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Research Paper

Enhancing Coal Quality through Efficient Sulfur Removal: The Role of Hydrogen Peroxide in the Desulfurization Process

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ABSTRACT*: Indonesia relies heavily on coal as a primary energy source; however, its high sulfur content reduces coal quality and contributes to sulfur dioxide emissions that pollute the environment. This study focuses on an experimental investigation limited to the reduction of sulfur content in coal using 3% H_2O_2, supported by relevant literature studies, to evaluate the effectiveness of H_2O_2 as an environmentally friendly oxidative agent in the coal desulfurization process aimed at improving coal quality and calorific value. The results indicate that 3% H_2O_2 is capable of removing both pyritic and organic sulfur with an efficiency of approximately 20–24% under optimal conditions (28–30°C and pH 3–5) without the use of transition metal catalysts. The process operates through the formation of active hydroxyl radicals that oxidize sulfur compounds without significantly damaging the primary carbon structure of the coal. Furthermore, the use of low-concentration H_2O_2 without metal catalysts or additional physical methods, such as microwave irradiation and ultraviolet radiation, has proven effective in reducing sulfur content through a gradual oxidative mechanism. The application of low-concentration H_2O_2 without catalysts represents an initial approach to evaluating the effectiveness of coal desulfurization and provides a promising foundation for the development of desulfurization technologies that are more cost-effective, easier to implement, and potentially suitable for broader industrial applications.*

Keywords: *low-rank coal; quality; coal upgrading; desulfurization; hydrogen peroxide*

1. INTRODUCTION

Coal remains the primary energy source supporting electricity generation and industrial needs in Indonesia. However, most coal reserves contain high sulfur levels, typically exceeding 2%, particularly in coals from India, which reduces quality and poses serious environmental concerns [1], [2]. The emission of sulfur dioxide (SO_2) from coal combustion contributes to air pollution, acid rain, and industrial equipment corrosion, thereby necessitating the development of cleaner and more efficient coal treatment technologies [3], [4]. Globally, countries with high-sulfur coal reserves such as India and Indonesia require effective and economically viable desulfurization approaches [5], [6]. Several studies have reported total sulfur removal efficiencies exceeding 70% under optimized operating conditions, indicating significant potential for industrial implementation [7], [8]. However, challenges remain in understanding the underlying chemical mechanisms during oxidation and their influence on coal quality [9], [10].

Some studies also highlight the trade-off between sulfur removal efficiency and the reduction of coal calorific value after treatment [11], [2]. In addition, the roles of metal catalysts and complexing agents in enhancing oxidative reactions are not yet fully understood [12], [13]. The environmental footprint resulting from the use of chemical reagents and the formation of liquid waste also requires further assessment to ensure process sustainability [3], [4]. Research on the use of hydrogen peroxide for coal desulfurization has become an important field in coal upgrading technologies [14], [15]. Various studies have demonstrated that hydrogen

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peroxide is an effective oxidative agent capable of removing both pyritic and organic sulfur from different coal types. Its effectiveness continues to improve through the incorporation of catalytic systems, complexing agents, and physico-chemical methods such as microwave heating and froth flotation [13], [14], [16].

The current conceptual framework focuses on the oxidative chemistry of hydrogen peroxide, including the Fenton mechanism and the generation of hydroxyl radicals (•OH) as the primary driving force for oxidation reactions [14], [17], [18]. The selective oxidation of sulfur into sulfone and sulfate forms has been shown to play a crucial role in improving coal cleanliness [6], [14]. By linking chemical oxidation processes with coal quality enhancement, this research reinforces the development of environmentally friendly clean coal upgrading technologies [19], [20].

This study was conducted to synthesize knowledge regarding the role of catalyst-free H_2O_2 in coal desulfurization and to evaluate the effectiveness of H_2O_2 without catalysts in reducing the sulfur content of coal. This study is an experimental investigation supported by relevant literature, with its scope limited specifically to a 3% H_2O_2-based desulfurization process focusing on the reduction of sulfur content in coal. This experimental study is expected to address scientific gaps related to the mechanistic understanding and potential industrial application of catalyst-free H_2O_2 desulfurization, supported by findings from previous studies. Furthermore, the study is intended to support the optimization of cleaner and higher-value utilization of Indonesian coal.

