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Potential Yield of Oil from Middle Jurassic Sargelu Oil Shale in the Zagros Mountains, Southwest Iran: A Preliminary Study

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Abstract

This study presents the first preliminary evaluation of oil (bitumen) recovery from the Middle Jurassic Sargelu oil shale using the Fischer Assay, thermal dissolution, and both direct and indirect hydrogenation methods. Three oil shale samples were collected from the Sargelu Formation at three locations in the Zagros Mountains of southwestern Iran. The results showed no significant difference in oil yield between the standard Fischer Assay and the modified Fischer Assay, despite variations in the final temperature and residence time. The maximum oil yields obtained from the standard and modified Fischer Assays were 34.29 and 33.70 wt.% of organic matter (OM), respectively. However, the modified Fischer Assay improved the quality of the recovered oil by increasing the API gravity from 18.30 to 24.82 and reducing the viscosity from 7.34 to 4.13 cP. Thermal dissolution experiments using different solvents demonstrated that methanol was the most effective solvent, producing the highest oil yield at 350°C after 4 hours. Oil recovery varied considerably with solvent type, ranging from 23.1 to 59.4 wt.% of OM. Direct hydrogenation, conducted under hydrogen pressures of 20 and 30 bar at relatively low temperatures, achieved a maximum oil yield of 53.68 wt.% of OM. Indirect hydrogenation using a 25 wt.% aqueous sodium formate (HCOONa) solution at 380°C for 5 hours produced an oil yield of 51.59 wt.% of OM, whereas indirect hydrogenation in the presence of water and zinc further increased the yield to 62.93 wt.% of OM. Overall, the results demonstrate that both thermal dissolution and hydrogenation are more effective than conventional pyrolysis for enhancing oil (bitumen) recovery from the Sargelu oil shale. The highest oil yield was achieved through indirect hydrogenation at 400°C with a reaction time of 2 hours, highlighting the potential of this method for maximizing bitumen recovery from the Sargelu oil shale

Keywords: Sargelu Oil Shale, Pyrolysis, Fischer Assay, Thermal Dissolution, Hydrogenation.

Introduction

Oil shale is an immature, unconventional, and non-renewable energy resource with considerable potential to help meet the growing global demand for energy (Shekarifard et al., 2021). It is a fine-grained sedimentary rock rich in organic matter (OM) that can generate significant quantities of oil and gas through destructive distillation, in which the rock is heated in the absence of oxygen (Sinag and Canel, 2010; Dyni, 2003). This thermal conversion process is commonly referred to as retorting, pyrolysis, or semi-coking (Sinag and Canel, 2010). In the oil shale industry, the Fischer Assay is the standard laboratory method used to evaluate the oil yield of an oil shale deposit. During this analysis, the sample is heated under controlled

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conditions in a small retort under an inert atmosphere, producing oil, water, and gas (Heistand, 1976).

Oil shale consists primarily of kerogen, bitumen, and inorganic minerals (Ding et al., 2021). Kerogen, the dominant organic constituent, is an insoluble solid that cannot be directly recovered as crude oil or natural gas under natural conditions (Kang et al., 2020). The inorganic fraction typically accounts for 50–85 wt.% of the rock and consists mainly of silicates, carbonates, quartz, and pyrite (Zhao et al., 2017). The chemical composition of the organic matter is commonly determined by ultimate analysis, which measures the contents of carbon, hydrogen, nitrogen, sulfur, and other elements. In contrast, proximate analysis provides information on the moisture, volatile matter, fixed carbon, and ash contents of the oil shale (Foltin et al., 2017).

The first significant oil shale discoveries in Iran were made in the 1970s during exploration campaigns conducted by the National Iranian Oil Company (NIOC) in the Zagros Basin. These investigations identified two major oil shale-bearing units: the upper part of the Middle Jurassic Sargelu Formation and the lower part of the Upper Cretaceous Garau Formation (Shekarifard et al., 2024). Rasouli et al. (2015) investigated organic matter-rich sediments from five locations in southwestern Iran and identified the Sargelu and Garau formations as promising unconventional hydrocarbon resources. Their geochemical analyses indicated that the organic matter is dominated by oil-prone Type II kerogen capable of generating predominantly liquid hydrocarbons (Rasouli et al., 2015). Subsequently, Shekarifard (2022) investigated the thermochemical behavior of Sargelu oil shale through thermo-oxidative decomposition experiments. The decomposition process was divided into three stages: (1) oxidation of bitumen, (2) decomposition of kerogen, and (3) decomposition of calcite (Shekarifard, 2022).

