Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 4, Issue 2, 2026

ADVANCES IN ACID AND ALKALI LEACHING FOR COAL DESULFURIZATION: A REVIEW

Muhammad Azam Usto[*1], Abdul Rehman Memon[2], Abdul Quddus Bhutto[3], Zulfiqar Solangi[4]

[*1]*Department of Chemical Engineering, Dawood University of Engineering and technology, Karachi, Sindh.*
[2,4]*Department of Chemical Engineering, Mehran University of Engineering and technology, Jamshoro, Sind*
[3]*Marafiq-Plant and Machinery Water maintenance Department KSA*

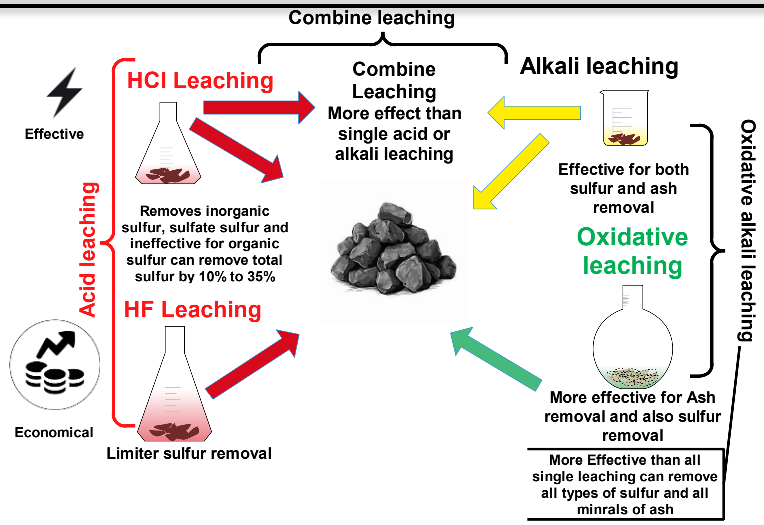
DOI: https://doi.org/10.5281/zenodo.19482409

Keywords
Acid leaching, Alkali leaching, Coal desulfurization, Oxidative Alkali leaching.

Article History
Received: 17 December 2025
Accepted: 01 February 2026
Published: 16 February 2026

Corresponding Author: *
Muhammad Azam Usto

Abstract
Coal is a key global energy source. However, using it creates considerable environmental challenges. This is due to the mineral matter and sulfur compounds in coal, which contribute to ash production and the release of pollutants like sulfur dioxide when the coal is burned. Chemical leaching has proven to be a successful method for coal beneficiation, significantly decreasing ash and sulfur content while maintaining calorific value. This article offers an extensive examination of diverse leaching methodologies, encompassing acid leaching, alkali leaching, acid–alkali combination treatments, and oxidative leaching. Acid leaching with hydrochloric acid (HCl), hydrofluoric acid (HF), nitric acid (HNO_3), and hydroiodic acid (HI) effectively facilitates the selective extraction of mineral matter and sulfur compounds, with HNO_3 and HI attaining a sulfur reduction of up to 90% under optimal conditions. Alkali leaching efficiently solubilizes silicates and alumina, whereas integrated acid–alkali treatments improve demineralization by treating remaining constituents. Oxidative leaching, utilizing agents like hydrogen peroxide and ozone, enhances the removal of pyritic and organic sulfur. The combined use of these processes can yield ultra-clean coal with negligible environmental impact. This article examines process characteristics, constraints, and recent improvements, emphasizing avenues for sustainable coal consumption and cleaner energy production.



INTRODUCTION

Coal continues to be one of the most abundant and extensively utilized fossil fuels, functioning as a vital energy source for electricity production and industrial uses globally.(Meshram, Purohit, Sinha, Sahu, & Pandey, 2015) Nonetheless, its use presents considerable environmental issues due to the inclusion of mineral matter and sulfur compounds, which lead to ash production and the release of detrimental pollutants like sulfur dioxide during combustion(Lei, Zhang, Hong, & Ye, 2022). These issues reduce coal-based operations' efficiency and increase air pollution and acid rain, making inorganic mineral and sulfur extraction essential to cleaner coal technologies(Usto & Memon, 2024).