2. RESEARCH METHOD

2.1. Process Description

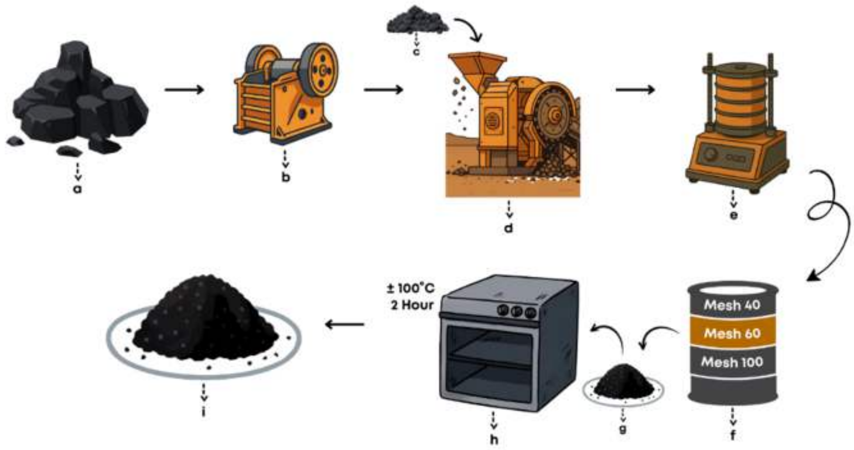
This study was conducted to evaluate the effectiveness of the coal desulfurization process using 3% H_2O_2 through a standardized laboratory experimental approach supported by relevant literature. The experiments were carried out over periods of 10, 20, and 30 days, representing the initial kinetic phase (day 10), the intermediate phase (day 20), and the near-saturation or steady-state phase (day 30). These time intervals were selected based on previous studies reporting a reduction in reaction rate over time due to limited reagent penetration and the decomposition of H_2O_2 within coal/mineral systems [10], [15]. This study was specifically limited to the reduction of sulfur content in coal and was intentionally designed using a purposive approach to focus the evaluation on the effect of reaction time on the effectiveness of coal desulfurization within a simple and controlled oxidative system. This approach was intended to minimize bias arising from multivariable interactions, thereby allowing the sulfur reduction mechanism to be observed more clearly and quantitatively.

The research stages included sample preparation, the desulfurization process, laboratory analysis, and data analysis supported by validation through scientific literature. This method was selected because it represents an environmentally friendly oxidative approach that has been scientifically proven to reduce sulfur content without decreasing the calorific value of coal, as reported in several recent studies [5], [14]. The description of the research process consists of:

2.1.1. Coal Sample Preparation

Coal samples were collected from Lahat Regency, South Sumatra, Indonesia, and conditioned at ambient temperature to minimize inherent moisture. The samples underwent progressive size reduction using a jaw crusher, pulverizer, and sieve shaker until a particle fraction of –60 mesh was obtained. Subsequently, the samples were oven-dried at approximately ± 100°C for 2 hours to achieve a completely moisture-free condition prior to chemical treatment.

Fine particle sizes produce higher sulfur removal efficiency than coarse particle sizes in the desulfurization process using hydrogen peroxide [21]. The –60 mesh fraction demonstrated better sulfur reduction performance, as finer particle sizes enhance reagent penetration into the coal pores. In addition, this particle fraction remains within an effective range for increasing the reaction surface area while still being operationally practical [22]. Therefore, in this study, the - 60 mesh particle size was considered capable of providing a sufficiently large reaction surface area while maintaining preparation efficiency and potential applicability on an industrial scale. This consideration is highly relevant to the implementation of coal particle fraction sizing in the present study.



Description: a. lump of coal; b. jaw crusher; c. coal from crushing; d. pulverizer; e. sieve shaker; f. sieve; g. 60 mesh coal; h. oven; i. coal ready for testing

Figure 1. Coal Sample Preparation

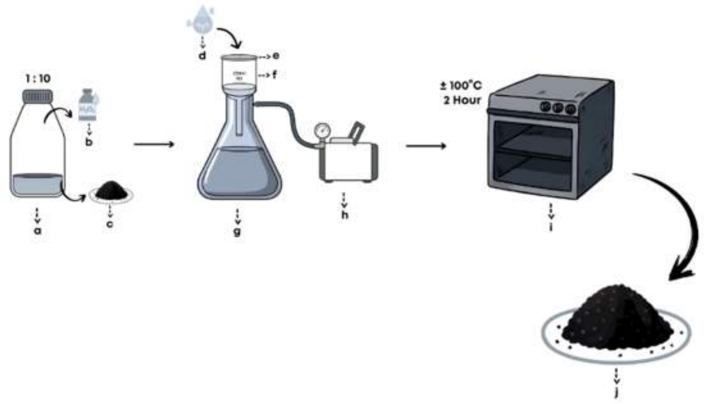
This preparation stage is essential to ensure particle size homogeneity and consistency of surface reactivity, as particle size has been shown to significantly influence oxidative reaction kinetics and the diffusion of oxidizing agents into the coal matrix [8], [23].

