A mini-investigation on enhanced oil recovery evolution (2007 – 2020)

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Abstract. Energy plays an important role in sustaining humanity. With rising worldwide energy demand and the great dependence of energy generation on fossil fuels, it is inevitable that enhanced oil recovery must be deployed to recover more possible reserves. This report focuses on reviewing publications related to enhanced oil recovery from 2007 to 2020 through the utilization of bibliometric analysis. Of the 5498 documents retrieved from Web of Science, 569 journals, 90 countries, 2025 organizations, and 8684 authors are involved. China, the United States, Iran, Canada, and India published the most documents. The United States has the highest h-index at 61. The analysis of keywords had shown that the hot issues lie around four main domains namely carbon capture, utilization, and sequestration (CCUS), microbial enhanced oil recovery (MEOR), development of unconventional reserves, and chemical enhanced oil recovery. This study provides some useful insights for future research directions. From there, discussions were subsequently placed on chemical EOR.

1. Introduction

Amidst the urge of renewable energy usage fiasco and the critical need to reduce greenhouse gases emissions, hydrocarbons have remained the world's major energy source. Alternative energy sources have yet to be technically, socially, or economically plausible to support the recent blooming increase in worldwide energy demand, which has risen by more than 40 % over the past 15 years. It is known that hydrocarbon energy sources comprised of oil, natural gas, and coal, provide 82 % of the total primary energy supply (TPES). In comparison, renewable energies collectively provided only about 14% of the TPES in 2016 [1]. Thus, reliance on hydrocarbon-based energy sources will not be halted at this moment, as shown by BP's energy outlook where oil and gas demand will continue to surge until 2040 [2].

It is approximated that merely up to one-third of the original oil in place (OOIP) in a reservoir is accessible. There are three stages of hydrocarbon recovery: (1) primary oil recovery, which utilizes intrinsic reservoir's pressure, and harvests up to one-tenth of OOIP; (2) secondary oil recovery, which employs water injection, obtains up to 40 % of OOIP; (3) tertiary or enhanced oil recovery (EOR) which maximizes the remaining oil production [3]. Thus, with the current scarcity of economically viable conventional reservoirs, coupled with fluctuating oil prices, the development of EOR is critical for the time being, prior to the reliable maturity of alternative energy sources. This is to ensure sustainable energy supply and demand [4]. During an EOR process, oil displacement and volumetric sweep efficacies are subsequently improved through several mechanisms such as oil viscosity reduction, mobility ratio improvement by raising the injected fluid phase viscosities, interfacial tension, and capillary pressure reduction at the oil/water interface due to wettability alteration [5]. These mechanisms result in the mobilization of trapped oil that could not otherwise be produced. However, formation rock properties such as permeability and porosity heterogeneities, fluid properties, formation surface wettability, and reservoir energy drive mechanisms affect the efficacies of the EOR process, most notably rock properties [6].

Heterogeneity in porosities and permeability has great influences on the efficacy of oil production. For instance, tight formations which have a porosity of about 20% and permeability ranges between the scale of micro-Darcy (μD) and mD, possess lower recovery factor (RF) of about 5 % - 30 % [7]. Conventional reservoirs can reach RF of up to 50 % under primary and secondary recovery combined [8]. Recently, countries such as Australia, Argentina, China, Canada, and the United States are actively participating in the discoveries and exploitations of unconventional hydrocarbon reserves such as tight formations, shale oil and gas, coal bed methane (CBM), bitumen hydrocarbons, oil sands, and heavy oil reservoirs. China specifically, possesses 643 billion barrels of shale oil in place, but only about 5 % of the total OOIP, mainly from Junggar, Tarim and Songliao Basins are technically producible [9]. The rise in the development of unconventional reserves is mostly due to the shortage of new conventional reservoirs. In the United States, 75 % of gas and 50 % of hydrocarbon liquid production are sourced from unconventional reservoirs [10]. On the other hand, heavy oil occupies one-quarter of the world's oil reserves, with total reserves of 5.6 trillion barrels However, only about 11.6 % of the total reserves can be extracted with currently available technology [11].

