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*Original Research*

# Monitoring Global Science of Petroleum Engineering Based on Co-citation Analysis Networks

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## Abstract

The development of purposeful and principled programs meant to improve the scientific level of countries requires the assessment and measurement of research, and oil industry research is no exception. Therefore, examining the quantitative and qualitative growth trend of products in petroleum engineering can be a guideline for decision-makers and politicians to develop and advance this field. This research is a scientometric study conducted using the co-citation analysis technique. The statistical population of the present study includes all articles in the field of petroleum engineering indexed in the Web of Science database from January 1, 1985, to December 31, 2019. All full record and cited references with tagged format were marked as plain text files to performing analysis. Ravar PreMap, UCINET and NetDraw software were used to identify countries and researchers in question and do a co-citation study. The annual growth trend of articles in petroleum engineering has had an upward trend between 1985 and 2019. Finally, by examining the research in this area, it was found that based on centrality indices, "BAHADORI, ALIREZA" from New South Wales Oil and Gas Company of Australia and "MOHAMMADI, AMIR H." from the University of KwaZulu-Natal in South Africa have played a more important role in scientific production in the field of petroleum engineering according to rank and intermediate centrality indices. Co-citation analysis of articles can show the most important articles and their relationships. Such analyses can be useful for large-scale policymaking or identifying existing gaps and addressing them.

**Keywords:** Social Network Analysis, Co-citation Analysis, Petroleum Engineering, Web of Science Database.

## Introduction

The expansion of scientific productions in various branches has led to the lack of comprehensive study of texts related to specialized fields of science (Jeyasekar & Saravanan, 2014). Fortunately, however, access to information in various areas is possible using information and citation databases, enabling the assessment of scientific productions using database indicators and comparing them. Quantitative and as much as possible qualitative analysis of the process of production, distribution, and application of scientific information and its influential factors, as well as description, explanation, and prediction of this process for planning, policymaking, promotion, awareness, scientific and research foresight in individual, group, organizational and international dimensions is called scientometrics (Norouzichakli, 2013), which can identify and specify the strengths, weaknesses, and gaps in the field of science. Formulation of purposeful and principled plans to promote the scientific level of countries demands the measurement of research, and the research in the oil industry is no exception to this rule**.**

The oil industry has always had a strong position in shaping societies in the past. It is expected to play an essential role in modeling modern societies in the foreseeable future via presenting advanced technology to maintain the supply and demand of crude oil both nationally and globally (University of Kansas, 2020). Petroleum engineering is a branch of engineering that focuses on processes concerned with developing and exploiting crude oil and natural gas fields and technical analysis, computer modeling, and forecasting their future production performance. Therefore, scientometric studies in this area encourage researchers to recognize various technologies and innovations. Petroleum engineering has evolved from mining engineering and geology. It is also closely related to geological sciences, which helps engineers understand oil reserves' geological structures and proper conditions. The goal of petroleum engineering is to extract gaseous and liquid hydrocarbon products from the ground; therefore, it includes all the drilling, production, processing, and transportation processes of these products and addresses all economic and legal considerations (Naderi, Fathianpour & Tabaei, 2019; Britannica, 2020). In addition to mastering the principles of mathematics, physics, and chemistry (Cunha & Cunha, 2004), basic petroleum engineering skills involve other fields related to petroleum engineering, geology, fluid flow in porous media, well drilling technology, economics, and so forth (Cunha & Cunha, 2004; Archer & Wall, 1986).

The study of science from different perspectives provides researchers with a clear view of the current situation of a specific scientific branch compared to other neighboring fields. Therefore, detecting resource usage behaviors in different subject areas such as petroleum engineering through citation analysis methods in databases is also important. Zhou, Guo, Ho and Wu (2008) also conducted a hierarchical scientometric analysis to classify authors, countries, institutes, and journals concerning geological research worldwide from 1967 to 2005 and found that more than 81% of articles had been published between 1995 and 2005, which were mainly in English and covered geological sciences. In addition, Bhakta and Bhui (2018) reviewed the University of Petroleum and Energy Studies research with a scientometric approach during the 2017-2018 period and demonstrated that the highest number of scientific publications was related to 2017 and that the International Journal of Applied Engineering Research was the most favorable journal among 299 journals with Kumar as the most influential author. Busygina and Rykova (2020), in a study, dealt with scientometric analysis and mapping of petroleum science and oil products in soil and groundwater and showed that this area has dynamically grown since the mid-1990s. They used WoS analytics tools and CiteSpace visualization software to specify the leading authors, organizations, and countries in this field with the highest publishing activity in journals, the most important publications, and the names of scientific events behind the problems. The findings of this study can be helpful for experts investigating the impact of oil pollution on the environment.

On the other hand, similar to Bhakta and Bhui (2020), Das and Ghosh (2020) scientifically analyzed the productivity of research at the University of Petroleum and Energy Studies in a different period (2004-2018) and observed that the mentioned university has had the highest level of collaboration with the United States, followed by South Korea and UAE with 51 publications and that the faculty members tend to publish articles in various popular journals and to collaborate effectively with foreign universities. Diodato (1994) introduced citation analysis as one of the main approaches to bibliometrics and examined citation in both forms and to a document. Citation analysis of documents and their authors examines and evaluates the journals in which the document is published or the countries as producers of those documents. Social network analysis (SNA) is a tool for data analysis and visualization in information behavior and modern information retrieval research. SNA is a set of techniques that examine activists, their links, and network (Meier, 2020). A social network is a functional theoretical structure in social sciences consisting of individuals, organizations, groups, or even all societies called "nodes" connected by one or more internal dependencies called edges (Rahman & Karim, 2016). In recent years, social networks have attracted the attention of many disciplines due to their critical role in a wide range of applications (Wang & Song, 2015).

Today, it is customary to research various sciences and disciplines. Therefore, in this study, the quantitative aspects and citation analysis of the global petroleum engineering science are for the first time examined to have an overview of the research process in this field and to help policymakers and planners concerning the progress or regress of studies in petroleum engineering and familiarize them with possible shortcomings in terms of quantity and quality. This research analysis leads to extensive technological advances in the oil, gas, refining, distribution, and petrochemical industries. Furthermore, the production level in the coming years depends on advances in technology and innovation. On the other hand, achieving and establishing progressive and new technologies as the most effective factor in production requires appropriate and purposeful research like the current study. Therefore, the present study intends to analyze scientific publications in the field of petroleum engineering, and to this end, will answer the following questions:

## Research objectives

The main objective of the present study is to analyze scientific publications in the field of petroleum engineering based on co-citation analysis networks. To this end, the following specific goals are pursued:

1. What is the growing trend of articles by researchers by petroleum engineering in the WoS database from 1985 to 2019?
2. What is the frequency distribution of articles by researchers in petroleum engineering in the WoS database from 1985 to 2019 based on different countries of the world, and which countries have had the most scientific cooperation in this field?
3. What is the frequency distribution of top specialized journals in petroleum engineering in WoS database from 1985 to 2019 based on the total number of citations?
4. How is the frequency distribution of petroleum engineering researchers in the WoS database from 1985 to 2019 based on the total number of citations, co-citations, and

influential researchers in creating and forming each cluster?