2.1.2. Desulfurization Experiment

The desulfurization process was carried out by immersing the prepared coal samples in a 3% hydrogen peroxide solution using a solid-to-liquid ratio of 1:10 (coal/fluid) under optimal conditions (28–30°C and pH 3–5). Several previous studies employed relatively high concentrations of hydrogen peroxide and involved the use of additional materials; however, H_2O_2 does not always require catalysts to produce effective oxidation reactions [24]. Therefore, this research was primarily designed as a preliminary fundamental study.

The oxidation process was conducted for 10, 20, and 30 days under identical treatment conditions for each sample to ensure system homogeneity and stable reaction rates. After the oxidation process was completed, the mixture was filtered to separate the solid residue from the reaction solution. Although the extended reaction time may appear less representative for direct industrial application, the 30-day treatment period in this study was intentionally selected to observe sulfur reduction behavior at the laboratory scale under mild oxidative conditions using low-concentration H_2O_2. This approach is consistent with previous studies reporting that diluted hydrogen peroxide treatment does not cause immediate degradation, but instead promotes gradual oxidative transformation and may require prolonged exposure to induce measurable physicochemical changes within the coal matrix [25]. Consequently, this method allowed the identification of reaction efficiency reduction patterns over time.

The coal residue was subsequently washed repeatedly with ultrapure water until the pH approached neutral conditions (≈7) to remove residual oxidants and dissolved reaction products. The samples were then dried again in an oven at approximately ± 100°C for 2 hours. This procedure was designed to minimize mass loss and preserve the structural integrity of the coal while simultaneously simulating actual reaction conditions in a low-cost wet oxidation system relevant to medium-scale industrial applications.

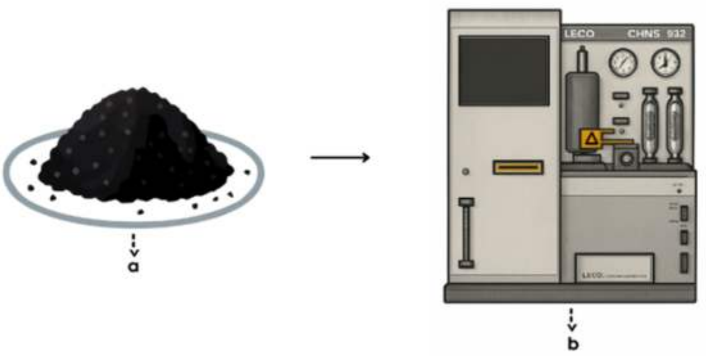


Description: a. vial; b. hydrogen peroxide 3%; c. coal ready for testing; d. ultra-pure water; e. Whatman No. 42 filter paper; f. buchner funnel; g. erlenmeyer; h. vacuum pump; i. oven; j. final coal sample

Figure 2. Desulfurization Coal Sample Experiment

2.1.3. Laboratory Analysis

The initial coal sample used as the reference for comparison with the coal samples treated with H_2O_2 was subjected to the same immersion procedure using ultrapure water. Subsequently, both the initial and treated samples were analyzed using a LECO CHNS Analyzer to determine the elemental composition of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S). The analytical results were used to calculate sulfur removal efficiency (desulfurization efficiency) and to evaluate changes in the elemental composition of the coal resulting from the hydrogen peroxide treatment. The CHNS method was selected due to its high accuracy in total sulfur analysis and its ability to provide quantitative characterization that can be directly compared with international research standards.



Description: a. final coal sample; b. Leco CHNS Analyzer

Figure 3. Coal Laboratory Analysis

2.1.4. Data Analysis and Literature Validation

The experimental data were analyzed using a descriptive-quantitative approach to determine the effect of oxidative treatment on sulfur content and coal quality. Desulfurization efficiency was calculated based on the difference in sulfur content before and after the reaction, while changes in other elemental compositions were evaluated to assess the structural stability of the coal.

The experimental results were subsequently validated through comparison with recent scientific literature published between 2000 and 2024, including studies related to hydrogen peroxide oxidation processes. This approach ensures that the present study maintains direct relevance to current scientific developments while contributing to the advancement of sustainable desulfurization technologies in the national coal mining sector.