Organic solvent extraction is widely used in geochemical studies of oil shale to recover soluble hydrocarbons and evaluate organic matter characteristics. The extraction efficiency and composition of the recovered hydrocarbons strongly depend on the solvent employed. For example, Nassef et al. (2015) evaluated several organic solvents, including tetrahydrofuran, toluene, methylene chloride, n-hexane, and chloroform, for the extraction of hydrocarbons from Egyptian oil shale. Their results demonstrated that tetrahydrofuran provided the highest extraction efficiency and oil yield (Nassef et al., 2015).

Hydrogenation represents another promising approach for enhancing liquid hydrocarbon recovery from oil shale and can be carried out by either direct or indirect methods. In direct hydrogenation, pyrolysis is performed under elevated hydrogen pressure, which promotes hydrogen transfer reactions and increases liquid hydrocarbon production (Burnham, 2017). Compared with conventional thermal extraction, direct hydrogenation generally provides higher oil yields at lower decomposition temperatures. In indirect hydrogenation, hydrogen donor compounds are introduced into the reaction system to supply hydrogen during pyrolysis. One of the most widely used hydrogen donor systems is an aqueous sodium formate solution, which facilitates hydrocarbon production at lower temperatures than conventional thermal extraction. Friedman demonstrated that hydrogenation of Estonian kukersite oil shale in the presence of water at 400–430°C for 30 minutes achieved a hydrocarbon conversion efficiency of approximately 93%. Compared with conventional semi-coking, this process produced hydrocarbons with lower molecular weights and reduced phenol contents (Klesment and Nappa, 1980). Similarly, Maloletnev et al. (2011) subjected Baltic oil shales to hydrogenation under relatively low hydrogen pressures and obtained liquid and gaseous product yields of 76–78% and 18–20%, respectively. Klesment and Nappa (1980) also investigated the structure and decomposition mechanism of kukersite oil shale at sub-industrial temperatures and compared hydrocarbon production by sodium formate-assisted hydrogenation with that obtained using the standard Fischer Assay.

The present study provides the first comprehensive comparison of the standard Fischer

Assay, modified Fischer Assay, thermal dissolution, and both direct and indirect hydrogenation for evaluating oil (bitumen) recovery from the Middle Jurassic Sargelu oil shale. The primary objective is to identify the most effective extraction method for maximizing oil yield while improving the quality of the recovered bitumen.

Samples and analytical methods

Sample Preparation

Three oil shale samples were collected from the Middle Jurassic Sargelu Formation at three different locations in the Zagros Mountains of southwestern Iran. The samples were crushed using a laboratory grinder and subsequently sieved through standard meshes to obtain particles ranging from 0.4 to 1.0 mm in size for subsequent analyses and experiments.

Proximate and Ultimate Analysis

The prepared samples were subjected to proximate and ultimate analyses to characterize their physicochemical properties. Proximate analysis was performed to evaluate the fuel characteristics of the as-received oil shale by determining its moisture, volatile matter, fixed carbon, and ash contents, thereby providing an assessment of its organic matter (OM) content and overall fuel quality. In addition, the amount of CO₂ released during the analysis was used to estimate the proportion of carbonate minerals present in the inorganic fraction. The higher heating value (HHV) was also determined to evaluate the energy potential of the oil shale during combustion.

Ultimate analysis was conducted to determine the elemental composition of the organic matter by measuring the contents of carbon, hydrogen, nitrogen, sulfur, and oxygen. The results of the proximate and ultimate analyses are summarized in Table 1.

Standard and modified Fischer Assay

The standard Fischer Assay was performed in accordance with the ISO 647 standard procedure. For each experiment, 100 g of oil shale with a particle size of 0.4–1.0 mm was heated to 520°C over 80 minutes, followed by a 10-minute holding period at the final temperature. The quantities of oil, water, gas, and spent shale were then determined.