5. How is the hierarchical clustering of co-citation for researchers in petroleum engineering?

## Methodology

The present research is a scientometric study using a co-citation analysis technique. The statistical population of the present study is all articles in the field of petroleum engineering indexed in WoS from January 1, 1985, to December 31, 2019. These 35 years was chosen because it appears to appropriately indicate the intellectual structure of knowledge in petroleum engineering over the last four decades or so. Because in some countries, the scientific output indexed in validated databases such as WoS under Thomson Reuters (and recently Clarivate Analytics) is an indicator for allocation of funding to universities and institutions as well as an important criterion for scientific assessment and ranking of countries, researchers, institutions, and universities in the world, we chose WoS database for assessment.

In the first step, researchers searched the WoS database for TS= (petroleum engineering*) OR TS= (oil reservoir engineering *) in the subject search field, in all languages and all types of documents from 1985 to 2019. A total of 5006 records (2452 articles) were retrieved due to this search. All the retrieved records were downloaded in 500-record packages as Full Record with Cited References in the tagged format of plain text files, which were transferred to a PC after combining them and creating an integrated file. In the second step, the names of the researchers were edited, modified, deleted, and standardized in Ravar PreMap software (version 1.0.0.0, 2017). In the third step, UCINET software (version 6.528.0.0, 2017) was employed to convert the raw matrices to readable matrices by network analysis software, including NetDraw (2017). We then extracted co-citation pairs to identify countries and researchers with common research interests. For this purpose, the entire list of article sources was converted to the format of Ravar PreMap software, and the data related to the cited pairs were taken from the software. Subsequently, to specify the most important researchers regarding the number of connections they have made with other nodes, the rank, intermediate, and closeness centrality indices were used in UCINET software and its complementary package of NetDraw. Finally, the following formula was used to calculate the growth coefficient of scientific production in the field of petroleum engineering on the WoS database:

$$1 - 2^R = \frac{Log_e W_2 - Log_e W_1}{T_2 - T_1}$$

In this formula, $1\text{-}2^R$ shows the relative growth coefficient in a given period, $Log_e W_1$ the logarithm of the initial number of articles, $Log_e W_2$ the logarithm of the final number of articles in the desired period $T_2\text{-}T_1$ the difference between the two periods of time.

## Results

**1. What is the growth trend of articles by researchers in petroleum engineering in the WoS database from 1985 to 2019?**

Diagram 1 shows the annual growth trend of articles published by petroleum engineering researchers in the WoS database from 1985 to 2019. The results show that the growth diagram has had an upward trend (growth coefficient of 8.22%) between 1985 and 2019. Petroleum engineering articles in the WoS database were declined in 2006 (growth coefficient of -0.14%). Still, in 2012 we were suddenly faced with an increase in the production of scientific articles in this area. The number of articles in petroleum engineering has increased from 209 articles in 2011 to 289 in 2012 (growth coefficient 2.45%).

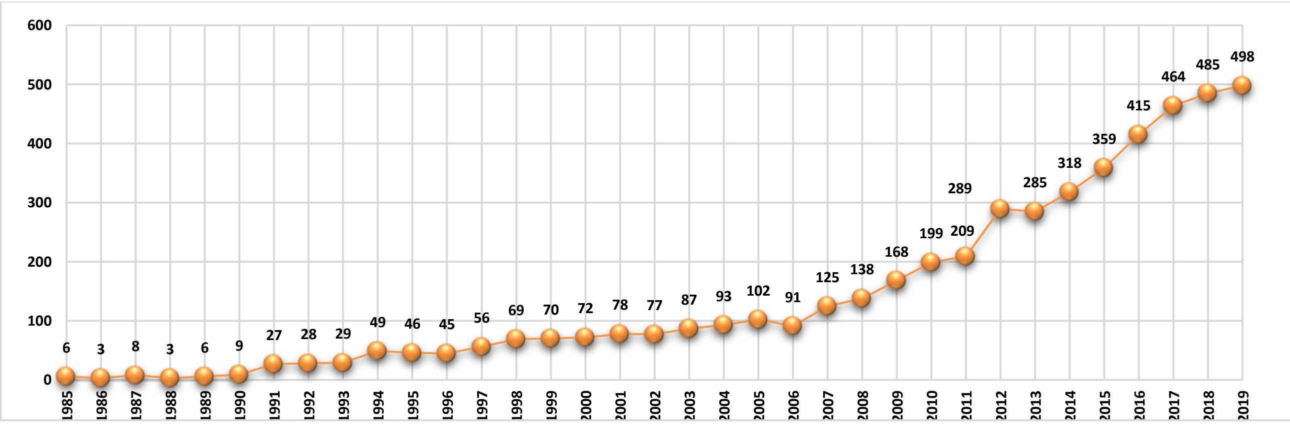



*Diagram1*: Growth Trend of Articles Published by Petroleum Engineering Researchers in the Web Science Database

**2. What is the frequency distribution of articles by researchers in petroleum engineering in the WoS database from 1985 to 2019 based on different countries of the world, and which countries have had the most scientific cooperation in this field?**

The frequency distribution of articles published by petroleum engineering researchers was extracted based on the country to answer the second research question. The findings show that most scientific productions in petroleum engineering among different countries belong to the USA, followed by the Republic of China. Table 1 shows the twenty countries with more than 50 scientific productions and the frequency of their productions.

Table 1

*Scientific Productions of the Top Twenty Countries in the field of Petroleum Engineering along with the Frequency of Productions*

| Rank | Country | Frequency | Rank | Country | Frequency |
|---|---|---|---|---|---|
| 1 | USA | 1353 | 11 | Saudi Arabia | 113 |
| 2 | Peoples Republic China | 1054 | 12 | Malaysia | 110 |
| 3 | Canada | 380 | 13 | Norway | 99 |
| 4 | Iran | 355 | 14 | Germany | 98 |
| 5 | England | 204 | 15 | Russia | 89 |
| 6 | Brazil | 185 | 16 | Japan | 81 |
| 7 | India | 174 | 17 | Scotland | 81 |
| 8 | France | 165 | 18 | Italy | 64 |
| 9 | Australia | 164 | 19 | Netherlands | 62 |
| 10 | South Korea | 120 | 20 | Mexico | 50 |

The results show that with 1353 articles produced between1985 to 2019 in the WoS database, the United States is ranked first in the world in producing scientific articles in petroleum engineering. After the United States, "China" and "Canada" ranked second and third with 1054 and 380 articles in petroleum engineering. It should be noted that among the top countries producing articles in petroleum engineering, "Iran" ranks fourth with 355 articles.

