Research on Engineering Structures & Materials
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Research Article

Investigation and optimization of the impact of microwave irradiation on the extraction of sulfur from diesel fuel

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Article Info

Article History:

Received 13 Oct 2025

Accepted 11 Nov 2025

Keywords:

Microwave;
Desulfurization;
Oxidation of sulfur;
Diesel fuel

Abstract

The widespread use of diesel in transportation, industry, and power generation leads to many environmental problems caused by high sulfur compound emissions. Diesel fuel must be free of sulfur-containing compounds due to their potential to cause severe environmental pollution. Oxidative desulfurization of diesel fuel using microwave irradiation technology is considered one of the most efficient methods to achieve this goal. This simple, economical, and effective approach for treating sulfur-containing diesel fuel employs peroxide oxidation facilitated by pimelic acid and heating through microwave radiation. The research sought to examine the effectiveness of the acid as a catalyst and hydrogen peroxide as an oxidizing agent. The technology relies on microwave electromagnetic radiation. A Central Composite Design (CCD) was used to plan experiments with three variables and five levels, and to analyze the effect of these variables on the desulfurization efficiency of diesel fuel. The results indicated that the highest efficiency for sulfur extraction from diesel fuel occurred at 400 W, with an optimal processing time of 150 seconds and a peroxide-to-diesel volume ratio of 0.5, achieving approximately 75% sulfur removal under these optimal conditions. Microwave technology thus represents an effective and cost-friendly environmental approach for sulfur removal from diesel fuel.

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1. Introduction

Environmental pollution constitutes a substantial global issue, affecting public health, ecosystems, and the economy. Pollutants originating from transportation, industrial activities, and manufacturing plants have enduring impacts on the environment and human health [1,2]. Diesel fuel, a significant energy source for transportation, industry, and power generation, is a prominent contributor to air pollution, emitting pollutants such as particulate matter, nitrogen oxides, and sulfur oxides [3,4]. These sulfur compounds, prevalent in fossil fuels, can result in acid rain, soil pollution, and ecological degradation, notably adversely affecting aquatic systems and infrastructure [5]. The rising utilization of diesel fuels in industrial and transportation sectors intensifies air pollution owing to elevated sulfur emissions [6,7]. Organosulfur compounds, including methyl mercaptan and thiophenes, are abundant in crude oil and lead to catalyst poisoning during gasoline production [8,9]. The necessity to diminish sulfur content in diesel fuel to enhance air quality, particularly in urban regions, has propelled the quest for efficient desulfurization techniques [10]. The advancement of effective desulfurization methods is essential for mitigating the environmental and health repercussions of fossil fuel usage. Diverse techniques have been investigated, encompassing hydrodesulfurization [11], oxidative desulfurization [12], adsorptive desulfurization [13], bio desulfurization [14], and solvent extraction [15]. Hydrodesulfurization, a prevalent technique, employs hydrogen gas and catalysts to decompose sulfur-containing compounds but encounters difficulties with specific organosulfur compounds

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DOI: http://dx.doi.org/10.17515/resm2025-1251ic1013rs

such as thiophene [16]. The procedure is energy intensive and expensive due to elevated hydrogen and temperature requirements [17]. Oxidative desulfurization (ODS) has garnered interest as an effective alternative, functioning under gentler circumstances without requiring hydrogen [18]. Oxidative desulfurization techniques employing oxidizing agents such as hydrogen peroxide and ozone have demonstrated efficacy in eliminating sulfur from diesel fuels, with various adsorbents, including activated carbon and metal oxides, utilized to augment the process [19–25]. ODS commences with the oxidation of sulfur compounds to sulfone, which can subsequently be isolated using solvents such as acetonitrile [12]. Numerous studies have investigated catalytic desulfurization employing both homogeneous and heterogeneous catalysts. Peroxotungstate (PW4) immobilized in SBA-15 has demonstrated desulfurization effectiveness of up to 89% [26]. Alternative strategies involve the utilization of ionic liquids and composite catalysts to enhance the process [27–30]. Certain systems employ ultrasound and ultraviolet irradiation to improve desulfurization [29]. Although effective, numerous catalysts necessitate intricate preparation and are costly, hence constraining their extensive application. Metal-free catalysts are deemed more economical and safer, presenting a viable option for commercial applications [31–33]. These methods eliminate the usage of toxic metals, rendering them more eco-friendly and economically feasible [34]. Bigdeli et al. proposed carbon nanofibers synthesized on activated carbon (AC) surfaces via microwave-assisted chemical vapor deposition (CVD) techniques. Methane and ethane served as source gases to investigate their textural and particle characteristics and efficacy in sulfur adsorption from a fuel model. The maximum yield of nanofibers was observed when subjected to a nitrogen-hydrocarbon mixture. The enhanced AC surface increased sulfur removal effectiveness by as much as 87% relative to the original [35]. Mesdour proposed research into the efficacy of MECODS, a straightforward technique for desulfurizing diesel fuel, employing $VO(acac)_2$/oxidant reagents in acid-based pyridinium ionic liquid. It attained a 99.1% elimination of sulfur compounds using a combination of H_2O_2 and H_2SO_4. The approach provided rapid reaction times, elevated conversion rates, selectivity, gentle reaction conditions, recyclability, sulfur reduction, and cost-effective materials. Additional investigation was required to comprehend MECODS dynamics and the activation energy influenced by temperature [36]. Coletti showed that a green chemistry methodology for fuel desulfurization using vanadium salen and salophen complexes could oxidize model aromatic sulfides such as dibenzothiophene (DBT) utilizing H_2O_2 as an eco-friendly oxidant under microwave irradiation.