Chemical leaching has developed as an effective technique for coal beneficiation, providing the potential to reduce ash content and desulfurize coal without sacrificing its calorific value(Shah et al., 2023). Numerous leaching methods such as acid leaching, alkali leaching, acid alkali combination treatments, and oxidative leaching have been thoroughly investigated to enhance coal quality. Alkalis transform silicates and alumina into soluble compounds, acids dissolve mineral materials and some sulfur species, and oxidative agents break down pyritic and organic sulfur structures to remove sulfur.

This article gives a thorough analysis of chemical leaching methods for cleaning coal, discussing their principles, efficacy, and factors that affect them. It also examines the synergistic effects of combining treatments and oxidative methods to produce ultra-clean coal with low environmental impact.

Single acid leaching

Acid leaching dissolves metal ions and minimizes sulfur and mineral waste in coal cleaning. It demineralizes and partially desulfurizes coal by mineral content. Acid leaching is an effective method for coal cleaning, targeting both mineral matter and sulfur compounds(Usto et al., 2024). Hydrochloric acid (HCl) efficiently dissolves ash-forming minerals like carbonates and phosphates but cannot remove silicates or inorganic sulfur. Hydrofluoric acid (HF) is essential for breaking down silicates such as kaolinite and quartz, while nitric acid (HNO_3) can remove 80–90% of inorganic and organic sulfur, though excessive use may alter coal structure. Combined or repeated treatments with acids like HCl and HF can nearly eliminate all minerals, producing ultra-clean coal

Hydrochloric acid (HCl) leaching

Sulfur dioxide emissions from coal must be reduced to reduce acid rain. Hydrochloric acid (HCl) leaching is a well investigated chemical process for coal desulfurization, typically compared to other acids and combined with alkali treatments for better results. HCl leaching can remove inorganic sulfur, including sulfates and some pyritic sulfur, but only to a minor extent compared to stronger oxidizing acids like nitric acid (HNO_3). HCl alone can remove 10% to 32% sulfur with higher acid concentrations, elevated temperatures (60–80°C), and extended leaching durations, according to studies (WIDYA, TOMMY, & WINDHU, 2024). However, HCl is less effective at removing organic sulfur, which often remains in the coal matrix (Pantović Spajić et al., 2021).

Acid leaching with HCl was used to desulfurize PT Anugerah Krida Utama coal, which had 4.05% of total sulfur. The optimal concentration for HCl leaching was 1 M, which reduced sulfur content to 2.91% adb, a 28.14% decrease. This approach reduces sulfur levels, reducing coal combustion sulfur dioxide.(WIDYA et al., 2024). It was observed by Steel (Steel & Patrick, 2001) that HCl is effective to dissolve almost all minerals present in the coal ash like carbonates, phosphates sulphate that are largely combined with major elements such as Calcium, Magnesium Iron Aluminium Potassium. But it is unable to solubilise the silicates alum and inorganic sulfur in the coal . Lakhra coal acid leaching with 0.2 N HCl removed 7.6% sulfur. The coal sample was stirred with acid solution at room temperature for one hour to leach. The modest sulfur content drop suggests that the sulfur removed was mostly inorganic, as organic sulfur is covalently linked to the coal matrix and insoluble in aqueous acidic solutions (Ahmad, Ahmad, Ahmad, Ullah, & Ibrahim, 2022).

Hydrogen Floride (HF) leaching

Using hydrogen fluoride (HF) leaching to remove sulfur from coal is an important coal desulfurization technology because it can target particular sulfur compounds in moderate circumstances. This method is particularly effective in removing sulfidic and oxidized sulfur, and to some extent, thiophenic sulfur, which are major contributors to environmental pollution and degradation of coal quality. In order to perform desulfurization at relatively low temperatures and improve coal's extractability by lowering its sulfur content, HF is occasionally used in conjunction with boron trifluoride (BF3). It was expected that hydrogen sulphide is an strong acid (Speight, 2012). Kaolinite and quartz can be broken by hydrofluoric acid. Quartz is harder to prepare than kaolinite, because coal demineralization depends on the amount of both in hard coal (Wang & Tomita, 1998). Most coal minerals were dissolved, but not pyrites. Thus, repeated HCl and HF treatments were advised to virtually remove minerals. Pyrite removal procedures were developed by Steel and Patrick (Meshram et al., 2015). Coal sulfur content is reduced by roughly 26% and ash is removed through a two-stage chemical leaching process that starts with hydrofluoric acid treatment, which removes primarily aluminum- and silicon-bearing minerals without affecting pyrite, and ends with ferric ion leaching, which removes most pyrite and HF-derived fluorides (Wu & Steel, 2007).