To evaluate the effect of pyrolysis conditions on oil recovery and product quality, a modified Fischer Assay was also conducted using lower final temperatures and longer residence times. The final pyrolysis temperatures were reduced from the standard 520°C to 440°C, 480°C, and 400°C for Samples 1, 2, and 3, respectively. The heating period to reach the target temperature ranged from 30 to 50 minutes, after which each sample was maintained at the final temperature for 3 hours.

The quality of the recovered shale oil was evaluated by measuring its API gravity and dynamic viscosity. The operating conditions and experimental results for the standard and modified Fischer Assays are presented in Tables 2 and 3, respectively.

Thermal dissolution

Thermal dissolution experiments were conducted to evaluate bitumen recovery from the selected oil shale samples using different extraction solvents. The experiments were performed in 20 cm³ stainless-steel autoclaves at a constant temperature of 350°C for 4 hours. Six solvent systems were investigated: water, methanol, acetone, n-hexane, benzene, and a 1:1 (w/w) water–benzene mixture. In all experiments, the sample-to-solvent ratio was maintained at 5:8 (w/w).

Table 1. Results of proximate and ultimate analyses on selected Sargelu oil shales

	Sample -1	Sample-2	Sample-3
Proximate analysis			
W _a ^d (%)	0.68	1.65	0.57
A _a (%)	59.43	58.57	57.83
OM (%)	17.61	28.39	23.93
CO ₂ of carbonates (%)	22.28	11.38	17.67
Calorific value (MJ/kg)	6260.00	10150.00	8940.00
Ultimate analysis			
C (%)	21.00	26.90	25.4
H (%)	1.24	2.11	1.84
N (%)	0.43	0.70	0.49
S (%)	2.25	3.31	3.40

Table 2. Results of the standard Fischer Assay

	Fischer Assay (Wt%)					Density @15°C (g/cm³)	API gravity	Viscosity (cP)
	Oil	Semicoke	Pyrogenetic water	Gas+losses	Oil from OM			
Sample-1	9.49	85.89	1.26	3.37	34.29	0.9196	22.40	7.40
Sample-2	9.25	86.12	2.02	2.61	33.49	0.9446	18.30	7.34
Sample-3	3.98	90.77	2.10	3.16	22.27	0.9194	22.41	6.47

Table 3. Results of modified Fischer Assay

	Modified Fischer Assay (Wt%)						Density @15°C (g/cm³)	API gravity	Viscosity (cP)
	Isother m. 3hr	Oil	Semicoke	Pyrogenetic water	Gas+losses	Oil from OM			
Sample-1	430-450	8.74	87.34	1.33	2.60	31.92	0.9111	23.86	3.84
Sample-2	480	9.24	86.40	1.83	2.53	33.70	0.9052	24.82	4.13
Sample-3	400	3.12	94.65	1.32	0.91	17.74	0.9080	24.47	3.54

Hydrogenation

Direct hydrogenation experiments were carried out on Samples 1 and 2. For Sample 1, hydrogenation was performed in a 500 cm³ autoclave under a hydrogen pressure of 20 bar at 400°C with residence times ranging from 1 to 4 hours. To investigate the influence of a hydrogen donor solvent, an additional experiment was conducted under the same operating conditions (20 bar and 400°C for 2 hours) in the presence of 100 mL of benzene.

For Sample 2, direct hydrogenation was performed under a hydrogen pressure of 30 bar at temperatures ranging from 250 to 410°C with a fixed residence time of 2 hours. The effect of residence time was further investigated by conducting additional experiments at a constant temperature of 410°C and a hydrogen pressure of 30 bar for 1, 2, and 6 hours.

Indirect hydrogenation experiments were conducted on all three samples using hydrogen donor systems consisting of either an aqueous sodium formate solution or a water–zinc mixture. The reactions were carried out in 20 cm³ autoclaves at 380°C for up to 5 hours and at 400°C for up to 4 hours to evaluate the effects of reaction temperature, hydrogen donor system, and residence time on bitumen recovery.