The application of microwaves facilitated 98% DBT oxidation and nearly total sulfur extraction within 1000 seconds, rendering it a straightforward, quick, and environmentally benign procedure [37]. Fadhil developed efficient and regenerable catalysts using CuO–ZnO nanocomposites for catalytic oxidative desulfurization of gasoil fraction under microwave irradiation. The CuO–ZnO catalyst demonstrated superior conversion (93% under specific conditions), with performance remaining steady after five cycles. The microwave-based method showed promise due to efficient microwave energy transfer and enhanced protonation, improving sulfur conversion efficiency [38]. Kareem proposed a Ni@SiO_2–PWA nanocatalyst synthesized for microwave-assisted catalytic oxidative desulfurization of the gasoil fraction. The catalyst, consisting of phosphotungstic acid on magnetic silica, demonstrated a high sulfur conversion rate of 94.5% under microwave irradiation. The recyclability of the nano catalyst was examined, revealing that the catalytic activity remained consistent after six reaction cycles. The microwave-assisted catalytic ODS approach exhibits considerable potential for desulfurization, with its effective performance resulting from the synergistic effects of microwave activation energy and subsequent protonation [39]. Bartoli demonstrated that biosolids utilized in lipid pyrolysis could diminish sulfur content in crude pyrolysis oils. Elevating reaction temperature and extending processing duration reduced sulfur concentration, while pretreatments and direct amalgamation with adsorbents also proved beneficial. The Soxhlet procedure was found to be the most efficient method for recovering adsorbers. A liquid–liquid extraction method for oxidative desulfurization retrieved unreacted fatty acids, which could be transformed into hydrocarbon fuels, producing low-sulfur products [40]. Kareem examined the oxidative degradation of partially hydrotreated diesel utilizing a tripartite system comprising hydrogen peroxide, ferric chloride, and carboxylic acids (formic acid, acetic acid, or propanoic acid). It was determined that formic acid, acetic acid, and PA were completely soluble in diesel, rendering them inappropriate as aqueous extractants. AA demonstrated superior extraction efficacy compared to FA owing to its greater void radius. A molar ratio of nH_2O_2/nS of 36 facilitated optimal elimination of sulfur compounds at 55 °C, achieving 65.1% sulfur removal [41]. Solouki and Jafferproposed a novel microwave-assisted method for the demetallization and desulfurization of crude petroleum oil, employing aqueous sodium hydroxide solutions and sulfuric acid. The procedure demonstrated a regeneration efficiency of 99%. A techno-economic analysis indicated that it is economically advantageous compared to hydrodesulfurization, with projected CAPEX of 16–21 million USD and OPEX of 1.27–9.1 dollars per barrel. Additional benefits encompassed catalyst-free operation, ambient processing temperatures, and energy conservation via selective microwave heating. Subsequent research was recommended to refine basic process parameters such as microwave power, DMDSA-to-oil ratio, and residence time to enhance economic efficiency [42]. Ahmed and Barham proposed an oxidative desulfurization method for high-sulfur diesel fuels utilizing citric acid, pimelic acid, and α-ketoglutaric acid as activators for H_2O_2. The technique was effective in eliminating sulfur-containing compounds from diesel fuels. Pimelic acid was identified as the most efficacious activator owing to its hydrophobic carbon structure and enhanced solubility in diesel fuel. The system exhibited superior desulfurization efficacy and prospective industrial applicability. The research proposed an uncomplicated and economical H_2O_2/carboxylic acid method for extensive desulfurization [43]. Despite these advancements, current oxidative desulfurization methods face several limitations, such as high chemical consumption, long reaction times, and incomplete sulfur removal. Therefore, the aim of the present work is to employ a green and efficient microwave-assisted oxidative desulfurization process using pimelic acid as an activator for hydrogen peroxide, combined with optimization techniques (Central Composite Design, CCD) to identify the optimal conditions—microwave power, irradiation time, and oxidant-to-fuel volume ratio—for maximum sulfur removal. The novel contribution of this study lies in integrating microwave irradiation with pimelic acid activation to enhance desulfurization efficiency while minimizing reaction time and reagent usage, offering a sustainable, cost-effective, and environmentally friendly alternative for sulfur removal from diesel fuel.