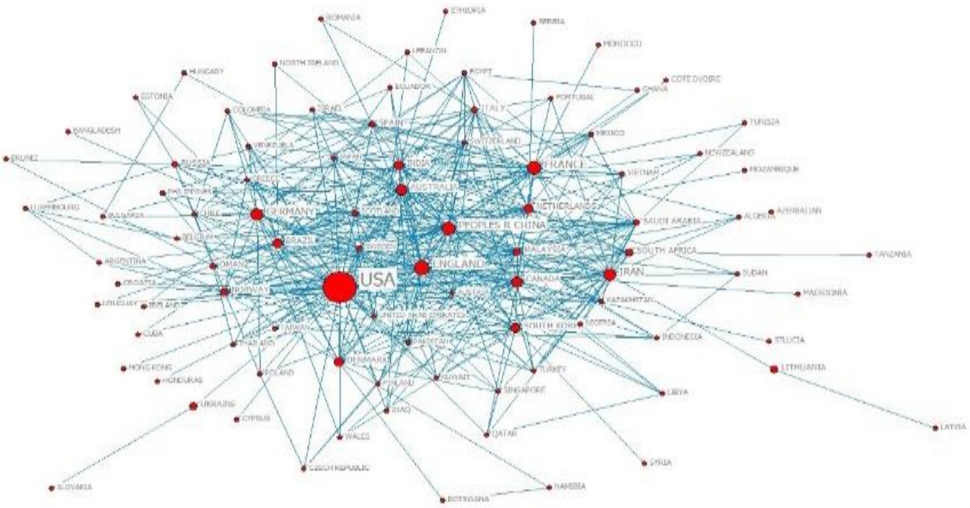



*Figure 1*: Map of Scientific Production of Top Twenty Countries in the field of Petroleum Engineering

Figure 1 shows a map of the scientific production of the top twenty countries in the field of petroleum engineering. As can be seen, the United States ranks first in the world in producing scientific articles in the field of petroleum engineering.

Table 2 shows the level of scientific cooperation between the top twenty countries producing articles in petroleum engineering.

Table 2

*The Level of Scientific Cooperation of the Top Twenty Countries Producing Articles in Petroleum Engineering*

| Rank | Country | Number of cooperation | Rank | Country | Number of cooperation |
|---|---|---|---|---|---|
| 1 | USA- China | 111 | 11 | USA- France | 16 |
| 2 | USA- Canada | 38 | 12 | USA- Saudi Arabia | 16 |
| 3 | Canada- Iran | 32 | 13 | USA- South Korea | 15 |
| 4 | China- Canada | 30 | 14 | USA -Germany | 15 |
| 5 | USA- England | 28 | 15 | China- England | 15 |
| 6 | USA- Brazil | 25 | 16 | Iran- Australia | 15 |
| 7 | USA- Australia | 23 | 17 | USA- Netherlands | 14 |
| 8 | USA- Iran | 21 | 18 | England- Scotland | 14 |
| 9 | Canada- Australia | 21 | 19 | USA- Japan | 12 |
| 10 | China- Australia | 17 | 20 | Iran- France | 11 |

Table 2 shows that the "US-China" with a total of 111 joint papers have had the most scientific cooperation in the production of petroleum engineering articles, followed by "USA-Canada" and "Canada-Iran" with 38 and 32 joint papers, respectively, which ranked second and third in the global scientific cooperation in the production of scientific papers in petroleum engineering.

**3. What is the frequency distribution of top specialized journals in petroleum engineering in the WoS database from 1985 to 2019 based on the total number of citations?**

The total citations, impact factor, publisher, country of publication, number of published articles, and highly cited articles in specialized journals in petroleum engineering were extracted to answer the third research question. Finally, the specialized journals in petroleum engineering were ranked based on the total citations. Table 3 only introduces the top ten journals in petroleum engineering in the WoS database from 1985 to 2019. Out of 1099 available journals, the core journals, according to the Bradford rule ($R^2$ = 0.9493 fit), include 25 journals, shown in diagram 2. The names and frequency of articles in these core journals are listed in Table 3.

Table 3

*Top Ten Journals in the field of Petroleum Engineering*

| Rank | Publication | Number of citations | Impact factor 2018 | Publisher | Country | Number of published articles | Number of highly cited articles |
|---|---|---|---|---|---|---|---|
| 1 | JOURNAL OF PETROLEUM SCIENCE AND ENGINEERING | 3241 | 2.88 | Elsevier | Netherlands | 6235 | 39 |
| 2 | ADVANCED FUNCTIONAL MATERIALS | 2548 | 15.62 | John Wiley & Sons Ltd. | United Kingdom | 11047 | 504 |
| 3 | MACROMOLECULAR MATERIALS AND ENGINEERING | 2080 | 3.03 | WILEY-V C H VERLAG GMBH | Germany | 2639 | 9 |
| 4 | NATURE | 1882 | 43.07 | Nature Publishing Group | United Kingdom | 106001 | 3611 |
| 5 | AICHE JOURNAL | 1847 | 3.51 | Wiley-Blackwell | UNITED STATES | 10842 | 6 |
| 6 | CURRENT OPINION IN BIOTECHNOLOGY | 1482 | 8.08 | Elsevier | Netherlands | 4028 | 46 |
| 7 | METABOLIC ENGINEERING | 1367 | 7.80 | Elsevier | UNITED STSTES | 1529 | 15 |
| 8 | RENEWABLE & SUSTAINABLE ENERGY REVIEWS | 1342 | 10.55 | Elsevier | Netherlands | 9605 | 986 |
| 9 | JOURNAL OF INDUSTRIAL AND ENGINEERING CHEMISTRY | 1319 | 3.37 | Korean Society of Industrial Engineering Chemistry | South Korea | 6041 | 26 |
| 10 | APPLIED MICROBIOLOGY AND BIOTECHNOLOGY | 1116 | 3.67 | Springer Verlag | Germany | 16316 | 28 |

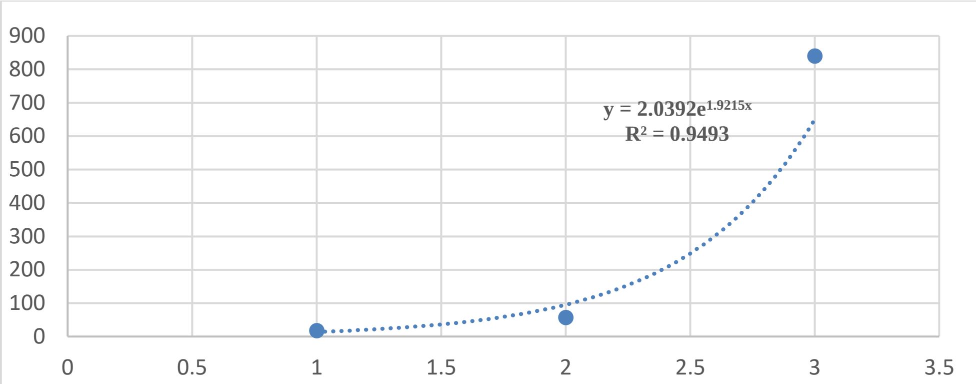



*Diagram 2*: Fitting the Frequency Distribution of Journal Articles in the field of Petroleum Engineering

Research findings show that the "Journal of Petroleum Science and Engineering" published by "Elsevier" in the Netherlands has ranked first in top journals in petroleum engineering with a total of 3241 citations, an impact factor of 2.88. Furthermore, "Advanced Functional Materials" published in Europe by "John Wiley & Sons Ltd." ranked second among the top journals of petroleum engineering with a total of 2548 citations and an impact factor of 15.62. The journal "Macromolecular Materials and Engineering" published in Germany by "WILEY-V C H VERLAG GMBH" had a total of 2080 citations, an impact factor of 3.03, which ranked third among the top journals in the field of petroleum engineering.

