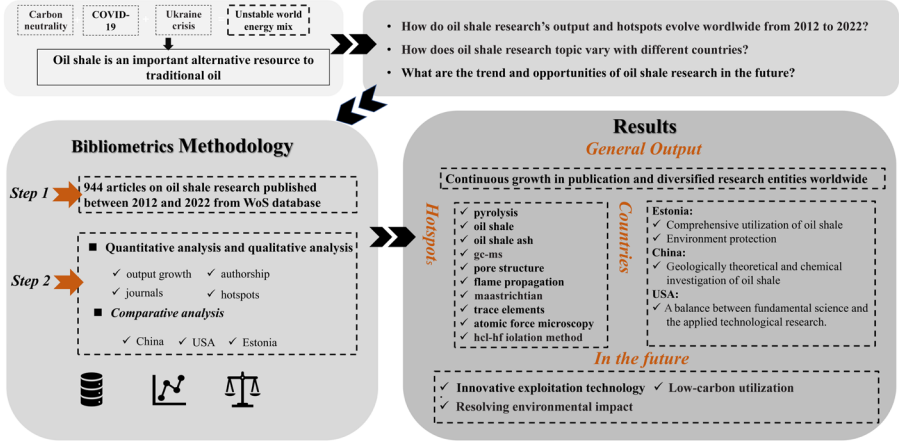

Fig. 13. Differences and trends in the general oil shale research focuses based on bibliometric analysis.

5. Conclusions

Through the bibliometric analysis of the 944 publications on oil shale research from 2012 to 2022, and the comparison of regional research characteristics, the following conclusions can be drawn.

1. The overall oil shale research has experienced continued growth from 2012 to 2022 and maintans a relatively stable state, which can be observed from the publication production. Various authors have participated in oil shale studies, which demonstrates the diversification of oil shale research entities.

Topics on oil shale also enjoy popularity among academic publishers, among which Oil Shale is one of the most representative contributors. The research in this period has greatly extended oil shale research topics and produced highly influential articles.

2. The main research topics during the last 10 years include “pyrolysis”, “oil shale”, “oil shale ash”, “gc-ms”, “pore structure”, “flame propagation”, “maastrichtian”, “trace elements”, “atomic force microscopy”, and “hcl-hf isolation method”. This covers the aspects from oil shale’s geological and chemical characteristics to the exploitation and utilization methods and technologies.
3. As for the regional characteristics, the publications from China feature the geologically theoretical and chemical investigation of oil shale; Estonia focuses on the comprehensive utilization of oil shale and stands out in its engagement in the environment protection; USA keeps a balance between fundamental science and the applied technological research.
4. In the future, the oil shale research needs to further innovate the exploitation technology represented by underground in-situ conversion, improve green and low-carbon comprehensive utilization technology and resolve the current or possible environmental impact to seize the development opportunities in the challenging energy situation.

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