2. Microwave Irradiation Mechanism for Desulfurization

Features of the applied waves, such as their wavelength and frequency [44]. The fundamental idea behind microwave heating technology is the transformation of electromagnetic energy into thermal energy [44–48]. The maximum temperature increase that can be achieved depends on the amount of electromagnetic energy that the irradiated material absorbs. An efficient substitute for traditional heating methods used in the extraction and delivery of crude oil is the stimulation of fluid particles using electromagnetic waves to generate heat [46]. This approach can work in settings with complicated geological conditions and is economical and environmentally benign. The fundamental process of microwave heating is the use of oscillating electric and magnetic fields to stir polar molecules or ions [47,48]. Conventional heating, on the other hand, stimulates the material's exterior molecules or atoms by applying energy to its surface. The energy produced by electromagnetic waves' interaction with petroleum molecules promotes molecular motion as the ambient temperature rises, eventually transforming this energy into thermal energy [49,50]. A microwave-assisted method for desulfurizing commercial diesel fuel was given by Mostafa et al. [51], who focused on the effects of solvent type, solvent-to-feed ratio, microwave intensity, and irradiation duration. The findings showed that because of its polarity, ethyl acetoacetate is the best solvent. A solvent-to-feed ratio of 3:1, 180 W of microwave intensity, and 7 minutes of irradiation were the ideal desulfurization settings.

3. Materials and Methods

This study involved the supply of high-sulfur diesel fuel sourced from the Dora refinery in Baghdad. The present work utilized liquid hydrogen peroxide (30% GR Merck, Darmstadt, Germany) and acetonitrile (99% Biochem, Beijing, China). Pimelic acid (99% Merck, Darmstadt, Germany) was used in the oxidative desulfurization technique. To process the high-sulfur diesel with a starting sulfur concentration of 2865 mg/L, a microwave reactor device operating at 2.45 GHz was employed, with control over irradiation power and processing time, using a 1500 RPM electric mixer. A 50 mL sample of diesel fuel was used, and this ratio remained constant in all experiments. It was mixed with varying amounts of hydrogen peroxide (5, 15, 25, 35, 45 mL) and different amounts of pimelic acid (0.1, 0.3, 0.5, 0.7, 0.9 mL). All components were blended using an electric mixer (1500 RPM) for 10 minutes. The resulting mixture was then subjected to microwave irradiation at energy levels of 200, 300, 400, 500, and 600 W for different time intervals of 50, 100, 150, 200, and 250 seconds. After microwave treatment, an equal volume of acetonitrile was added to the mixture, which was then mixed thoroughly and placed in a separating funnel for approximately 15 minutes to allow phase separation. The lower layer, representing the treated diesel fuel, was collected for analysis. A sample was taken, and the sulfur content was determined. As shown in Table 1 and Figures 1 and 2, the sulfur removal rate was calculated using the following equation:

$$Removal\ rate = (x - y)/x \times 100 \tag{1}$$

where x is original diesel and y is diesel after treatment.

Each experiment was conducted twice (in duplicate), and the standard deviation of the sulfur removal data was calculated. The standard deviations are presented in Figures 3–7 as error bars to illustrate experimental variability**.** A schematic illustration of the experimental setup, including the microwave reactor, mixing system, and separation process, was provided to clarify the technique and system components. The sulfur concentration of the model diesel, actual diesel fuel, and products was measured at the Refining and Gas Research Department of the Petroleum Research and Development Center under the Ministry of Oil, using the XOS Sindie OTG sulfur analyzer (USA) employing monochromatic wavelength-dispersive X-ray fluorescence according to ASTM D7039.