Results and discussion

Characterization of initial oil shale

The heating value of the Sargelu oil shale samples varied considerably, ranging from 6260 to 10,150 MJ/kg, primarily due to differences in their organic matter (OM) contents. The calorific value increased proportionally with increasing OM content, indicating the significant contribution of organic components to the energy potential of the oil shale. The moisture content of the Sargelu oil shale was relatively low, with an average value of 0.96 wt.%, compared with commercially exploited oil shales (Shekarifard, 2022). In comparison, Estonian and Chinese oil shales generally exhibit higher moisture and ash contents, exceeding 5% and 65%, respectively (Qing et al., 2007; Trikkel et al., 2008).

Pyrolysis by Fischer Assay

The standard and modified Fischer Assay results indicated oil yields ranging from 3.98 to 9.49 wt.% and 3.12 to 9.24 wt.%, respectively. The oil yields obtained from the modified Fischer Assay were slightly lower than those obtained from the standard Fischer Assay.

To investigate the effects of final temperature and residence time on oil recovery, the results of the standard and modified Fischer Assays were compared. The reduction of the final temperature from 520°C in the standard Fischer Assay to 400–480°C in the modified Fischer Assay, combined with an increase in residence time from 10 minutes to 3 hours, did not significantly affect the oil yield of the Sargelu oil shale samples (Fig. 1a). This indicates that lower-temperature pyrolysis with an extended residence time can achieve comparable oil recovery while operating under milder thermal conditions.

Although the modified Fischer Assay did not significantly increase oil yield, it improved the quality of the recovered shale oil. The API gravity increased from 22.40, 18.30, and 22.41 to 23.86, 24.82, and 24.47 for Samples 1, 2, and 3, respectively. Based on API gravity values, the produced shale oils can be classified as heavy to medium crude oils (Fig. 1b). Furthermore, the modified Fischer Assay resulted in a substantial reduction in oil viscosity. The viscosity values decreased from 7.40 to 3.84 cP, 7.34 to 4.13 cP, and 6.47 to 3.54 cP for Samples 1, 2, and 3, respectively (Table 3; Fig. 1c).

The influence of pyrolysis temperature on shale oil production has also been reported by Na et al. (2012), who observed an increase in shale oil yield with increasing reaction temperature up to 500°C. However, at higher temperatures, the proportion of gaseous products increased due to secondary cracking reactions, which reduced the conversion of organic matter into liquid hydrocarbons (Na et al., 2012). Therefore, controlling the pyrolysis temperature is essential for maximizing liquid hydrocarbon production while minimizing gas formation.

Pyrolysis in autoclave in presence of solvent

The results of thermal dissolution experiments demonstrated that the type of solvent has a significant influence on oil recovery from Sargelu oil shale (Fig. 2). Among the investigated solvents, water, n-hexane, and benzene resulted in relatively low oil yields, indicating their limited effectiveness for bitumen extraction under the applied conditions. In contrast, methanol exhibited the highest extraction efficiency for the studied samples, producing oil yields of 59.4 and 54.2 wt.% of organic matter (OM) for Samples 1 and 2, respectively.

Compared with the Fischer Assay results, thermal dissolution using methanol increased oil recovery by approximately 20% while operating at a lower temperature, demonstrating the effectiveness of solvent-assisted extraction for enhancing bitumen production from Sargelu

oil shale.

Shawaqfeh and Al-Harashah (2004) investigated bitumen extraction from El-Lajjun and Sultani oil shales using various solvents and reported that the solubility index decreased with increasing solvent molecular weight among alcohol solvents, including methanol, ethanol, propanol, and butanol. This behavior was attributed to the reduced mobility of solvent molecules at higher molecular weights, which limits their ability to penetrate and dissolve organic compounds within the oil shale matrix (Shawaqfeh & Al-Harashah, 2004).

Pyrolysis in autoclave in presence of hydrogen

The effect of hydrogen addition on improving oil recovery from Sargelu oil shale was investigated through two approaches: direct and indirect hydrogenation. In the first stage, Samples 1 and 2 were subjected to direct hydrogenation under hydrogen pressures of 20 and 30 bar, respectively. The effects of reaction temperature and residence time on hydrocarbon production during pyrolysis were evaluated under these conditions. In the second stage, Sample 3 was treated by indirect hydrogenation using hydrogen donor systems, including a 25 wt.% aqueous sodium formate solution and zinc in water, to enhance the production of liquid hydrocarbons and other pyrolysis products.