Unconventional reservoirs usually face low recoverability challenges and a production life expectancy of fewer than 10 years due to their complex intrinsic geographical, rock and fluid properties [9]. For instance, the high viscosity of heavy oil and the presence of heavy metals and high molecular weight components such as asphaltene and resins result in production difficulties [12]. Hence, the development of facile, effective, and flexible EOR techniques for both conventional and unconventional reservoirs is of utmost importance. Many review articles on EOR have recently been published, mainly on chemical EOR and development of unconventional reservoirs [10, 13-16]. With a progressively surging number of academic outputs, this study employs bibliometric analysis to assemble and process the existing literature on EOR. As a statistical-based tool that manages full records of publications and integrates information regarding the progression of specific research fields and whole subject areas, bibliometric analysis is a facile but efficient method to quantitatively and qualitatively analyze academic literature [17]. This report aims to analyze worldwide research trends in EOR throughout of 2007 – 2020 by exploring the Web of Science (WoS) database. Specifically, the publication trends, geographical distributions of publications, and research hotspots based of keyword analysis are analyzed appropriately in this study. The bibliological results will provide a holistic view on the development trajectory of worldwide EOR development and grant future insights into EOR research direction.

2. Methods

A comprehensive search was performed using the search expression of TS = "enhanced oil recovery" or "oil recovery enhancement" or "enhanced oil-recovery" or "enhanced-oil recovery" or "enhanced-oil-recovery" or "tertiary oil recovery" or "advanced oil recovery" in WoS database. The results were further refined by limiting only article and review because these two types of publications possess comprehensive state-of-the-art in the research field [18]. The bibliometric data were processed using Vosviewer 1.6.9 (www.vosviewer.com) to allow better visualization of the complex network formed by investigating different gauges. A complex network is formed from communities that comprising nodal sets containing strongly-interacting nodes [19]. Interaction strengths are represented by the thickness of lines connecting each node [18].

3. Results and discussions

3.1. General trends

The yearly number of articles and reviews total publication (TP) from 1973 to 2020 are depicted in Fig. 1. Two relevant trends were observed. The first trend was from 1973 to 2007, while the second was from 2007 to 2019. The growth rate in terms of publication number is slow in the first trend as compared to the second trend, which is represented by their slopes, respectively. The first trend has a slope of 1.91, while the second trend has a slope of 69.1, which is 36 times greater. Generally, from 2009 onwards, there is a small fluctuation in the rate of increase with a slight regressing slope. This signifies continual research efforts that maintain the rate of publications amidst the plummeting oil prices from 2014 to 2016 [20].

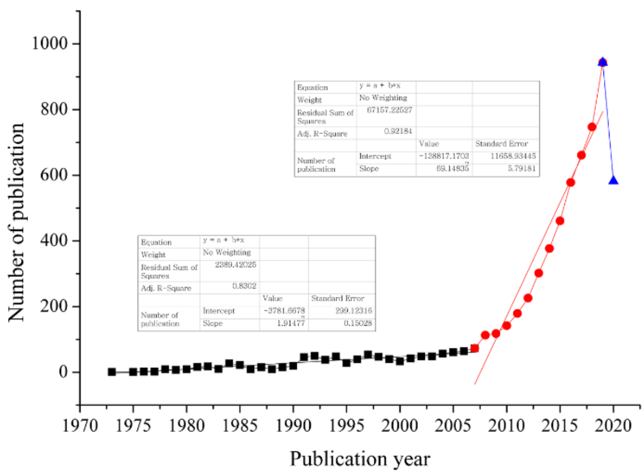

Fig. 1. Number of publications from year 1973 to 2020.