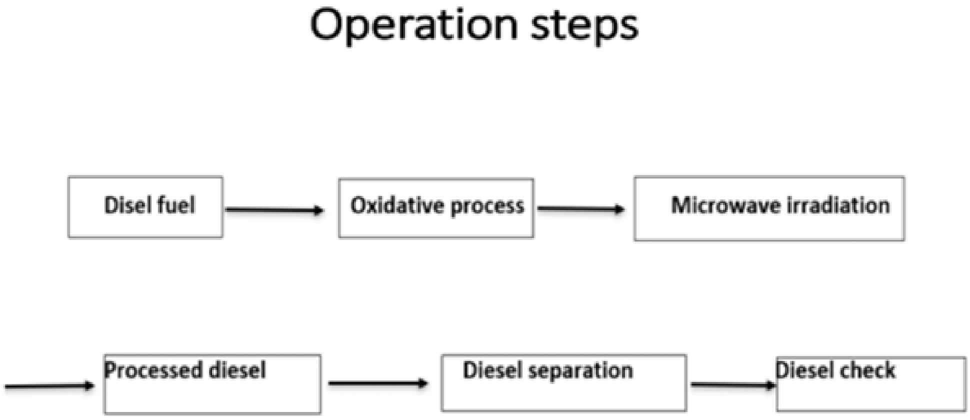

Fig.1. Operation steps

Fig. 2. Experimental procedure of testing

4. Design Results and Discussion

The results are presented in Tables 2 to 4 and Figures 3 and 4. This method proved to be effective for the removal of oxidized sulfur compounds from diesel fuel. Microwave irradiation can serve as an efficient and rapid technique for sulfur removal through oxidation, owing to its volumetric and selective heating characteristics.

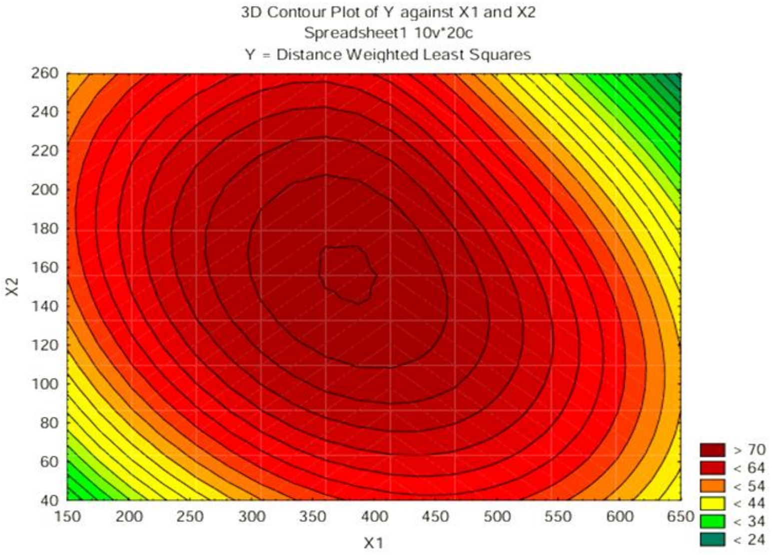

Fig. 3. 3D Plan of power emitted (W) and treatment time (s)

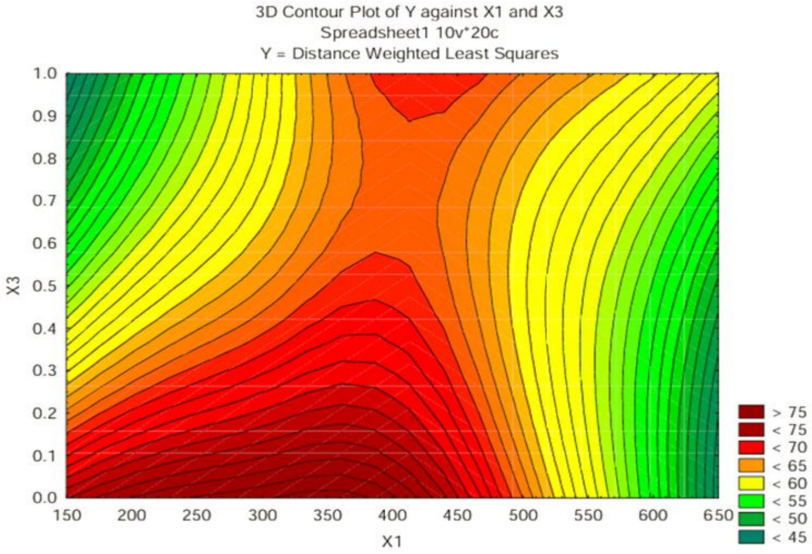

Fig. 4. 3D Plan of power emitted (W) and rate volume (ml)