**4. What is the frequency distribution of top specialized journals in petroleum engineering in the WoS database from 1985 to 2019 based on the total number of citations?**

The total citations and the number of articles published by petroleum engineering researchers in the WoS database were extracted from 1985 to 2019 to answer the fourth research question. Finally, the top petroleum engineering researchers were ranked based on the total citations. Table 4 introduces only the top ten petroleum engineering researchers in the WoS database from 1985 to 2019 according to the total number of citations.

Table 4

*Top Ten Researchers in Petroleum Engineering in Wos Database from 1985 to 2019*

| Rank | Researcher | Number of citations in WoS | Total citations | Number of articles |
|---|---|---|---|---|
| 1 | KEASLING, JAY D | 2738 | 2840 | 15 |
| 2 | JOHNSON, CHRISTOPHER S | 2529 | 2562 | 1 |
| 3 | KIM, DONGHAN | 2529 | 2562 | 1 |
| 4 | LEE, EUNG JE | 2529 | 2562 | 1 |
| 5 | SLATER, MICHAEL D | 2529 | 2562 | 1 |
| 6 | MISRA, MANJUSRI | 1961 | 2032 | 10 |
| 7 | MOHANTY, AMAR K | 1937 | 1998 | 8 |
| 8 | HINRICHSEN, G | 1795 | 1850 | 1 |
| 9 | DEL CARDAYRE, STEPHEN B | 1429 | 1481 | 2 |
| 10 | PERALTA-YAHYA, PAMELA P | 1090 | 1121 | 3 |

Analysis of articles in the field of petroleum engineering based on the number of citations (impact) indicates that "KEASLING, JAY D." from the University of California has had a total of 15 articles published in the WoS database between 1985 and 2019 by receiving a total of 2840 citations (2738 in WoS database) and ranks first among the top researchers in petroleum engineering, which shows the credibility and high impact of his articles in this field of research.

In the following, we will extract co-citation pairs to identify petroleum engineering researchers who have common research interests. The frequency distribution of twenty co-citation pairs in petroleum engineering articles can be seen in Table 5.

Table 5
*Frequency Distribution of Twenty Co-Citation Pairs in Petroleum Engineering Articles*

| Rank | Co-citation pairs | Number of co-citations | Rank | Co-citation pairs | Number of co-citations |
|---|---|---|---|---|---|
| 1 | BAHADORI, ALIREZA-ZENDEHBOUDI, SOHRAB | 8 | 11 | CHAN, CHRISTINE W.-HARRISON, ROBERT | 5 |
| 2 | MISRA, MANJUSRI-MOHANTY, AMAR K | 8 | 12 | BAI, BAOJUN- HOU, JIRUI | 5 |
| 3 | ABDULRAHEEM, ABDUL-AZEEZ- MAHMOUD, MOHAMED | 6 | 13 | RIAZI, MASOUD-AYATOLLAHI, SHAHAB | 5 |
| 4 | BAI, BAOJUN- WEI, MINGZHEN | 6 | 14 | MANSHAD, ABBAS KHAKSAR- ASHOORI, SIAVASH | 5 |
| 5 | CLARKSON, CHRISTOPHER R.- QANBARI, FARHAD | 6 | 15 | BINOUS, HOUSAM-BELLAGI, AHMED | 5 |
| 6 | SHEREMETOV, LEONID-BATYRSHIN, ILDAR | 6 | 16 | HOU, JIRUI- ZHU, DAOYI | 5 |
| 7 | NIELSEN, JENS- SIEWERS, VERENA | 6 | 17 | MAHMOUD, MOHAMED-ELKATATNY, SALAHELDIN | 5 |
| 8 | MATSUMOTO, KENICHIRO-TAGUCHI, SEIICHI | 6 | 18 | ISMAIL, NOOR ILYANA-YUSOF, MUHAMMAD ASLAM MD | 5 |
| 9 | ZENDEHBOUDI, SOHRAB-CHATZIS, IOANNIS | 5 | 19 | YU, WEI- WU, KAN | 5 |
| 10 | ABDULRAHEEM, ABDUL-AZEEZ- TARIQ, ZEESHAN | 5 | 20 | ZOU, CAINENG- ZHU, RUKAI | 5 |

According to an analysis of data related to co-citations of researchers, it was found that "BAHADORI, ALIREZA-ZENDEHBOUDI, SOHRAB" had the highest number of co-citations (8) with each other and are in the first place. "MISRA, MANJUSRI-MOHANTY, AMAR K" (8) are in the second place and "ABDULRAHEEM, ABDUL-AZEEZ-MAHMOUD, MOHAMED" (6) in the third-place of co-citations in the field of petroleum engineering.

Subsequently, the rank, intermediate, and closeness centrality indices were used to determine the most influential researchers in co-citation in terms of the number of connections they made with other nodes. The node or entity studied in this research is researchers in petroleum engineering. Table 6 shows the names of top researchers in petroleum engineering based on the rank centrality index.

Table 6
*Top Ten Researchers in the field of Petroleum Engineering based on the Rank Centrality Index*

| Rank | Researcher | Centrality index |
|---|---|---|
| 1 | BAHADORI, ALIREZA | 21 |
| 2 | ZENDEHBOUDI, SOHRAB | 15 |
| 3 | MOHAMMADI, AMIR H | 14 |
| 4 | SHOKROLLAHI, AMIN | 11 |
| 5 | BAI, BAOJUN | 11 |
| 6 | MAHMOUD, MOHAMED | 11 |
| 7 | ABDULRAHEEM, ABDUL-AZEEZ | 10 |
| 8 | ARABLOO, MILAD | 10 |
| 9 | ROSTAMI, ALIREZA | 10 |
| 10 | ELKATATNY, SALAHELDIN | 9 |

As can be seen in Table 6, "BAHADORI, ALIREZA" from New South Wales Oil and Gas Company of Australia with a centrality of 21 ranked first among the top researchers in petroleum engineering based on the centrality index, followed by "ZENDEHBOUDI, SOHRAB" from Memorial University of Canada and "MOHAMMADI, AMIR H." from the University of KwaZulu-Natal in South Africa who ranked second and third with the centrality of 15 and 14, respectively. According to the rank centrality index, the following is an overview of the network of highly cited researchers in petroleum engineering. In Figure 2, the most cited and influential researchers are identified with larger circles. The larger the diameter of the circle representing the researcher, the greater the number of links and the higher the impact on the network.