Meanwhile, from 2007 to 2008 there is an obvious increment rate surge in terms of publication numbers. This is due to the oil price surge of 57.68 % from 2007 to 2008 with a closing price of $ 99.67 per barrel in 2008 [20]. This condition can also be explained using Price's law. According to Price's law, four different stages do exist: (1) precursors stage which signify the beginning stage of research where scientists just started publishing researches; (2) exponential growth stage where the number of research is increasing exponentially due to the increased interests on the specific topic; (3) consolidation stage where researches are mainly on fortifying previous findings; (4) saturation stage where publication number starts to decrease [21]. Judging from the result obtained in Fig. 1, the current research stage could be situated between stage 2 and stage 3. This is due to the surge in publication numbers from 2018 to 2019. Nonetheless, this proved that the research on EOR is still progressing steadily in the recent decade due to the growing worldwide energy demand and the need to recover more oil from currently producing reservoirs and unconventional reservoirs.

3.2. Countries or regions

Fig. 2 depicts the global distribution of contributing countries and regions. 90 countries or regions have contributed to the 5498 publications on EOR. Among the 90 countries, 51 countries produced 10 or fewer publications (56.67 % out of the 90 countries), followed by 24 countries that produced less than 100 publications (26.67 %) and 15 countries that produced 100 or more publications (16.67 %). Table

1 depicts the information on the top 10 most productive countries. It was found that China and USA are the main publication producers, accounting for 53.70 % of the total publication number. It should be noted that the number of publications reported includes documents with authors affiliated with different countries/regions or authors originating from different countries. This implied that certain papers might be considered a publication from two or more countries, resulting in overlapping entries [17]. Nonetheless, most analysis was solely based on the former publication numbers containing overlapping entries to prevent confusion, including the h-index analysis. 5 of the 7 major world industrialized countries (G7) namely USA, Germany, Canada, France, and England are in the top-20 most productive ranking. This seemed to show that optimistic economic progression had encouraged the current bloom of scientific researches [21]. The USA has the highest h-index of 61, followed by China; 47, Iran; 47, Canada; 40, and India; 37.

Table 1. Top 10 most productive countries in EOR research.

No.	Countries/Regions	TP	TC	TC/TP (R)	h-index (R)
1	Peoples R China	1596	16476	10.32 (9)	47 (2)
2	USA	1282	19991	15.59 (5)	61 (1)
3	Iran	766	10218	13.34 (8)	47 (=2)
4	Canada	497	7595	15.28 (6)	40 (4)
5	India	250	5547	22.19 (1)	37 (5)
6	England	223	4788	21.47 (2)	34 (6)
7	Norway	207	3621	17.49 (4)	34 (=6)
8	Netherlands	194	3653	18.83 (3)	29 (8)
9	Malaysia	176	1793	10.19 (10)	21 (10)
10	Australia	168	2481	14.77 (7)	24 (9)

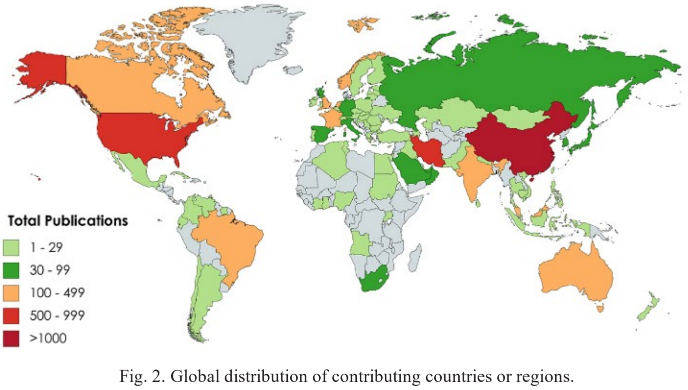

Fig. 2. Global distribution of contributing countries or regions.