It is worth noting that the microwave irradiation method was successfully applied to remove oxidized sulfur compounds from diesel fuel at various power levels and irradiation times. At 400 W and 150 s, a sulfur removal efficiency of approximately 70% was achieved (Figure 3), representing the highest efficiency obtained in this study. Figure 4 illustrates that the maximum separation efficiency (~75%) occurred at 400 W with a peroxide-to-diesel volume ratio of 0.5**.**

The optimization results obtained from the response surface methodology (RSM) are summarized as follows: the final value (5.7670) The model's high accuracy is confirmed by the root mean square error (RMSE = 0.533), and the lack-of-fit score (541.12) shows that the model is statistically significant and sufficiently describes the experimental data.

Table 1. Three-factors, five-level central composite design

Run no.	Coded values			Real values			Removal rate
	x_1	x_2	x_3	Power emitted [W]	Treatment time [sec]	volume of H_2O_2 to the volume of diesel [ml]	Y [%]
1	-1	-1	-1	300	100	0.3	66
2	1	-1	-1	500	100	0.3	64
3	-1	1	-1	300	200	0.3	71
4	-1	-1	1	300	100	0.7	61
5	1	-1	1	500	100	0.7	65
6	-1	1	1	300	200	0.7	63
7	1	1	-1	500	200	0.3	61
8	1	1	1	500	200	0.7	60
9	-2	0	0	200	150	0.5	60
10	2	0	0	600	150	0.5	55
11	0	-2	0	400	50	0.5	59
12	0	2	0	400	250	0.5	62
13	0	0	-2	400	150	0.1	74
14	0	0	2	400	150	0.9	67
15	0	0	0	400	150	0.5	70
16	0	0	0	400	150	0.5	70
17	0	0	0	400	150	0.5	70
18	0	0	0	400	150	0.5	70
19	0	0	0	400	150	0.5	70
20	0	0	0	400	150	0.5	70

Table 2. Sequence of experiments and separation results according to response surface methodology (RSM)

Factor	Symbol	Level				
		-2	-1	0	+1	+2
Power emitted, W	x_1	200	300	400	500	600
Treatment time, sec	x_2	50	100	150	200	250
Volume of H_2O_2 to the volume of diesel fuel ml	x_3	0.1	0.3	0.5	0.7	0.9

Table 3. Summary coefficient of polynomials results

Polynomial coefficients	Estimate	Standard error	Low. conf. limit	Up. conf. limit	p-level
a0	-5.2670	5.727262	-18.0281	7.4941	0.379411
a1	0.2580	0.016135	0.2260	0.2939	0.000000
a2	0.4807	0.031405	0.4017	0.5507	0.000000
a3	-32.8930	7.764768	-50.3840	-15.6820	0.001695
a4	-0.0004	0.000045	-0.0005	-0.0003	0.000038
a5	0.0813	0.013425	0.0513	0.1112	0.000123
a6	-0.0625	0.026849	-0.1223	-0.0027	0.042207
a7	-0.0003	0.000015	-0.0004	-0.0003	0.000000
a8	-0.0010	0.000061	-0.0011	-0.0008	0.000000
a9	1.4205	3.786240	-7.0158	9.8567	0.715371

The model is:

$$y = a_0 + a_1 \times x_1 + a_2 \times x_2 + a_3 \times x_3 + a_4 \times x_1 \times x_2 + a_5 \times x_1 \times x_3 + a_6 \times x_2 \times x_3 + a_7 \times x_1^2 + a_8 \times x_2^2 + a_9 \times x_3^2 \qquad (2$$

Dep. Var: y and Level of confidence: 95.0% (α = 0.050).