This research is positioned as a preliminary study under mild operating conditions, supported by literature-based and fundamental experimental studies, to understand the behavior of sulfur reduction using low-concentration H_2O_2 under mild operational conditions. Therefore, the primary focus of this study is not direct industrial optimization, but rather the identification of reaction trends and sulfur removal effectiveness as a foundation for further research toward more applicable and intensified operating conditions at the industrial scale.

3. RESULTS AND DISCUSSION

3.1. Oxidation Mechanism of Hydrogen Peroxide in Coal Desulfurization

The desulfurization results obtained using a 3% hydrogen peroxide solution demonstrate a systematic reduction in sulfur content across all immersion durations, exhibiting a trend consistent with the radical-based oxidation mechanisms widely reported in the literature. After 10 days of treatment, the sulfur content decreased from 0.183% to 0.145%, followed by a more pronounced decline on day 20 from 0.211% to 0.161%, before reaching a quasi-static or saturation state on day 30 with a relatively unchanged value of 0.155% to 0.154%. This behavior reflects the fundamental characteristics of hydrogen peroxide as a strong oxidizing agent that decomposes to form hydroxyl radicals (•OH) and hydroperoxyl radicals ($HO_2\bullet$), either spontaneously or through catalysis by transition-metal ions. The systematic reduction in sulfur content was quantified by calculating the sulfur removal efficiency using Equation (1).

Desulfurization Efficiency: $\frac{(S_0 - S_t)}{S_0} \times 100\%$ .... (1)

with:

S_0= initial sulfur content (%)

S_t= sulfur content after treatment (%)

Table 1. presents a comparison of sulfur content before and after treatment, along with the resulting sulfur removal percentages.

Table 1. Desulfurization Efficiency Use H_2O_2 3%

Reaction Time	Initial Sulfur (%)	Final Sulfur (%)	Sulfur Reduction (%)
10 Days	0.1832	0.1456	20.52%
20 Days	0.2114	0.1614	23.65%
30 Days	0.1555	0.1547	0.51%

Quantitatively, the sulfur removal efficiency obtained in this study cannot yet be considered high. The relatively low sulfur removal efficiency indicates that the desulfurization process using 3% H_2O_2 under non-catalytic conditions remains within the category of mild oxidative desulfurization. The low sulfur removal efficiency observed in this study was likely influenced by a combination of several factors, including the low oxidant concentration, the absence of catalysts for hydroxyl radical generation, limited diffusion of H_2O_2 into the coal matrix, decomposition of H_2O_2 during prolonged reaction periods, and the possible predominance of organic sulfur compounds that are more resistant to oxidation. Nevertheless, the results still demonstrate the capability of H_2O_2 to reduce sulfur content through a gradual oxidative mechanism.

These findings are consistent with previous studies in which H_2O_2 without catalysts was capable of performing effective oxidation processes in breadfruit starch due to its intrinsically strong oxidative properties [24]. Hydrogen peroxide remains effective as an oxidizing agent even without the addition of external catalysts because of its high intrinsic oxidizing capability. The catalyst-free approach was selected in this study to simplify the process and reduce operational costs, whereas previous studies generally employed catalysts to enhance sulfur removal efficiency. Therefore, this study may serve as a preliminary investigation in the development of an effective desulfurization method based on a simple, economical oxidation approach with minimal additive requirements.

An increase in sulfur removal efficiency was observed with increasing immersion time from 10 to 20 days. However, after 30 days of immersion, the reduction in sulfur content became relatively insignificant. Although the initial coal samples used in this study possessed different sulfur contents, the overall trend remained consistent, namely an increase in sulfur removal efficiency within the 10–20 day period followed by relatively stagnant conditions on day 30. This behavior indicates that the oxidation process proceeded more effectively during the early to intermediate immersion stages, when most of the readily oxidizable sulfur, particularly sulfur located on the surface of coal particles, was still available and the oxidant concentration remained sufficient for optimal reaction.

After 30 days of immersion, the rate of sulfur reduction became very small, indicating that the oxidative capability of the solution had begun to decline due to the depletion of active reagents caused by the natural decomposition of hydrogen peroxide over time, without additional reagent replenishment or catalyst introduction. Furthermore, the possible formation of oxidation product layers on the coal particle surfaces may have inhibited contact between the oxidizing agent and the remaining sulfur within the coal matrix, thereby limiting the oxidation of sulfur compounds that were more difficult to remove. Consequently, increasing the reaction time was only effective up to a certain optimum condition, specifically within the 10–20 day range, after which sulfur removal efficiency began to decline [21].