3.3. Research hotspots

A total of 9101 author keywords and 7090 Keywords Plus involved in the past 13 years (2007-2020) were obtained after annihilating and unifying repeated words, abbreviations, and terms in singular and plural forms. By comparing both author keywords and keywords plus, many terms were found to be repeated, and some of them have a similar meaning or fall into the same type of subject albeit having different spelling. It was also found that most of the keywords are general terms, with only a few specific terms such as asphaltene, *Bacillus subtilis* and heavy oil.

In Fig. 3, 6 co-occurrence clusters of author keywords can be seen. Cluster 1 (red) mainly comprises of keywords related to CCUS, recovery of heavy oil, and modelling works on topics such as phase behavior, reservoir properties, and flowing behavior. Meanwhile, cluster 2 (green) mostly comprises of terms related to microbial enhanced oil recovery (MEOR). Cluster 3 (dark blue) is mainly about chemical EOR where surfactant and nanoparticles are highly frequented keywords. The adequate link between nanoparticles and surfactants also suggests investigations involving both chemicals. Cluster 4 (yellow) is mostly related to the application of polymer in EOR where properties such as adsorption on formation surface, rheology, and viscosity are of main concern. Furthermore, cluster 5 (purple) is mostly on investigating interfacial properties where the link between contact angle, interfacial tension, and wettability are found to be adequately strong. Moreover, cluster 6 (light blue) mostly involves investigations on surfactants. This is because two of the keywords in this cluster namely foam and emulsion, are analogously similar that they are formed in the presence of surfactant. Nevertheless, we group them into three distinctive groups, namely CCUS and unconventionals, MEOR, and chemical EOR.

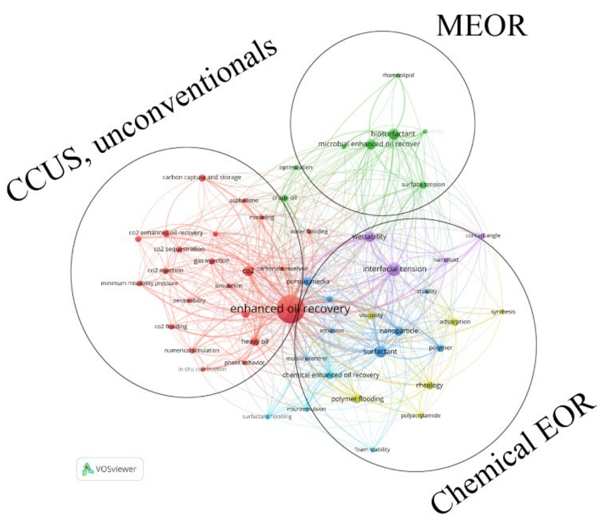

Fig. 3. Co-occurrence map of top 50 author keywords.

3.3.1. Carbon capture, storage and sequestration (CCUS)

CCUS is of hottest concern as evidenced by the recent Intergovernmental Panel on Climate Change report, stating that we have merely 12 years to mitigate unprecedented adverse effects brought by excessive greenhouse gases (GHG) emissions [22]. As the main contributor of anthropogenic GHG with approximately 34.1 ± 1.7 gigatons of emission per annum [23], hydrocarbons are still being relied heavily upon as the main energy contributor. To dampen excessive GHG emission, CO_2 had been widely utilized in EOR to provide oil recovery synergisms, and sequestrate them in hydrocarbon reservoirs at the same time [24]. Certain unconventional reservoirs have been investigated for their CO_2 storing capacity. For instance, CBM has been gaining wide interest as an excellent CO_2 storage site due to the vast presence of void spaces left by methane displaced by CO_2 flooding; at the same time, CO_2 facilitates the extraction of organic matter and dissolution of inorganic minerals in coals that results in permeability improvement, thus improving ultimate methane recovery [25-27]. Furthermore, CO_2 storage in shale reservoirs is also widely investigated due to their extraordinary CO_2 adsorption properties and low permeability inhibiting adsorbed CO_2 from escaping easily [9, 28]. Recently, several emerging CO_2 applications in EOR exist apart from ordinary ones, such as CO_2 flooding, CO_2 foam, carbonated water injection, and CO_2-alternate-gas injection [29-31]. CO_2-responsive materials were investigated, such as those viscosify/de-viscosify [32, 33], and emulsify/demulsify [34] upon CO_2 addition/removal cycles.