4.1 Effect of Power Emitted on Separation Efficiency

As seen in Figure 5, one important aspect affecting separation efficiency is the amount of electricity (W) that is released. Because improved reaction kinetics speed up the oxidative desulfurization process, efficiency first rises with increased power. Efficiency increases from 50% at 200 W to 57% at 400 W, for example, during 50 s and a volume ratio of 0.1 mL (blue curve). Nevertheless, efficiency decreases at higher powers (500–600 W), most likely as a result of partial hydrogen peroxide breakdown brought on by excessive microwave radiation, which lowers the amount of oxidant that is accessible. Similarly, efficiency rises with power up to 400 W and then falls at higher powers for longer treatment periods and bigger volume ratios (red and green curves). This pattern shows a compromise between better mass transfer and the negative consequences of reactant depletion or overheating. The equilibrium between sufficient reactant availability at lower ratios and dilution or competing side reactions at higher ratios is what allows for the existence of an ideal volume ratio. Once more demonstrating the existence of an ideal power when reaction circumstances are favorable and there are no notable side reactions, the sky-blue curve (200 s, 0.7 mL) reaches a maximum efficiency of 72% at 400 W. The impact of irradiation duration is further highlighted by the purple curve (250 s, 0.9 mL), which shows that more thorough oxidation is possible with longer exposure times. Efficiency rises from 72% at 50 s to 77% at 150 s. Efficiency somewhat declines after this, perhaps as a result of additional reactions or excessive oxidation. The current method using pimelic acid offers a simpler, environmentally acceptable alternative with reasonable performance (up to 77%), avoiding the use of costly or harmful metals, in contrast to existing methods that employ metal-based catalysts that yield >90% efficiency. Pimelic acid is a sustainable substitute for oxidative desulfurization applications because of its cost-effectiveness, operational simplicity, and green chemistry viewpoint, even though the realized efficiency is a little lower.

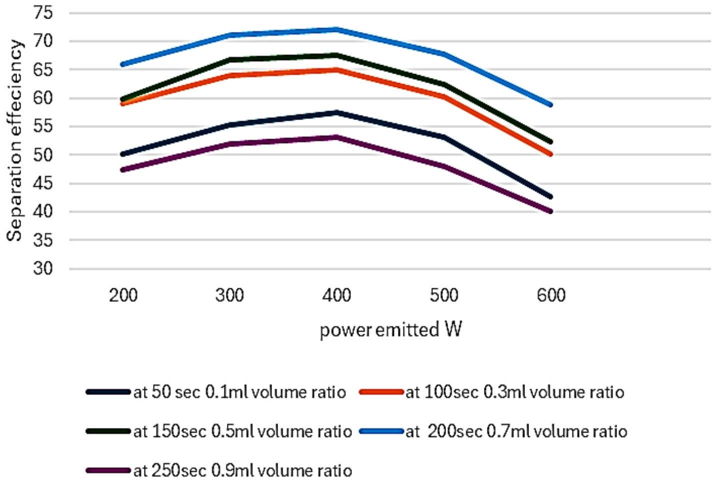

Fig. 5. The effect of power emitted on separation efficiency

4.2 Effect of Time on Separation Efficiency

Figure 6 illustrates the effect of irradiation time on desulfurization efficiency under different powers and volume ratios. The blue curve represents 200 W and a volume ratio of 0.1 mL. The efficiency reached 50% at 50 seconds and increased to 54% and 58% at 100 and 150 seconds, respectively. At 200 seconds, efficiency decreased to 52%, followed by a slight recovery to 57% at 250 seconds. The red curve corresponds to 300 W with a volume ratio of 0.3 mL. Efficiency rose from 60% at 50 seconds to 66.3% at 150 seconds, then declined to 62% at 200 seconds before recovering to 66% at 250 seconds. Similarly, the green curve (400 W, 0.5 mL) shows an increase from 67% at 50 seconds to a maximum of 75% at 150 seconds, followed by a slight drop to 72% at 200 seconds and a modest increase to 74% at 250 seconds. For higher powers, similar behavior was observed. The sky-blue curve (500 W, 0.7 mL) exhibited an increase from 70% at 50 seconds to 78% at 150 seconds, then a decline to 73% at 200 seconds and a small recovery to 74% at 250 seconds. The purple curve (600 W, 0.9 mL) followed the same trend, with efficiency increasing from

72% at 50 seconds to 77% at 150 seconds before decreasing to 70% at 200 seconds and slightly rising to 74% at 250 seconds. This overall trend suggests that desulfurization efficiency initially improves with irradiation time because longer exposure enhances mass transfer and allows more complete oxidation of sulfur compounds. However, beyond a certain point (around 150–200 seconds), efficiency tends to decline due to possible over-oxidation, secondary side reactions, or partial decomposition of hydrogen peroxide caused by prolonged microwave exposure. The slight recovery at 250 seconds may result from the reactivation of intermediate oxidation pathways or local redistribution of reactants under continuous irradiation. These results indicate that an optimal irradiation time exists where oxidative desulfurization proceeds efficiently without significant degradation of the oxidant or excessive thermal effects. Therefore, both microwave power and irradiation duration must be carefully balanced to maximize desulfurization efficiency while maintaining reaction stability.