This phenomenon is presumed to occur because hydrogen peroxide undergoes gradual decomposition over prolonged immersion periods, thereby reducing the oxidative capability of the solution over time. In addition, readily oxidizable sulfur compounds, particularly pyritic sulfur located on the surface of coal particles, were likely removed during the early stages of immersion. The remaining sulfur was primarily located within the internal coal matrix, making it more difficult for the oxidizing agent to penetrate and react effectively. These conditions caused the desulfurization reaction rate to decrease, and the system gradually approached a state of reaction equilibrium.

In the existing literature, hydrogen peroxide is a strong oxidizing agent widely utilized in coal desulfurization due to its ability to generate highly reactive radical species while remaining environmentally benign. In aqueous systems, hydrogen peroxide can decompose spontaneously or be catalyzed by transition metal ions to produce hydroxyl radicals (•OH), hydroperoxyl radicals (HO_2•), and other reactive oxygen species [5], [14]. The fundamental reactions for hydroxyl radical formation can be described by Equations (2) and (3).

$$H_2O_2 \rightarrow 2{\bullet}OH \quad (2)$$

or through a Fenton-like reaction:

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + {\bullet}OH + OH^- \quad (3)$$

The hydroxyl radical possesses an exceptionally high oxidation potential (E° = +2.8 V), enabling it to cleave Fe–S bonds in pyrite (FeS_2) as well as C–S bonds in organic sulfur compounds. The oxidation proceeds stepwise through the formation of intermediate species such as sulfone, sulfoxide, and ultimately soluble sulfate [17], [26]. The reaction pathway has often been investigated using model compounds such as dibenzothiophene (DBT), whose aromatic structure closely represents that of organic sulfur in coal [27].

In pyritic coal, oxidation begins with the conversion of FeS_2 into Fe^{3+} and SO_4^{2-}. In the case of organic sulfur, hydroxyl radicals attack aromatic C–S groups, yielding sulfonate or sulfoxide species. This reaction can be represented by Equation (4).

$R–S–R' + •OH \rightarrow R–SO–R' \rightarrow R–SO_2–R' \rightarrow SO_4^{2-}$ .... (4)

The efficiency of radical formation and reaction direction is strongly influenced by pH, temperature, and the presence of metal catalysts. Metal ions such as Fe^{2+}, Cu^{2+}, and Mo^{6+} are known to accelerate hydroxyl radical generation through the formation of metal–peroxide complexes [18], [28]. However, an excess of metal ions can cause non-productive decomposition of hydrogen peroxide into water and oxygen without generating useful radicals, thus lowering oxidation efficiency [12].

Beyond chemical factors, physical intensification techniques such as microwave and ultrasonic irradiation have been proven to enhance hydroxyl radical formation by accelerating the cleavage of the O–O bond in hydrogen peroxide molecules [5], [6]. The additional energy from these waves improves oxidant diffusion within coal pores and expands the reactive surface area, resulting in a faster and more selective oxidation rate for sulfur.

Spectroscopic analyses (FTIR and XPS) have confirmed that during oxidation with hydrogen peroxide, sulfonate and sulfoxide functional groups are formed without significant degradation of the carbon matrix [14]. This indicates that hydrogen peroxide acts selectively toward sulfur species, making it safer for coal's organic structure compared to stronger oxidants such as ozone or permanganate.