Nitric acid (HNO_3) Leaching

Demineralization is improved by HNO3, however nitric acid's efficacy depends on concentration. One study found that a single HNO3 could remove 80% to 90% of inorganic and organic sulphurs, but intensive treatment could affect coal structure.As a result, only one HNO3 washing has not been recommended. According to Rodriguez [11], atmospheric pressure nitric acid leaching of Spanish coal is effective for desulfurizing intermediate-rank coal, particularly for the removal of inorganic sulphur. Roman Alwarez [12] leached the coal using 90°C and 30% nitric acid. They found that during the first few minutes, most of the sulfur was decreased. A sulphur reduction of 28% organic, 86% sulphate, and 94% pyritic was achievable.

Hydroiodic Acid

acid treatment on coal, hydroiodic acid (HI) at 260 °C and 60 bar pressure removed all inorganic sulphur in 10 minutes and 70% of organic sulphur in 10 minutes on Spanish [9]. JM Andrés describes a new microwave-assisted desulfurization technique that uses concentrated hydroiodic acid to eliminate over 80% of total sulfur (including up to ~70% organic sulfur) from low-rank coals in 10 minutes. Time, temperature, and the acid's unique reactivity are the main factors influencing reaction efficiency(Andrés, Ferrando, & Membrado, 1996).

Alkali leaching

Alkali leaching can improve coal quality by increasing heating value recovery in addition to reducing sulfur content. Studies show that alkaline solutions increase sulfur extraction, especially organic sulfur, but their concentration must be carefully controlled to avoid hindering sulfur removal and heating value recovery.

It has been observed by many researchers that coal's ash and sulphur may be significantly reduced by using alkali solutions (Dhawan & Sharma, 2019; Nabeel, Khan, & Sharma, 2009; Song et al., 2016). Alkali treatment is an efficient way to remove ash from coal by removing most of the components that are rich in minerals. Due to their mutual influence, alkali solutions that are affected by coal minerals, can enter the coal infrastructure. By alkali leaching , the silica, alumina, and minerals matters in the coal are converted into hydrated soluble base while coal remains insoluble in the leaching solution therefore the alkali leaching is convenient, easy and economical method as compare to other desulfurization methods (sodalite)(Usto et al., 2023).A considerable percentage of ash-forming minerals, pyritic sulphur, and organic sulphur can be removed from coal by leaching with hot caustic solution.Treating with hot alkali solution is compelling in diminishing critical measures of ash minerals, and all types of sulfur (Adeleke, Ibitoye, Afonja, & Chagga, 2011; Duz, Hamamci, Erdoğan, Saydut, & Merdivan, 2008).The existence of the hydroxyl ion in the leachants, which has a strong affinity for the minerals that contain clay, may be the cause of the alkali attacking the main mineral (Casetou-Gustafson, 2019; Oyediran & Olalusi, 2017).

NaOH leaching

NaOH chemical desulfurization reduces coal sulfur, especially organic and pyritic sulfur, effectively. Coal is treated with aqueous NaOH solution at controlled temperature and duration to break down sulfur-containing compounds. NaOH interacts with sulfur-bearing functional groups to convert sulfur species into water-soluble sodium salts, which can be washed away. Alkaline conditions hydrolyze organic sulfur bonds and diminish pyritic sulfur's binding to coal. NaOH also increases coal matrix swelling at high temperatures, boosting reagent penetration and sulfur removal. Partial mineral matter dissolving helps desulfurize and reduce ash with this procedure.

Kara and Ceylan(Kara & Ceylan, 1988) have leached the Turkish lignite with aqueous solution of NaOH and could achieved the 83% demineralization rate and 47% desulfurization rate at 300°C. Saydut (Saydut, Duz, Erdogan, Tonbul, & Hamamci, 2011) looked at the impact of aqueous caustic leaching on asphaltite from Turkey. Asphaltite's ash content was reduced by 44.6%, pyritic sulphur by 83.3%, organic sulphur by 53.9%, total sulphur by 61.82%, and volatile matter by 46.29% by caustic leaching (1 M NaOH) at 180oC for 16 hours.A Wahab and Nawaz (Wahab et al., 2015) have leached the lakhra coal with hot caustic solution and could remove the ash 80% and total sulphur upto 40 %, coal heating value was increased. The rate of desulfurization was found to rise as coal particle size reduced and reaction temperature and time increased.According to Waugh (Waugh & Bowling, 1984) , the majority of the minerals that support bituminous coal's ash are either corrosive or insoluble in water, while 90% often ash can be eliminated by alkali leaching, at 200 °C to 300 °C under pressure and observed that a large portion of the significant minerals are to be changed over into sodium aluminosilicates at higher temperature which mad an insoluble stage in association with water or alkali solution.