Direct hydrogenation

The highest oil yield obtained under direct hydrogenation conditions of 20 bar and 400°C was 38.16 wt.% of organic matter (OM) after 1 hour of residence time. Increasing the reaction time beyond this point resulted in a decrease in oil yield, which can be attributed to the secondary cracking of heavier hydrocarbons in the presence of hydrogen, leading to enhanced formation of gaseous products.

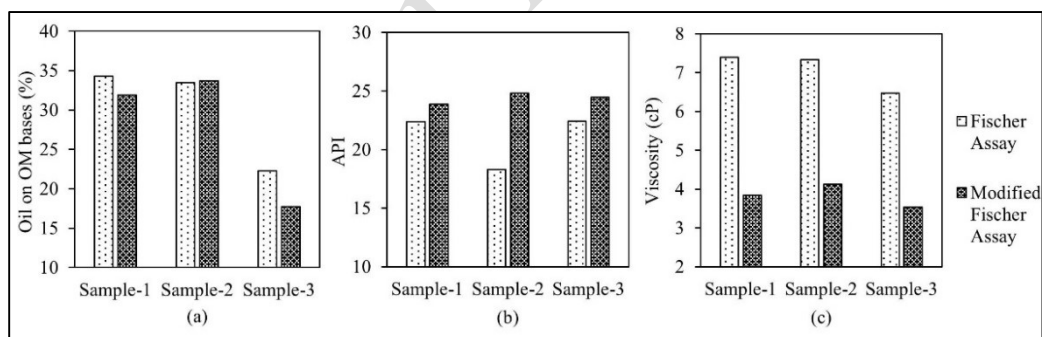


Figure 1. Comparison of oil yield (a), the API (b) and viscosity (c) from standard and modified Fischer Assays

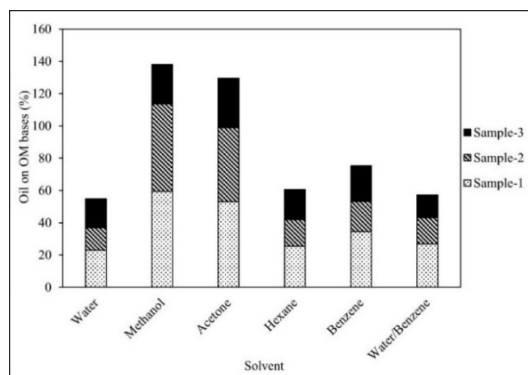


Figure 2. Comparison of the efficiency of bitumen extraction from Sargelu oil shale by thermal dissolution in the presence of different solvents

Figure 3 presents the results of direct hydrogenation of Sample 1 at a constant temperature of 400°C.

The addition of benzene during hydrogenation, compared with hydrogenation without a solvent, further promoted gas formation. In the presence of benzene, gas yield increased from 32.59 to 52.88 wt.% of OM, while the amounts of solid residue and recovered shale oil decreased. These results suggest that benzene enhances secondary cracking reactions, shifting the product distribution toward lighter gaseous hydrocarbons rather than liquid products.

The effect of hydrogenation temperature and residence time on oil recovery was further investigated using Sample 2. Similar to the results obtained for Sample 1, increasing the hydrogenation time led to a decrease in shale oil yield and a corresponding increase in gas production. Under constant hydrogenation conditions of 30 bar hydrogen pressure and 410°C, extending the reaction time from 2 to 6 hours resulted in a significant reduction in oil yield, from 53.68 to 17.34 wt.% of organic matter (OM) (Fig. 4). This decrease can be attributed to the progressive cracking of liquid hydrocarbons into lighter gaseous products during prolonged exposure to hydrogenation conditions. Therefore, an appropriate residence time is essential to maximize liquid hydrocarbon recovery and minimize excessive secondary cracking reactions.