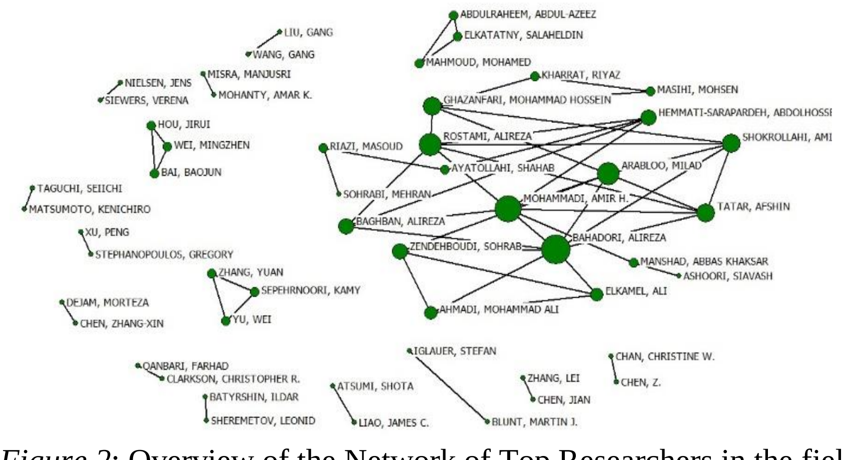



*Figure 2*: Overview of the Network of Top Researchers in the field of Petroleum Engineering based on the Ranking Centrality Index

As can be seen in Figure 2, "BAHADORI, ALIREZA", "ZENDEHBOUDI, SOHRAB", and "MOHAMMADI, AMIR H" rank first, second and third among top researchers in the field of petroleum engineering according to the centrality index, respectively.

Table 7 shows the names of top researchers in petroleum engineering according to the intermediate centrality index, which identifies a node with the least distance between two other nodes; in other words, it shows the power and influence of a researcher in the network. These researchers can isolate or enhance communication. Nodes with high intermediate centrality play an essential role in network connection and have a central position in the network.

Table 7
*Top Ten Researchers in the field of Petroleum Engineering based on the Intermediate Centrality Index*

| Rank | Researcher | Intermediate centrality |
|---|---|---|
| 1 | MOHAMMADI, AMIR H | 48.75 |
| 2 | HEMMATI-SARAPARDEH, ABDOLHOSSEIN | 45 |
| 3 | BAHADORI, ALIREZA | 35.75 |
| 4 | GHAZANFARI, MOHAMMAD HOSSEIN | 32.37 |
| 5 | AYATOLLAHI, SHAHAB | 32 |
| 6 | ROSTAMI, ALIREZA | 28.08 |
| 7 | ARABLOO, MILAD | 1908 |
| 8 | RIAZI, MASOUD | 17 |
| 9 | MANSHAD, ABBAS KHAKSAR | 17 |
| 10 | BAGHBAN, ALIREZA | 8.20 |

As shown in Table 7, "MOHAMMADI, AMIR H." from the University of KwaZulu-Natal in South Africa had an intermediate centrality of 48.75 and ranked first among the top researchers in petroleum engineering based on intermediate centrality index. "HEMMATI-SARAPARDEH, ABDOLHOSSEIN" from the University of Calgary (Canada) and "BAHADORI, ALIREZA" from the New South Wales Oil and Gas Company of Australia ranked second and third with intermediate centrality of 45 and 35.75, respectively. Researchers with high intermediate centrality, according to Table 7, are more powerful mediators in linking and streamlining knowledge in the network. Figure 3 shows an overview of the network of highly cited researchers in petroleum engineering based on the intermediate centrality index.

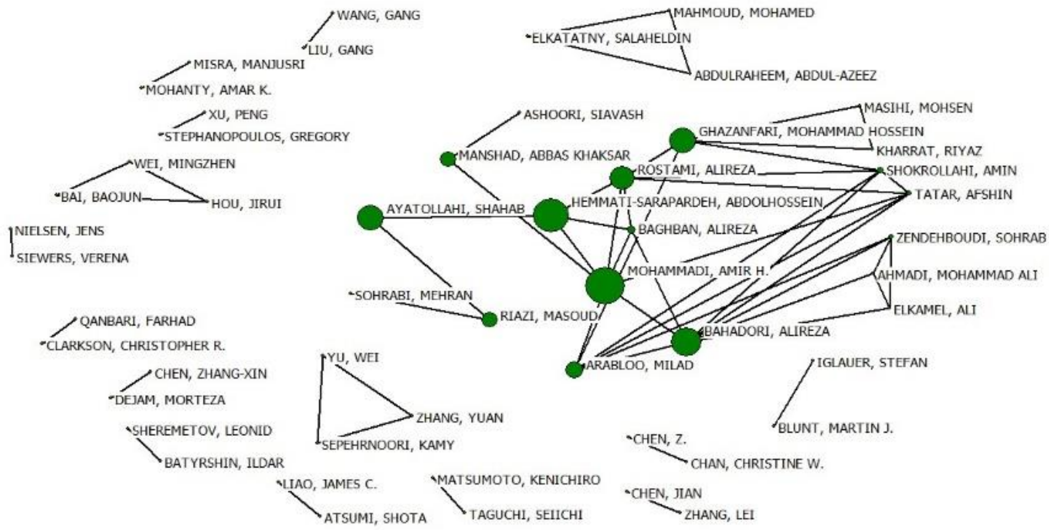



*Figure 3*: Overview of the Network of Top Researchers in Petroleum Engineering According to Intermediate Centrality Index

As shown in Figure 3, the larger the diameter of the circles, the higher the intermediate centrality, and the smaller the diameter of the circles, the lower the intermediate centrality. The largest circle belongs to "MOHAMMADI, AMIR H.", which has a greater intermediate centrality than other researchers in petroleum engineering, with "HEMMATI-SARAPARDEH, ABDOLHOSSEIN" and "BAHADORI, ALIREZA" in second and third positions, respectively.

Table 8 shows the names of top researchers in petroleum engineering according to the closeness centrality index. Closeness centrality determines the total shortest distance of the researcher to other researchers. In other words, it can be stated that researchers with a high closeness centrality have a higher chance of co-citation with other researchers.

Table 8

*Top Ten Researchers in the Field of Petroleum Engineering Based on the Closeness Centrality Index*

| Rank | Researcher | Closeness centrality |
|---|---|---|
| 1 | AGUILERA, ROBERTO | 0.143 |
| 2 | ALVARADO, VLADIMIR | 0.143 |
| 3 | BINOUS, HOUSAM | 0.143 |
| 4 | GUO, BOYUN | 0.143 |
| 5 | ISLAM, M. R. | 0.143 |
| 6 | ISMAIL, NOOR ILYANA | 0.143 |
| 7 | JANSEN, JAN DIRK | 0.143 |
| 8 | JIN, YAN | 0.143 |
| 9 | KE, YANG-CHUAN | 0.143 |
| 10 | KEASLING, JAY D | 0.143 |

As indicated in Table 8, "AGUILERA, ROBERTO" from University of Calgary (Canada), "ALVARADO, VLADIMR" from University of Wyoming (USA), "BINOUS, HOUSAM" from University of Carthage (Tunisia), "GUO, BOYUN" from University of Louisiana (USA), " ISLAM, M. R "from University of Dalhousie (Canada)," ISMAIL, NOOR ILYANA from the University of Monash (Australia)," JANSEN, JAN DIRK "from University of Delft (Netherlands)," JIN, YAN "and" KE, YANG-CHUAN "from the University of China and "KEASLING, JAY D" from University of Berkeley (USA) with closeness centrality of 0.143 ranked first in closeness centrality index. Researchers with a high degree of closeness have a higher chance of co-citation with other researchers in this field. Figure 4 shows a schema of the network of highly cited researchers in petroleum engineering according to the closeness centrality index.