It has been observed by many researcher that at higher alkali concentration the rate desulfurization was reduced (Chuang, Markuszewski, & Wheelock, 1983; Fu, He, Zhou, & Mao, 2021; Usto et al., 2021). It has been observed by many researchers that the reduction in the level of demineralization and desulfurization level of the coal at higher molarity amount of alkali solution is owing to the producing of sodium aluminosilicate during chemical reaction (Aditya et al., 2018; Behera, Chakraborty, & Meikap, 2018; Mukherjee & Borthakur, 2001) . This is because sodium-dissolvable aluminosilicate's component cannot be surpassed by the ratio of silicate and aluminate particulate. (Vogrin, Santini, Peng, & Vaughan, 2020). Blaz (Balaz, LaCount, Kern, & Turcaniova, 2001) has treated the Slovakia coal with hot alkali (NaOH) solution with 5% concentration at 90ºC, sulphur was reduced from 28% to 1.5%, while at higher concentration the reduction of desulfurization degree was observed due to formation of sodium-aluminosilicate. The treatment of a Nigerian coal from Nigeria was performed by Adeleke with sodium carbonate rather than NaOH and it was observed that ash decreased to 19.90% from 32.55%(Adeleke et al., 2011). Zheng proposed coal calcium hydroxide and sodium hydroxide to remove ash up to 90.14 percent. The optimal conditions were 650ºC boiling temperature, 60 min rosting time, 2% coal dose, and 4% aqueous calcium hydroxide solution. Reusing caustic is feasible. Na2CO3 at 120–150 C could remove all inorganic and 70% organic sulfate from one coal sample(Markuszewski, Chuang, & Wheelock, 1978).

KOH Leaching

Chemical leaching using potassium hydroxide (KOH) is a popular coal upgrading and desulfurization process(Saleem, Abbas, Dur-e-Shehwaar, Hassan, & Munawwar, 2021). KOH decomposes sulfur-containing organic structures and removes coal matrix inorganic sulfur species due to its strong alkaline nature and high reactivity(Ismail et al., 2023). KOH penetrates and swells better than other alkaline reagents, improving interaction with sulfur-bearing compounds. Washing and acid neutralization remove soluble potassium salts from KOH leaching of sulfur species. Alkaline conditions partially dissolve mineral materials, reducing sulfur and ash(Ahmad, Ahmad, Ahmad, & Shah, 2023). KOH concentration, reaction temperature, leaching period, particle size, and coal rank affect sulfur removal effectiveness. Higher temperatures and optimum reagent dosages improve sulfur removal(Ahmad, Ahmad, Ahmad, Yaseen, et al., 2022). KOH leaching works well for low-rank, high-sulfur coals with high organic sulfur concentration. Large-scale application still faces reagent recovery, process expense, and environmental control issues. KOH leaching is a potential chemical method for coal beneficiation and renewable energy use, especially when combined with post-treatment recovery and recycling.

A low grade coal with 3.69% total sulphur was treated with 1M of KOH at room temperature for 2 hours, although 3/4 of the reaction was finished in the first 30 minutes, as reported by Lolja(Lolja, 1999), An unreacted shrinking core model was utilised to examine the desulfurization process using a homogeneous coal particle of infinite size.

Acid alkali combines leaching

The combination leaching process may be effective for producing a higher amount of demineralization since it dissolves the un - reacted element and leftover ions from the first stage treatment(Ahmad, Ahmad, Ahmad, Ullah, et al., 2022). When leaching agents like NaOH and KOH are applied to coal particles, the principal minerals in the coal (silica, alumina, kaolinite, dolomite, and quartz) react with the sulphur to produce hydrated alkali compounds of silicate and aluminate. The unreacted minerals and complex compounds from the alkali-treated coal were then removed using an acid such as H2SO4 or HCl. Alkali leaching's unreacted by product formed during reaction could be because of the soluble ions concentrations exceeds the solubility product of its by products, the mineral coal's solubilization Shortly on, the residue began to precipitate and adsorb to the surface of the coal, which hindered the demineralization process. The acidic leachant makes these byproducts easily dissolvable. So, when alkali followed acid or combined leaching techniques were used, efficient demineralization was possible. The majority of clay minerals that are naturally present in low quality coals include silica, alumina, and other silica materials that are bonded to the coal matrix(Jatoi et al., 2023). The mineral-rich silica-alumina components of coal are significantly reacted by caustic leaching due to the great attraction of the leachant's hydroxyl ion, resulting in the formation of soluble sodium hydrated silicate and aluminate and sodium aluminosilicate compounds in the solution. Clay's mineral content (silica, alumina, and other forms) is present during acid-alkali leaching and cannot be dissolved in solution(Hashmi et al., 2023). Only iron and sulphur minerals are soluble in coal due to hidden mineral forms of silica and alumina in the lattice that are insoluble during acid leaching, however they both (Fe and S) are present in less quantity.