The effect of hydrogenation temperature on Sample 2 demonstrated that increasing the final reaction temperature enhanced the production of both shale oil and gaseous hydrocarbons. At 250°C, the limited oil and gas yields indicate that the thermal energy supplied was insufficient to overcome the activation energy required for effective pyrolysis. This is further supported by the high solid residue content (91.35 wt.%), suggesting that a significant portion of the organic matter remained unconverted under these conditions.

In contrast, increasing the hydrogenation temperature to 410°C promoted the conversion of organic matter into liquid hydrocarbons, resulting in higher shale oil recovery and a lower amount of solid residue (Fig. 5). Based on the direct hydrogenation experiments conducted at 30 bar hydrogen pressure, the maximum shale oil yield for Sample 2 was achieved at 410°C with a residence time of 2 hours.

Indirect hydrogenation

The indirect hydrogenation behavior of Sargelu oil shale Sample 3 was investigated using water and sodium formate as hydrogen donor systems. In this process, sodium formate decomposes at the reaction temperature (Eq. 1), generating carbon monoxide, which subsequently reacts with water through the water–gas shift reaction to produce hydrogen (Eq. 2). The in situ generated hydrogen promotes the conversion of organic matter into hydrocarbons.

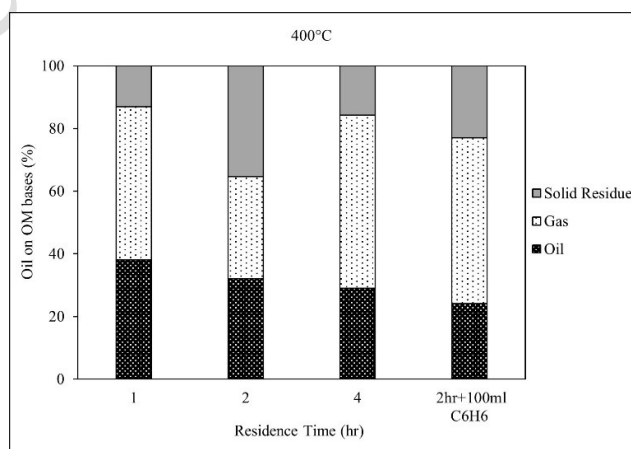


Figure 3. oil yield of the Sargelu oil shale sample 1 upon extraction in the presence of hydrogen at 20 bar and 400°C for different residence times in the range of 1 to 4 hours

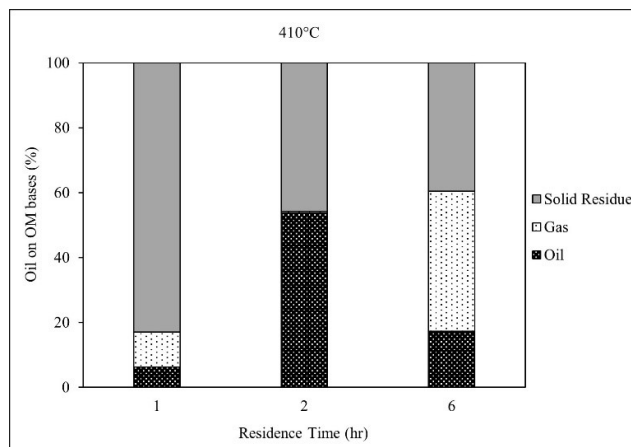


Figure 4. Comparison of the produced amounts of pyrolysis products via direct hydrogenation on the Sargelu oil shale sample 2 at 30 bar and 410°C for different residence times in the range of 1 to 6 hours

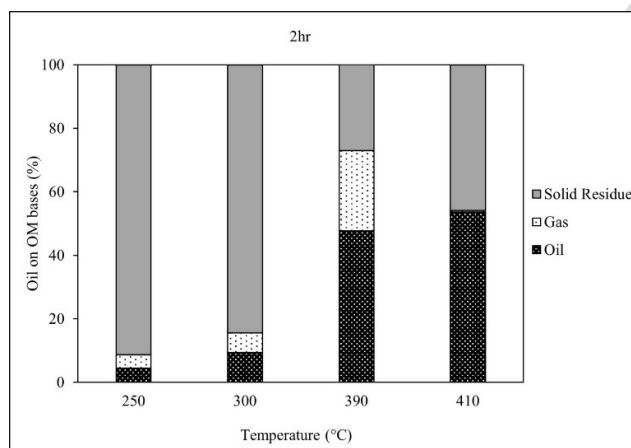


Figure 5. Comparison of the produced amounts of pyrolysis products via direct hydrogenation on the Sargelu oil shale sample 2 at 30 bar and temperatures in the range of 250 - 410°C for a residence time of 2 hours