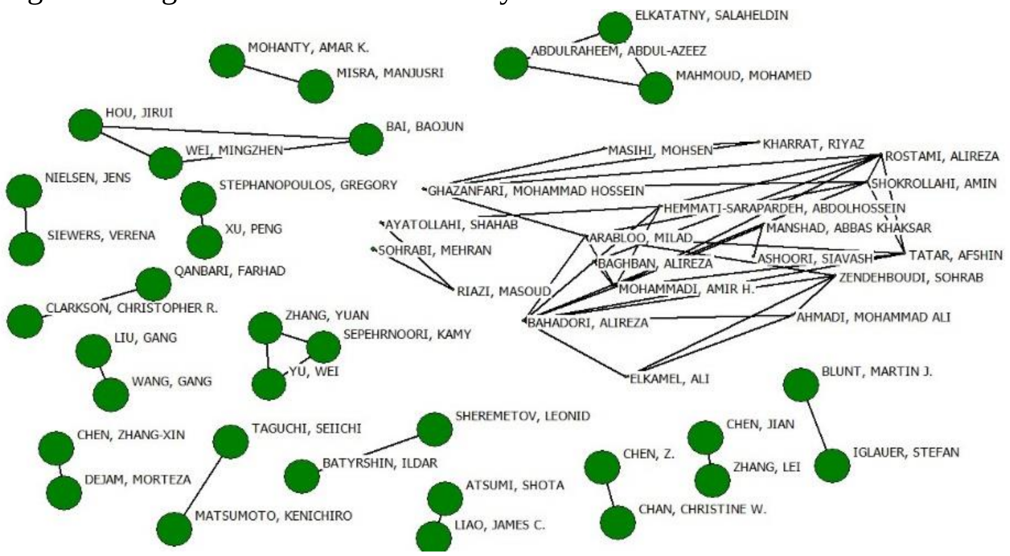


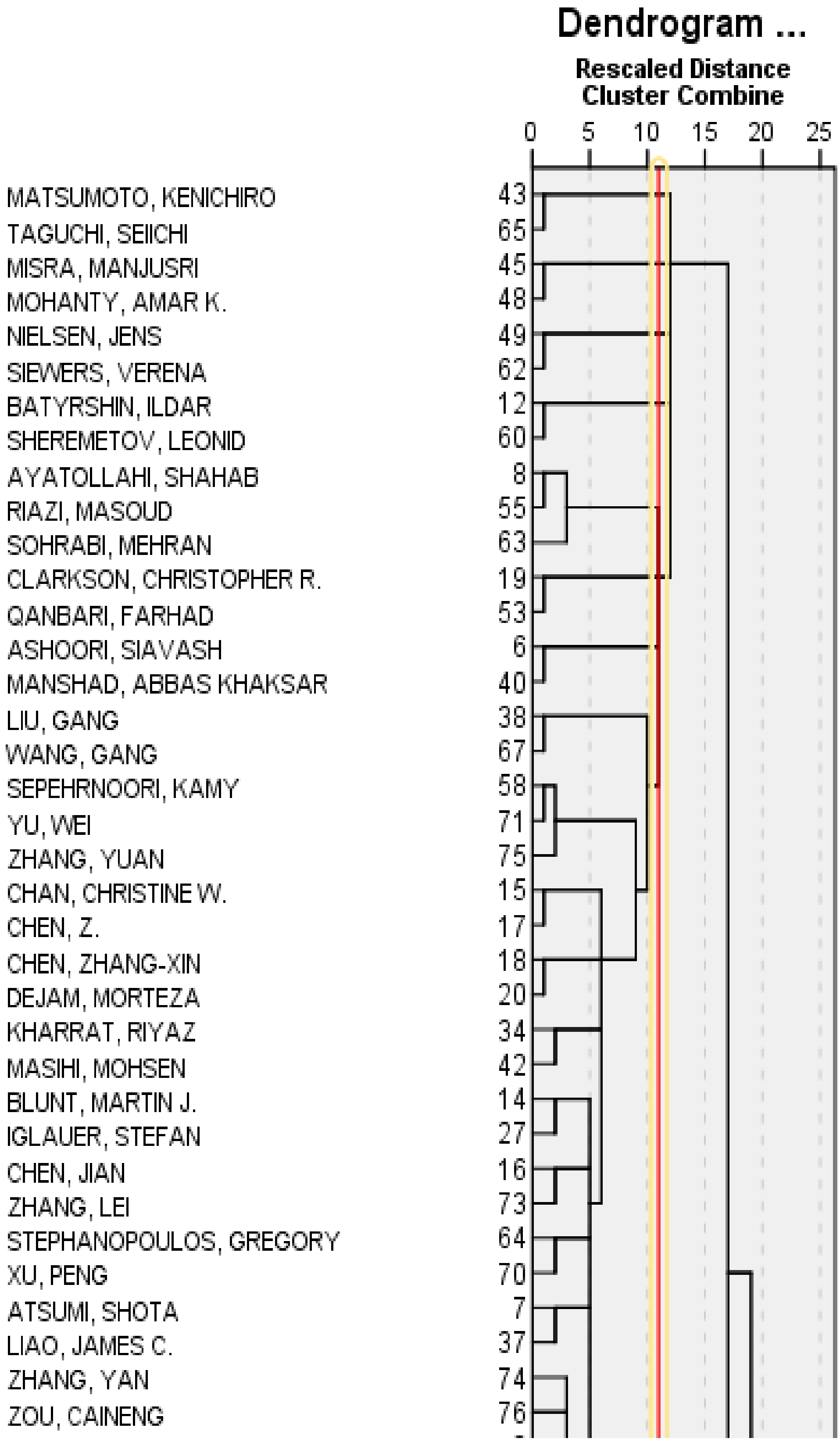

*Figure 4*: Overview of the Network of Top Researchers In Petroleum Engineering Based on Closeness Centrality Index

As shown in Figure 3, the larger the diameter of the circles, the higher the closeness centrality, and the smaller the diameter of the circles, the lower the closeness centrality. In this Figure, authors such as "ATSUMI, SHOTA", "BATYRSHIN, ILDAR", "BLUNT, MARTIN J", "CHAN, CHRISTINE W", "CHEN, JIAN", "CHEN, Z", "CHEN, ZHANG-XIN" , "CLARKSON, CHRISTOPHER R", "DEJAM, MORTEZA" and "IGLAUER, STEFAN" have a higher closeness centrality than other researchers in the field of petroleum engineering.

Overall, the survey of a network of petroleum engineering researchers according to centrality indices showed that "BAHADORI, ALIREZA" from New South Wales Oil and Gas Company of Australia and "MOHAMMADI, AMIR H" from KwaZulu-Natal University in South Africa ranked first and second in rank and intermediate centrality indices, respectively. Therefore, it can be said that these two researchers have played a more crucial role in scientific production in petroleum engineering.