With responsiveness, a more sophisticated control over the entire oil recovery process can be achieved. Furthermore, unlike the pH-responsive system, CO_2-responsive system does not leave insoluble precipitate after each addition/removal cycle, thus making this ubiquitous GHG a good candidate for being a green stimulus for smart materials to perform desirably [35]. Several challenges do exist to succeed a CCUS project in EOR, such as the difficulties in detecting and combat with the alteration of geomechanical and stress properties of formations when CO_2 is injected [10, 23, 36], formation damage concerns due to stresses heterogeneities [37], and economic viability of the project as a whole considering geological factors and optimization of parameters [38, 39]. Nonetheless, reducing anthropogenic GHG concentration while recovering hydrocarbons paves the path to sustainability.

3.3.2. Microbial enhanced oil recovery (MEOR)

The natural origin of microbial and the biodegradability advantages of their metabolites makes MEOR interestingly attractive. Metabolites such as biosurfactants, biopolymers, gases, acids, solvents, biomass, emulsifiers, and hydrocarbon degraders are utilized to resolve a wide variety of production problems, which is summarized by Safdel, et al. [40]. Specifically in China, extensive field tests on MEOR had been carried out in conventional reservoirs, tight formations, heavy oil reservoirs, high-temperature reservoirs, high salinity reservoirs, and high water-cut reservoirs. 70 % of the tests were found to have a satisfactory outcome and be profitable [41]. This showed that MEOR could sustain harsh reservoir conditions and be applied in unconventional reservoirs. While MEOR has several benefits, it is plagued by several factors. Screening criteria such as microbial strains, indigenous or exogenous to the reservoir, and the metabolites to be utilized are vital to be properly determined to ensure great efficacies of the MEOR process [40, 42]. This is difficult to achieve at the current stage due to process complexities and lack of sufficient field test data for a more thorough and accurate correlation. Besides, the reliable application of MEOR is further complicated by the effect of formation heterogeneities, interaction mechanisms between exogenous and indigenous bacteria, the stability of microbial metabolism, the potential side effects brought by MEOR such as microbial-induced corrosion of production facilities, and possible adverse health risk due to human exposure [43-45]. For instance, strains like *Pseudomonas aeruginosa* sp. were found to be opportunistic and highly antibiotic-resistant as they can adversely infect human’s respiratory system through its produced metabolite rhamnolipid, a biosurfactant. Nonetheless, with appropriate risk factors, optimization studies, and selection, MEOR can be reliably employed.

4. Conclusion

From the analyses carried out, the hot issues were found to fall into three discrete categories: (1) utilization of CO2 in oil recovery as well as treating hydrocarbon reservoirs as sequestration sites or CCUS, and the development of unconventional reservoirs mainly on heavy oil; (2) chemical EOR; (3) MEOR mainly on the production of biosurfactants. With the rapid energy demand increase and the deteriorating number of easily developed conventional reservoirs, it is vital to develop sustainable EOR so that the worldwide energy supply and demand can be more unceasing. A bibliometric study of EOR-related research from 2007 to 2020 was conducted and analyzed in different categories, including publication year, research areas, journals, countries, authors, organizations, and keywords. The propensity of EOR research has been steadily progressing for the past decade. Within this period, attention has been focused on the development of unconventional reservoirs and their subsequent in-depth mechanistic studies, the utilization of CO_2, chemical EOR and MEOR. Research on EOR has grown abruptly since 2012 with the annual publication number of more than 200 documents. A total of 5498 documents retrieved from 2007 – 2020 involve 90 countries.

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