The results showed that shale oil yield increased with increasing hydrogenation time at a constant temperature, reaching a maximum value of 51.59 wt.% of organic matter (OM) after 5 hours (Fig. 6). The significant contribution of sodium formate as a hydrogen donor enhanced the conversion of the organic fraction into hydrocarbon products, including extracted oil and gaseous hydrocarbons. During the reaction, the oil and gas yields became comparable after 1 and 3 hours, respectively, while the amount of semi-coke reached its minimum value. Compared with direct hydrogenation, the use of sodium formate in indirect hydrogenation improved oil recovery at lower processing temperatures. This indicates that hydrogen donor-assisted hydrogenation can facilitate hydrogen transfer reactions and enhance the conversion of kerogen into liquid hydrocarbons under milder operating conditions.



The addition of zinc to water (Eq. 3) promotes hydrogen generation through the reaction between zinc and water, thereby indirectly contributing to the hydrogenation process. The results demonstrated that indirect hydrogenation using an aqueous zinc solution at a constant reaction temperature and extended residence times effectively reduced the amount of solid residue. The generated hydrogen reacted with the carbon-rich organic matter of the oil shale,

facilitating the conversion of heavier organic compounds into bituminous liquids and lighter hydrocarbons into gaseous products.

Reaction time had a significant influence on product distribution and oil recovery. Increasing the reaction time to 2 hours resulted in the maximum oil yield of 62.93 wt.% of organic matter (OM), accompanied by a gas yield of 25.03 wt.%. However, further extension of the reaction time promoted additional cracking reactions, increasing gas production to 33.47 wt.% and reducing the solid residue content to 6.61 wt.% (Fig. 7).

Compared with sodium formate-assisted indirect hydrogenation, the use of zinc and water achieved a higher maximum shale oil yield at a lower reaction time. These results indicate that the zinc–water hydrogen donor system is more effective for enhancing bitumen recovery from Sargelu oil shale under the investigated conditions.



Overall, the results of direct and indirect hydrogenation experiments on the selected Sargelu oil shale samples demonstrated that indirect hydrogenation is a more effective approach for enhancing pyrolysis-based hydrocarbon recovery at lower temperatures.

The increase in shale oil yield during hydrogenation can be attributed to three main factors: enhanced pyrolysis conversion, the introduction of external hydrogen sources, and the displacement effect of steam. Hydrogen radicals generated from steam can promote the cleavage of chemical bonds within oil shale, facilitating the cracking and conversion of organic matter and consequently increasing shale oil production. In addition, steam acts as an external hydrogen donor by supplying hydrogen to reactive oil fragments generated during pyrolysis. The incorporation of hydrogen into these fragments suppresses secondary polymerization reactions and reduces the formation of solid char. Furthermore, steam exhibits a beneficial displacement effect by transporting released shale oil through the pore and fracture networks, thereby improving its mobility and recovery during pyrolysis (Kang et al., 2025).

Maloletnev et al. (2011) reported an organic matter conversion efficiency of 96–98% during shale liquefaction, with hydrogen consumption of 1.5–2.0%. The liquid product yield reached 76–78% based on the organic matter content of the shale paste, consisting of approximately 40–45% products with boiling points below 320°C, 18–20% gaseous products, and 8–9% water. The molecular hydrogen introduced into the process (1.5–2.0%) was primarily consumed in the formation of C₁–C₄ hydrocarbon gases, which accounted for 8–10% of the product yield. These gases could potentially be recycled into the process after conversion with steam (Maloletnev et al., 2011).