**5. How is the hierarchical clustering of co-citation for researchers in petroleum engineering?**

A dendrogram was prepared for hierarchical clustering of co-citation for petroleum engineering researchers in SPSS software using the correlation matrix derived from the square matrix. The dendrogram provides useful tips and information about the clusters, researchers in clusters, and the intellectual structure of the study area.



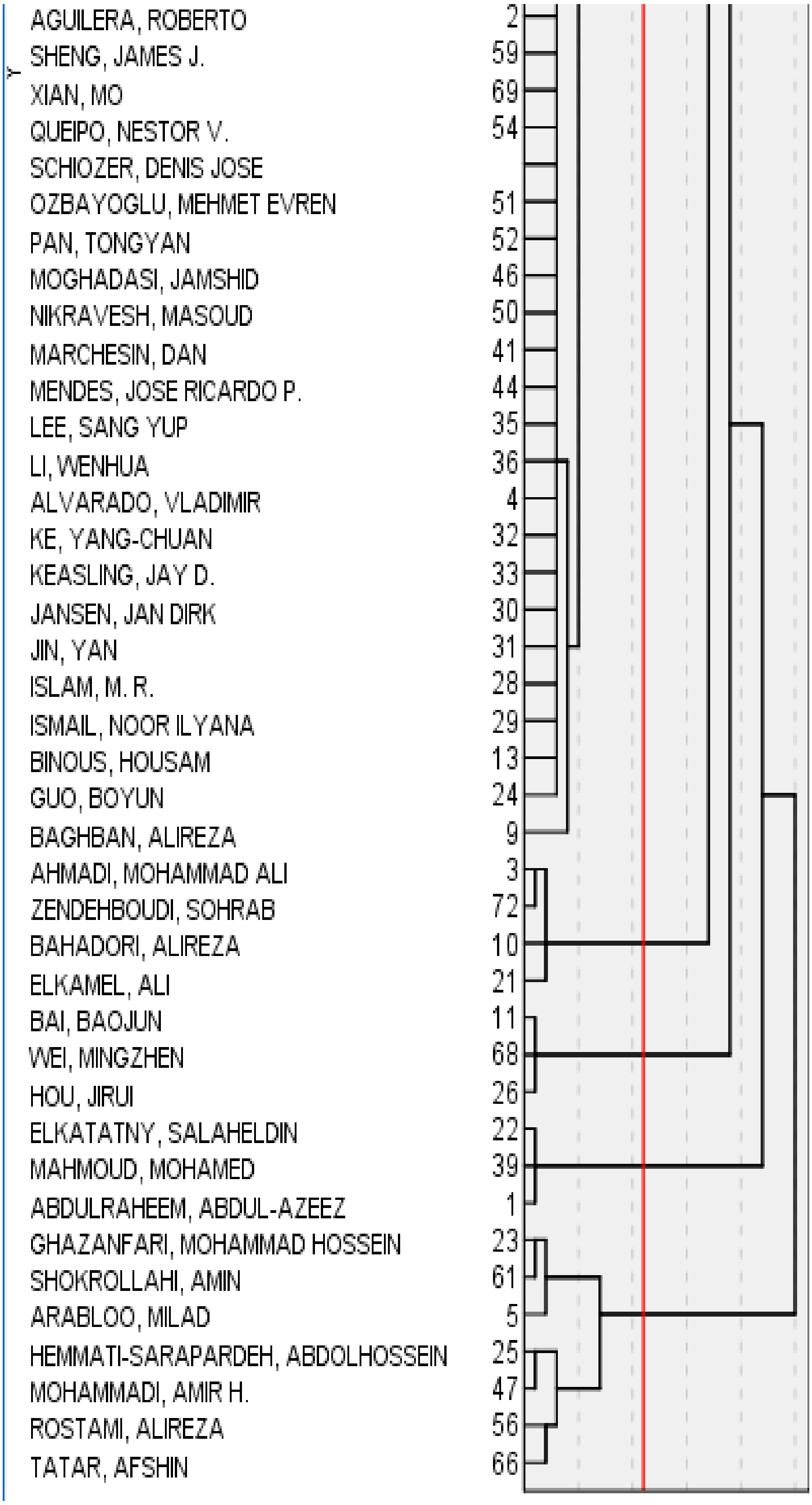



*Figure 5*: Dendrogram of Hierarchical Clustering of Co-Citation of Researchers in the field of Petroleum Engineering

As indicated in the dendrogram (Figure 5), the analysis of co-citations in the field of petroleum engineering has led to the formation of four clusters. More detailed information about each of the relevant clusters and researchers is provided in Table 9.

Table 9
*Thematic Clusters of Petroleum Engineering Articles*

| Researchers in the cluster | Cluster theme | Number of researchers | Cluster No. |
|---|---|---|---|
| ABDULRAHEEM, ABDUL-AZEEZ; ELKATATNY, SALAHELDIN; MAHMOUD, MOHAMED | Reservoir engineering | 3 | Cluster 1 |
| AGUILERA, ROBERTO; AHMADI, MOHAMMAD ALI; ALVARADO, VLADIMIR; ASHOORI, SIAVASH; ATSUMI, SHOTA; AYATOLLAHI, SHAHAB; BAGHBAN, ALIREZA; BAHADORI, ALIREZA; BATYRSHIN, ILDAR; BINOUS, HOUSAM; BLUNT, MARTIN J; CHAN, CHRISTINE W; CHEN, JIAN; CHEN, Z; CHEN, ZHANG-XIN; CLARKSON, CHRISTOPHER R; DEJAM, MORTEZA; ELKAMEL, ALI; GUO, BOYUN; IGLAUER, STEFAN; ISLAM, M. R; ISMAIL, NOOR ILYANA; JANSEN, JAN DIRK; JIN, YAN; KE, YANG-CHUAN; KEASLING, JAY D; KHARRAT, RIYAZ; LEE, SANG YUP; LI, WENHUA; LIAO, JAMES C; LIU, GANG; MANSHAD, ABBAS KHAKSAR; MARCHESIN, DAN; MASIHI, MOHSEN; MATSUMOTO, KENICHIRO; MENDES, JOSE RICARDO P; MISRA, MANJUSRI; MOGHADASI, JAMSHID; MOHANTY, AMAR K; NIELSEN, JENS; NIKRAVESH, MASOUD; OZBAYOGLU, MEHMET EVREN; PAN, TONGYAN; QANBARI, FARHAD; QUEIPO, NESTOR V; RIAZI, MASOUD; SCHIOZER, DENIS JOSE; SEPEHRNOORI, KAMY; SHENG, JAMES J; SHEREMETOV, LEONID; SIEWERS, VERENA; SOHRABI, MEHRAN; STEPHANOPOULOS, GREGORY; TAGUCHI, SEIICHI; WANG, GANG; XIAN, MO; XU, PENG; YU, WEI; ZENDEHBOUDI, SOHRAB; ZHANG, LEI; ZHANG, YAN; ZHANG, YUAN; ZOU, CAINENG | Exploration engineering | 63 | Cluster 2 |
| GHAZANFARI, MOHAMMAD HOSSEIN; HEMMATI-SARAPARDEH, ABDOLHOSSEIN; MOHAMMADI, AMIR H; ROSTAMI, ALIREZA; SHOKROLLAHI, AMIN; TATAR, AFSHIN | Drilling and mining engineering | 6 | Custer 3 |
| BAI, BAOJUN; HOU, JIRUI; WEI, MINGZHEN | Resource exploitation engineering | 3 | Cluster 4 |

After designing the dendrogram, at this stage, it is necessary to accurately identify and study the articles of researchers in each cluster and compare them with those of other researchers in that cluster to determine the main theme of that cluster finally. For this purpose, after obtaining complete information regarding the name and surname of researchers, the articles were reviewed and studied separately for each of the researchers in the clusters to specify the field of work for the relevant researchers. In the following, we will examine the clusters derived from the hierarchical clustering of co-citations for researchers in petroleum engineering.