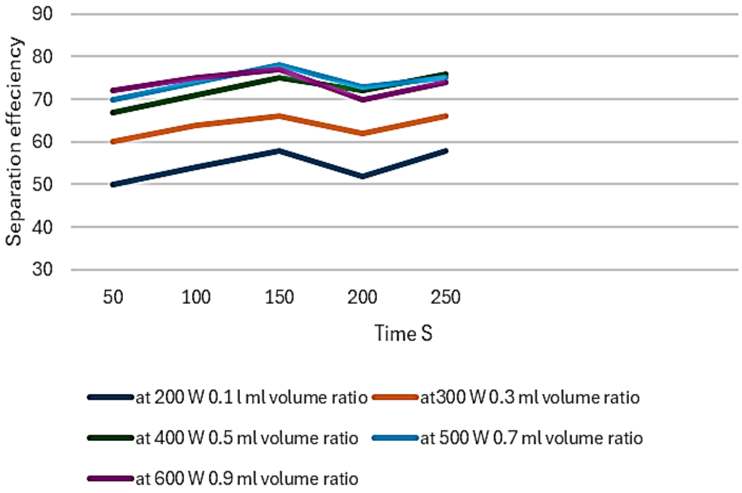

Fig. 6. The effect of time on separation efficiency

4.3 Effect of Volume Ratio on Separation Efficiency

Figure 7 presents the effect of the oxidant-to-fuel volume ratio on separation efficiency under various powers and irradiation times. The blue curve (200 W, 50 s) shows that the efficiency increased from 47% at a 0.1 mL ratio to 67% at 0.3 mL and reached a maximum of 71% at 0.5 mL. Further increases in the volume ratio caused the efficiency to drop to 60% at 0.7 mL and 34.3% at 0.9 mL. A similar trend was observed for higher powers. The red curve (300 W, 50 s) exhibited efficiencies of 44%, 64%, and 68% at 0.1, 0.3, and 0.5 mL, respectively, followed by a decrease to 59% and 34% at 0.7 and 0.9 mL. The green curve (400 W, 150 s) followed the same pattern, with efficiency increasing from 41% at 0.1 mL to 65% at 0.5 mL, then decreasing to 34.5% at 0.9 mL. The sky-blue (500 W, 200 s) and purple (600 W, 250 s) curves also displayed comparable behavior, with peak efficiencies of 62% and 58% at 0.5 mL, respectively, before declining sharply at higher ratios. This consistent trend indicates the existence of an optimal oxidant-to-fuel ratio around 0.5 mL, where separation efficiency reaches its maximum. At lower ratios, the amount of oxidant (hydrogen peroxide) is insufficient to fully oxidize the sulfur compounds, limiting the desulfurization process. As the oxidant volume increases, reaction kinetics improve because more reactive oxygen species become available, leading to higher efficiency. However, when the volume ratio exceeds the optimal value, the excess oxidant and solvent cause dilution of the reaction medium, reducing the contact between the organic and aqueous phases. Additionally, excess hydrogen peroxide may undergo self-decomposition or promote competing side reactions, both of which lower the effective oxidizing power. Therefore, the observed optimum results from a balance between reactant availability and reaction efficiency. Maintaining this balance ensures sufficient oxidation without significant dilution or side-product formation. These findings reinforce that the oxidant-to-fuel ratio, in combination with microwave power and irradiation time, must be carefully optimized to achieve maximum desulfurization efficiency while preserving process stability.