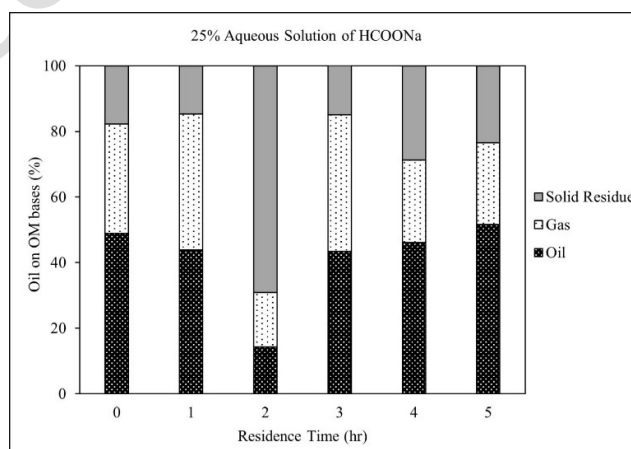


Figure 6. Comparison of the produced amounts of pyrolysis products via indirect hydrogenation on the Sargelu oil shale sample 3 in the presence of an aqueous solution of 25% sodium formate at 380°C for different residence times in the range of 0 – 5 hours

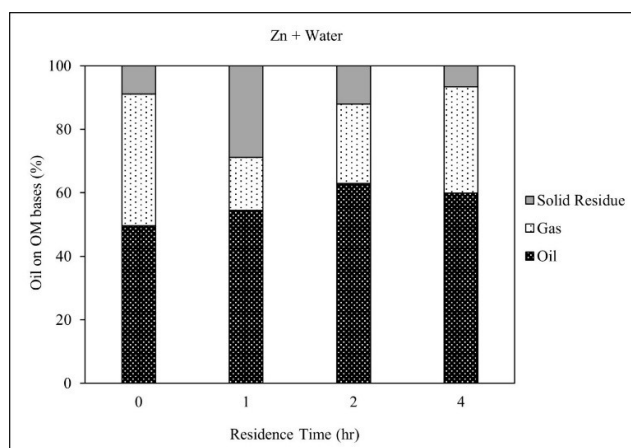


Figure 7. Comparison of the produced amounts of pyrolysis products via indirect hydrogenation on the Sargelu oil shale sample 3 in the presence of zinc-water solution at 400°C for different residence times in the range of 0 – 4 hours

Conclusion

The results of oil yield preliminary evaluation for Sargelu oil shale (a few samples) demonstrate the significant hydrocarbon generation potential of this unconventional source. However, the recovered oil yield strongly depends on the extraction method and conditions.

The Fischer Assay results indicated that variations in final temperature and residence time had no significant effect on oil yield. However, the modified Fischer Assay improved the quality of the recovered shale oil by increasing API gravity and reducing viscosity.

Thermal dissolution showed that solvent selection plays a critical role in enhancing oil recovery. Among the investigated solvents, methanol provided the highest extraction efficiency, achieving an oil yield of 59.4 wt.% of organic matter (OM), which was considerably higher than that obtained by the Fischer Assay.

In direct hydrogenation, increasing the residence time at a constant temperature of 410°C promoted secondary cracking reactions, resulting in higher gas production and lower oil yield. In contrast, increasing the reaction temperature under a fixed residence time of 2 hours enhanced oil recovery.

Direct hydrogenation produced a maximum oil yield of 53.68 wt.% of OM, which was significantly higher than the maximum yield obtained by the Fischer Assay (33.49 wt.% of OM). Indirect hydrogenation using a 25 wt.% aqueous sodium formate solution at 380°C resulted in an oil yield of 51.59 wt.% of OM, while the use of an aqueous zinc solution at 400°C further increased the oil yield to 62.93 wt.% of OM. For comparison, the same sample produced only 22.27 wt.% of OM as oil under standard Fischer Assay conditions at 520°C.

Overall, the findings indicate that appropriate selection of hydrogen donor systems, solvents, and pyrolysis conditions can enhance the conversion of Sargelu oil shale into liquid hydrocarbons at lower temperatures, reducing energy consumption compared with conventional pyrolysis. Nevertheless, variations in extraction conditions can significantly influence not only oil yield but also the quality and properties of the produced shale oil.

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