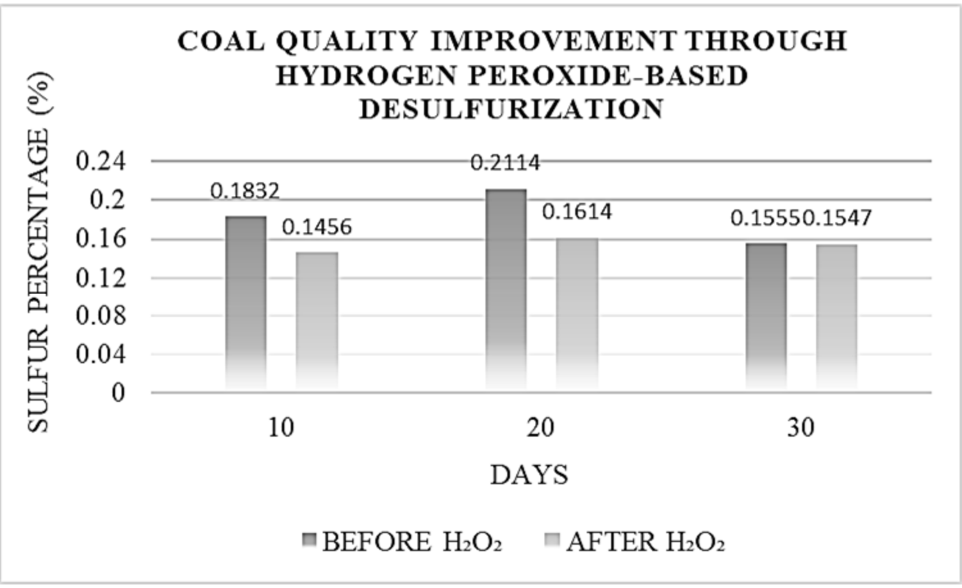


Figure 4. Coal Sulfur Removal Using 3% H_2O_2

3.2. Effectiveness and Variations of Sulfur Removal under Different Operating Conditions

The effectiveness of coal desulfurization using hydrogen peroxide largely depends on the operating conditions and the composition of the reaction system. The oxidative reactions dominated by hydroxyl radicals (•OH) and hydroperoxyl radicals (HO_2•) play a key role in converting both pyritic and organic sulfur into soluble oxidized forms such as sulfate and sulfonate [5], [14]. This process occurs through stepwise oxidation, where FeS_2 is converted into Fe^{3+} and SO_4^{2-} for inorganic sulfur, while C–S groups are transformed into $R–SO_2–R'$ for organic sulfur species [17], [26].

In the present study, coal desulfurization using a 3% H_2O_2 solution without catalysts exhibited relatively low efficiency throughout the reaction period. During the first 10 days, the system remained in the initial kinetic phase, in which hydroxyl radicals generated from H_2O_2 decomposition were still highly active and reactive sulfur compounds located on the coal surface were relatively easy to oxidize. By day 20, the desulfurization process was still ongoing, resulting in an increase in sulfur removal efficiency; however, indications of mass transfer limitations and a reduction in sulfur species readily accessible to the oxidizing agent had begun to appear. Meanwhile, by day 30, the system exhibited a quasi-saturation oxidation condition, in which the desulfurization rate became significantly slower due to the reduced activity of the oxidizing agent and the limited accessibility of sulfur species within the coal matrix as a result of oxidant diffusion limitations [25].

A comprehensive review of 25 scientific publications from 2000 to 2025 reveals that sulfur removal efficiency varies widely, ranging from 30% to 99%. This variation is primarily influenced by the type of coal, initial sulfur content, hydrogen peroxide concentration, reaction time, and the presence of transition metal catalysts [19], [25], [26]. In general, pyritic sulfur is more easily removed than organic sulfur, with pyritic sulfur removal efficiencies exceeding 70% under optimal conditions, while organic sulfur removal typically ranges between 30% and 60%.

Catalytic systems based on Fe(III), Cu(II), or Mo(VI) ions have been shown to enhance oxidation efficiency through Fenton-like mechanisms that accelerate hydroxyl radical formation [13], [18]. These catalytic systems can achieve removal efficiencies of up to 95% at temperatures between 40–60°C and pH values of 2–3. In contrast, non-catalytic systems generally exhibit maximum efficiencies below 70%, even with increased hydrogen peroxide concentrations [14]. In addition to catalysts, combining hydrogen peroxide with strong acids such as H_2SO_4 or HCl can accelerate pyrite oxidation by enhancing sulfide metal solubility [15], [23]. However, excessively acidic conditions may lead to degradation of the organic coal structure, a reduction in calorific value, and increased system corrosivity [11]. Therefore, several studies recommend using weak acids or citrate buffers to maintain selective sulfur oxidation while preserving the coal carbon matrix.

Physical intensification methods such as microwave and ultrasonic irradiation have also contributed significantly to improving desulfurization efficiency. Microwave treatment enhances internal coal heating, opens pore structures, and improves oxidant diffusion, while ultrasonic irradiation produces cavitation effects that promote hydroxyl radical formation [6], [31]. The combination of chemical and physical methods has been reported to reduce total sulfur content by more than 90% in shorter reaction times compared to conventional methods [7], [11].

A comparative evaluation of various oxidative systems indicates that hydrogen peroxide offers competitive performance relative to other oxidants such as ozone (O_3) and potassium permanganate ($KMnO_4$). Table. 2 presents a Summary of Coal Desulfurization Efficiency Using Hydrogen Peroxide based on relevant literature.