**Cluster 1: Reservoir Engineering.** This cluster includes three researchers. According to the identification, study, and review of the subject areas of researchers in cluster 1, "reservoir engineering" is the theme assigned to this cluster. These three researchers are among the top ten researchers in petroleum engineering based on the rank centrality index.

**Cluster 2: Exploration Engineering.** This cluster has the highest number of researchers so that 63 researchers have played a role in the formation and evolution of this cluster. After reviewing the researchers and their articles, the label "exploration engineering" was appropriate for this cluster. "AGUILERA, ROBERTO", "ALVARADO, VLADIMIR", "BINOUS, HOUSAM", "GUO, BOYUN", "ISLAM, M. R", "ISMAIL, NOOR ILYANA", "JANSEN, JAN DIRK" , "JIN, YAN" and "KE, YANG-CHUAN" are among the top ten researchers in the field of petroleum engineering according to centrality index; "AYATOLLAHI, SHAHAB", "BAGHBAN, ALIREZA", "MANSHAD, ABBAS KHAKSAR" and "RIAZI, MASOUD" are the top ten researchers in petroleum engineering based on intermediate centrality index; "BAHADORI, ALIREZA" is one of the top ten researchers in petroleum engineering according to rank and intermediate centrality index; ZENDEHBOUDI, SOHRAB is among the top ten researchers in petroleum engineering based on rank centrality index. Furthermore, the study of researchers in this cluster indicated that "KEASLING, JAY D" was in the first rank, "MISRA, MANJUSRI" in the sixth rank, and "MOHANTY, AMAR K" in the seventh rank among the most cited researchers in petroleum engineering, which indicates the credibility and high impact of their articles in this field of research and the critical role they play in advancing the knowledge in petroleum engineering.

**Cluster 3: Drilling and Mining Engineering.** This cluster includes six researchers. The central theme of this cluster seems to be "drilling and mining engineering". Among the researchers in this cluster, "GHAZANFARI, MOHAMMAD HOSSEIN" and "HEMMATI-SARAPARDEH, ABDOLHOSSEIN" are among the top ten researchers in petroleum engineering based on the intermediate centrality index; "MOHAMMADI, AMIR H" and "ROSTAMI, ALIREZA" are among the top ten researchers in petroleum engineering according to rank and intermediate centrality index; "SHOKROLLAHI, AMIN" are among the top ten researchers in petroleum engineering based on rank centrality index.

**Cluster 4: Resource exploitation engineering.** This cluster includes three researchers, and the main theme of this cluster appears to be "resource exploitation engineering". According to rank centrality index, among the researchers in this cluster, "BAI, BAOJUN" is one of the top ten researchers in petroleum engineering.

## Discussion

Although scientometric studies are often retrospective, their results effectively determine the potential of researchers and research institutes in the future. Such studies are based on the past and illuminate the way of the future. Accordingly, decision-makers in research policies and guidelines can apply the results of this research in their planning. Moreover, the growing trend of scientific productions has increased the need of the scientific community for scientometric studies and doubled the evaluation of research.

According to the results of the present study, it can be acknowledged that the growth trend of petroleum engineering has had an upward trend with a growth coefficient of 8.22%; however, the decrease in the production in this area in 2006 should be taken into account. The present study results are in line with the results of the research of Zhou et al. (2008) and Bhakta and Bhui (2018). They also pointed to the upward trend of publications in their research. Throughout history, prominent, well-known, and influential individuals, countries, and organizations have always been considered and have had key and influential roles, creating networks through connections that exist between them and their counterparts. Using network analysis, it was found that "BAHADORI, ALIREZA" from New South Wales Oil and Gas Company of Australia is more scientifically influential than other researchers and has been introduced as the most prominent figure in the field of petroleum engineering. Based on the centrality index, an individual's centrality in a research field indicates the authority and competence of the individual in that field. In other words, centrality is a criterion that quantifies the superiority of individual role-playing and is measured using the rank of different nodes in the network. Hence, the centrality index attempts to measure the number of internal and external links of a researcher, and a central researcher effectively communicates with other researchers. As a result, "BAHADORI, ALIREZA" from the New South Wales Oil and Gas Company of Australia, with a centrality of 21, ranked first among the top researchers in petroleum engineering as shown by the centrality index. In general, rank centrality usually reflects the reputation and communication activity of a researcher, and according to the intermediate centrality index, "MOHAMMADI, AMIR H." from the University of KwaZulu-Natal in South Africa has a higher ability as an intermediary link causing knowledge expansion in the network. Intermediate centrality identifies a researcher's position within a research area in terms of their ability to connect with other researchers on the network. Bhakta and Bhui (2018), Busygina and Rykova (2020), and Das and Ghosh (2020), in their research, expressed the top journal and the most influential authors.

## Conclusion

Interestingly, a node with a relatively low intermediate rank may play an essential intermediary role and be highly central to the network because it can increase communication. Moreover, researchers capable of reaching their peers in the shortest path and someone available to other researchers in the shortest distance have a high degree of closeness and a higher chance of being co-cited by other researchers in this field. The closeness centrality index determines how quickly a researcher on a network can access more researchers on that network. It is worth noting that the higher the closeness centrality of a researcher, the higher their visibility in that area. Therefore, network analysis provides valuable information for planning, managing, and forecasting long-term and short-term goals. Finally, the results reveal that although some countries such as Iran, Saudi Arabia, Iraq, Norway, and so forth are oil-rich globally, their scientific production is lower relative to countries lacking extensive oil reservoirs. Consequently, further attention should be paid to research and development in scientific fields of petroleum science, especially the global science of petroleum engineering with a development and exploitation approach.

Finally, the results of this research can lead to potential capabilities in the field of review and recognition of existing needs in this field. Also, the results of this research can encourage idea makers to present their creativity in the presence of engineers and capital owners and provide the ground for turning ideas into products in petroleum engineering (Janavi & Emami, 2021). Therefore, it can be said that by drawing scientific maps in different thematic areas, we can show the progress of knowledge, the flow of knowledge, and the formation of communication and play an effective role in scientific policies and planning. Therefore, paying attention to the analysis of social networks and how communication of articles in petroleum engineering can be fruitful in various fields. Co-citation analysis of articles allows the structure of the internal relations of a subject area to be objectively displayed and to help understand the structure of the relationship between researchers and the subject area. Therefore, using the results of this study, it can be said that scientific products have a vital role in petroleum engineering and can show the current state of communication and how the relationship between articles in this field.

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