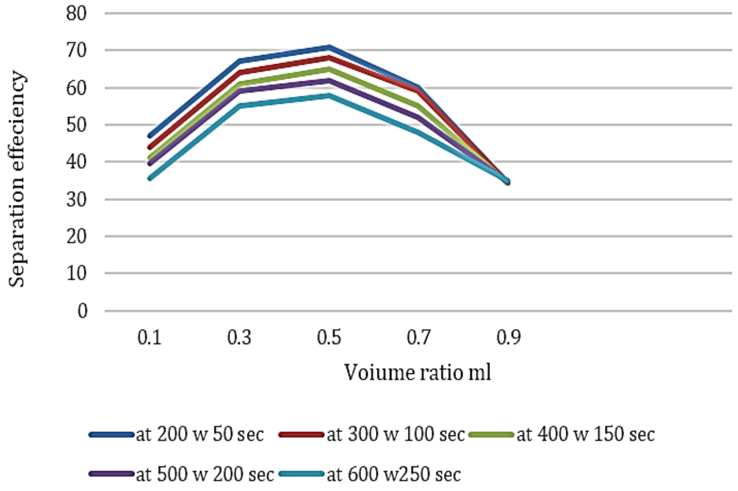

Fig. 7. The effect of volume rate on separation efficiency

Increasing microwave power and exposure duration accelerates the temperature rise, thereby enhancing the effectiveness of the interaction between hydrogen peroxide and sulfur compounds. The volume ratio influences the availability and concentration of reactants, which in turn affects the oxidation rate. This synergistic effect leads to improved sulfur removal efficiency under optimal conditions. Additionally, pimelic acid surpasses other carboxylic acids in promoting oxidation due to its enhanced solubility, suitable hydrophobicity, and favorable molecular configuration. These characteristics improve its interaction with sulfur compounds and hydrogen peroxide. Moreover, pimelic acid may absorb microwave energy more efficiently, further enhancing the oxidation process. Pimelic acid is a sustainable and economical organic catalyst that is reusable, although its efficacy diminishes over time due to chemical degradation.

Table 4. The ANOVA analysis values

Parameter	Value
Summation of square for regression	86038.23
Summation of square for residual	5.77
Degrees of freedom for regression	10.00000
Degrees of freedom for residual	10.00000
Degrees of freedom for regression vs. corrected total	10.00000
Mean of squares for regression	8603.823
Mean of squares for residual	0.577
Mean of squares for regression vs. corrected total	8603.823
f-Rate for regression	14918.94
f-Rate for regression vs. corrected total	326.42
p-Rate for regression	0.000000
p-Rate for regression vs. corrected total	0.000000

Conversely, metal catalysts demonstrate higher efficiency and stability in sulfur removal and can withstand multiple cycles; however, they are more expensive and less environmentally sustainable because of the presence of heavy metals. Therefore, pimelic acid is suitable for cost-effective and environmentally friendly applications, whereas metal catalysts are better suited for high-efficiency industrial processes. Microwave heating provides selective and rapid volumetric heating of materials, which enhances both reaction rate and efficiency. In contrast, conventional heating gradually raises the temperature from the outside, potentially leading to uneven heat distribution and reduced reaction efficiency. Microwaves can directly interact with reactive compounds, accelerate oxidation reactions, and shorten processing time, independent of traditional heating methods. Despite these promising results, certain limitations must be acknowledged. Scaling the microwave-assisted oxidation process from the laboratory to an industrial scale may present technological and economic challenges. Additionally, the cost of hydrogen peroxide, as the primary active reagent, could affect the economic feasibility of the process, especially when large quantities are required. Therefore, future research should focus on optimizing reagent usage, exploring more cost-effective alternatives, and evaluating the environmental impact and safety considerations associated with industrial-scale applications.

5. Conclusions

Based on the results of experimental work, the following points can be concluded:

- Microwave irradiation is considered a cost-effective and environmentally friendly method, requiring only a few minutes of treatment without using chemicals or producing emissions.
- Various irradiation durations, energy levels, and volume ratios were tested, with optimal sulfur removal efficiency of 75% achieved at 400 w, 150 seconds, and a peroxide-to-diesel volume ratio of 0.5ml.
- Optimization techniques effectively identified the best operational conditions. Efficiency is further enhanced when using pimelic acid as an activating agent and hydrogen peroxide as an oxidizing agent alongside microwave radiation.
- Microwave irradiation facilitates an improved separation process, enhancing sulfur removal outcomes by up to 75%.
- The rotatable central composite design (CCD) was employed to systematically model the surface responses through a second-degree quadratic model.
- Results from a three-level factorial experiment were analyzed using linear regression. Coded variables were commonly used in the experimental design for accuracy and clarity.
- Microwave irradiation exhibits superior energy efficiency relative to traditional processes, significantly decreasing the production of secondary waste, so rendering it an environmentally viable alternative.

The microwave-assisted oxidative desulfurization method demonstrates significant promise for commercial application owing to its efficiency, rapidity, and environmental advantages. Subsequent investigations should prioritize process scalability, the incorporation of catalysts to enhance reaction rates, and thorough economic evaluations to determine commercial feasibility. Addressing these factors will facilitate the successful implementation of this technology and assist in the advancement of cleaner fuel.

Acknowledgement

The authors would like to thank the Electromechanical Department and Oil Research and Development Center of the Ministry of Oil for assistance in providing materials and testing.

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