Table 2. Summary of Coal Desulfurization Efficiency Using Hydrogen Peroxide

No	Researcher (Year)	Coal Type	Main Process Conditions	Sulfur Type Removed	Removal Efficiency (%)	Key Findings
1	Ahmad et al. (2024)	Indonesian Sub-bituminous	H_2O_2 + Fe catalyst, 60°C, pH 3	Pyritic & Organic	85–95	High efficiency; good reagent stability
2	Ahmadi et al. (2022)	Indian Coal	H_2O_2 + H_2SO_4 (0.5 M)	Pyritic	80–90	Acid addition increases oxidation rate
3	Vasilakos & Clinton (1983)	Bituminous	Pure H_2O_2, 25°C	Total S	30–60	Low effectiveness without catalyst
4	Mukherjee et al. (2001)	Lignite	H_2O_2 + HCl (0.1 M)	Pyritic	70–85	Hydrochloric acid accelerates pyrite oxidation
5	Mukherjee & Srivastava (2004)	Lignite	H_2O_2 + strong acid	Pyritic & Organic	65–75	Better results achieved at low pH

No	Researcher (Year)	Coal Type	Main Process Conditions	Sulfur Type Removed	Removal Efficiency (%)	Key Findings
6	Ma et al. (2014)	Bituminous	Oxidation + froth flotation	Total S	80–90	Combined method enhances desulfurization efficiency
7	Sana et al. (2018)	Indian Coal	H_2O_2 + Mo catalyst	Pyritic	95–99	Near-complete pyritic sulfur elimination
8	Pecina et al. (2014)	Sub-bituminous	H_2O_2 + Fe–Cu complex	Organic	60–70	Metal complexes accelerate oxidation reactions
9	Levent et al. (2016)	Turkish Coal	$H_2O_2 + H_2SO_4$	Pyritic	70–80	Acid addition improves pyritic sulfur removal
10	Chen et al. (2023)	Bituminous	$H_2O_2 + Fe^{2+}$, 50°C	Pyritic & Organic	60–85	Efficiency varies with initial sulfur content
11	Pengqi et al. (2017)	Bituminous	H_2O_2 + microwave	Organic	50–65	Microwave enhances oxidation kinetics
12	Gürü et al. (2008)	Lignite	$H_2O_2 + Na_2CO_3$	Pyritic	55–70	Alkali neutralizes residual acidity
13	Ismail et al. (2024)	Kalimantan Coal	H_2O_2 + Fe catalyst	Total S	80–90	High efficiency; stable calorific value
14	Sidan et al. (2022)	Bituminous	H_2O_2 + ultrasonic	Pyritic & Organic	75–85	Ultrasonication promotes radical formation
15	Warzinski et al. (1980)	Bituminous	H_2O_2 without catalyst	Organic	30–40	Low efficiency; long reaction time required
16	This Research	Lignite	H_2O_2 3% without catalyst	Total S	20-24	Low efficiency

Desulfurization using 3% hydrogen peroxide without catalysts exhibited rapid kinetic characteristics during the initial stage and experienced significant reaction rate reduction after longer contact times. This reaction rate decline is consistent with the oxidative desulfurization mechanisms reported in previous studies, in which the effectiveness of H_2O_2 decreases over time due to oxidant decomposition, consumption of active radicals, limited reagent penetration into coal pores, and the transition from kinetic control to diffusion control.

Nevertheless, several previous studies have demonstrated that hydrogen peroxide-based desulfurization is highly effective in removing pyritic sulfur and provides reasonably good results for organic sulfur removal, with the primary advantage of selective reactions that do not produce hazardous residues. Furthermore, the decomposition products of hydrogen peroxide, consisting mainly of water and oxygen, make it a more environmentally friendly oxidizing agent compared with conventional chemical oxidants. These advantages support the potential application of H_2O_2-based desulfurization technology as part of coal upgrading efforts toward cleaner energy systems in Indonesia.

3.3. Optimization of Parameters and Process Intensification in Desulfurization

The efficiency of coal desulfurization using hydrogen peroxide is strongly influenced by several operational parameters, including temperature, pH, reagent concentration, reaction time, particle size, and the presence of catalysts or additives. Optimization of each parameter is essential to achieve a balance between effective sulfur removal and the preservation of the coal's organic structure. The main principle is to regulate the generation rate of hydroxyl radicals (•OH) so that it is sufficiently high to oxidize sulfur compounds but not excessive to the point of degrading active carbon. Careful control of these parameters ensures both high desulfurization efficiency and minimal structural alteration of coal.

The results of this study demonstrate that coal desulfurization using 3% H_2O_2 without catalysts was capable of removing both pyritic and organic sulfur with an efficiency of approximately 20–24% under optimal conditions (28–30°C and pH 3–5). The process operated through the formation of active hydroxyl radicals that oxidized sulfur compounds without damaging the primary carbon structure of the coal through a gradual oxidative mechanism. Under these conditions, hydrogen peroxide was presumed to maintain sufficient stability, allowing the sulfur oxidation process to proceed more effectively. At excessively high temperatures, hydrogen peroxide tends to decompose more rapidly into water and oxygen, thereby reducing the amount of active oxidizing species available in the system. In addition, mildly acidic conditions (pH 3–5) support the oxidation of pyritic sulfur because hydrogen peroxide remains more stable and sulfur oxidation products remain in dissolved form. Acidic conditions also help prevent the formation of hydroxide precipitates that could inhibit contact between the oxidizing agent and the coal surface.

In existing literature, a combination of moderate operating conditions (40–60°C, pH 3–4, H_2O_2 3–5 M), fine particle size, and a Fenton-like catalytic system results in the most efficient desulfurization, with overall efficiencies ranging from 85–95%. Integrating physical intensification methods such as microwave or ultrasonic irradiation can further increase process efficiency to over 90%, while reducing reaction time and reagent demand [5], [6]. With proper parameter control, hydrogen peroxide–based desulfurization can be optimized into an energy-efficient, effective, and sustainable reaction system. This intensification approach opens opportunities for pilot-scale industrial implementation in Indonesia's coal sector, supporting environmentally friendly coal upgrading technologies and advancing the nation's transition toward clean energy systems.

3.4. Environmental Evaluation and the Future Direction of Sustainable Desulfurization in Indonesia

The implementation of hydrogen peroxide-based coal desulfurization technology requires comprehensive evaluation not only from a technical perspective but also in terms of environmental and process sustainability. Compared to conventional methods that employ strong oxidants such as ozone, concentrated acids, or potassium permanganate, hydrogen peroxide offers a major advantage: it naturally decomposes into water and oxygen without generating toxic residues [3]. This characteristic makes hydrogen peroxide a "green oxidant" consistent with the principles of green chemistry, where chemical efficiency is achieved with minimal ecological impact.

In the context of Indonesia, the adoption of hydrogen peroxide-based desulfurization technology holds strategic importance, as most low-rank coals from Kalimantan and Sumatra contain high levels of sulfur and ash. Based on life cycle assessment (LCA) studies, this process offers a more favorable environmental-benefit ratio compared to acid-based oxidation methods, particularly in terms of SO_2 emission reduction, minimal solid waste generation, and improved energy efficiency [3], [7]. However, industrial-scale application still requires in-depth evaluation of reagent costs, wastewater management, and integration with existing coal upgrading systems.

Moving forward, the development of this technology should focus on the implementation of closed-loop systems for reagent and process water recovery, the replacement of homogeneous catalysts with natural mineral based heterogeneous catalysts, and the establishment of industrial-scale pilot plants equipped with LCA and economic feasibility assessments. National policy support for eco-friendly desulfurization innovations is also necessary to enable wider adoption in the mining sector. With its clean reaction pathway, high efficiency, and alignment with green energy principles, hydrogen peroxide-based desulfurization has strong potential to become a key component of Indonesia's transition toward sustainable energy.

4. CONCLUSION

The results of this study demonstrate that coal desulfurization using 3% H_2O_2 without catalysts is capable of reducing both pyritic and organic sulfur through a gradual oxidative mechanism under moderate operating conditions without damaging the primary carbon structure of the coal. The desulfurization process achieved a sulfur removal efficiency of approximately 20–24%, indicating that H_2O_2 remains effective as an environmentally friendly oxidizing agent despite the relatively limited efficiency obtained under non-catalytic conditions. The reaction exhibited rapid kinetics during the initial stage, followed by a significant decrease in desulfurization rate over longer reaction times due to the low oxidant concentration, the absence of hydroxyl radical-generating catalysts, limited diffusion of H_2O_2 into the coal matrix, and the gradual decomposition of hydrogen peroxide during prolonged oxidation. Nevertheless, the findings confirm the potential of low-concentration H_2O_2 as a simple, economical, and low-additive approach for coal desulfurization. This study serves as a preliminary foundation for the further development of more effective desulfurization technologies through process optimization and intensification methods, such as the use of catalysts, microwave irradiation, or ultrasonic assistance, particularly to support sustainable coal utilization and the transition toward cleaner energy systems in Indonesia. These findings provide a preliminary basis for further optimization of catalyst-assisted and intensified desulfurization systems toward industrial-scale implementation.

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