The use of NaOH or Ca(OH)2 soluble compounds followed by an acidic leaching using either hydrochloric acid or sulfuric acid can produce more than 75% level of demineralization of coals, even high ash coals, according to Sharma and Gihar.(Sharma & Gihar, 1991). Dash (Pratik S Dash, Sriramoju, Kargupta, Banerjee, & Ganguly, 2015)utilized high temperature pressure conditions in the acid alkali treatment for coals indicating the higher degree (70%) of demineralisation. The complexity of the interaction between the Phosphorous in coal has been analysed when the occurrence of Phasphoreous as oxalate and other phosphate minerals has been confirmed (Behera et al., 2018). Factors that could change include the solvent extraction pretreatment studies of the coal samples, pressure changes, oxidation conditions, and coal rank. Three different methods were used in one of the studies stated to conduct kinetic studies and then calculate the activation energy and K0 for the processes of coal leaching.(P. Dash et al., 2015). Choudhury(Chaudhary et al., 2021) achieved demineralization using NaOH and HCl at the optimal conditions of 0.22 mm particle size of coal , 90 ºC and 2-hour retention time. 70% of ash removing was observed in these conditions. Sriramoju also proved the mechanism of alkali-acid leaching in a 50 kg batch pilot plant study, and it was discovered that the constant temperature for the precipitation of sodalite during while other parameters (concentration, particle size and reaction time) are(Sriramoju, Dash, Suresh, & Ray, 2021). Through the optimization of the process, a 70% recovery of the used acid has been observed, while most of silica and 80% alumina were removed. In a separate study published by Srirmajou (Sriramoju, Dash, & Majumdar, 2022) , the impact of higher temperatures, shortened reaction times, and increased alkali concentrations on an Indian coal was investigated. The results showed a 68% reduction in ash with a decrease with ratio of 0.53 to 0.25 of alumina to silica.

Sharma and Singh's research was conducted at softer normal pressure environments. It has also been observed on a comparison of the amount of demineralization using aq. NaOH alone, followed by Hydrochloric acid or Sulfuric acid treatments. Additionally, lime was used in place of NaOH. The inorganic mineral matter present in the cash of some Indian coals was shown to be less reactive toward aqueous Sodium hydroxide under normal pressure conditions, although having larger ash contents 45%. With some Indian coals, the application of aqueous Sodium hydroxide solution at a higher reaction temperature resulted in the creation of sodium silicate salts with varying propensities to leach HCl or H2SO4(Dhawan & Sharma, 2019). There have been reports of caustic solution treatment followed by acid washing reducing the ash level of physically beneficiated Indian coals . The degree of demineralization was improved by lengthening the reaction time, raising the temperature and alkali concentration, and by decreasing coal particle size. After the acid treatment, only a small drop in sulphur concentration and a considerable reduction in phosphorous level were seen(Pratik Swarup Dash, Kumar, Banerjee, & Ganguly, 2013). Nabeel (Nabeel et al., 2009) produced der mild and ambient pressure . More than 75–80% of the coal ash can be removed from lower ranked coal using a three step chemical reaction that involves 1% or 5% aqueous Sodium hydroxide leaching , followed by 1% or 5% Sulfuric acid treatment. Doymaz (Doymaz, Gulen, Piskin, & Toprak, 2007) studied over how aqueous NaOH and other acid leaching affected the removal of mineral material from asphaltite. After pre treating the coal with a 5% Sodiumhydroxide solution, 10% H_2SO_4 and 40% HF were able to remove about 59.6% of the mineral content.

Figure 5. advantages of acid alkali leaching

Oxidative leaching

An oxidative leaching of Indian coal was performed by Shubhangi singh (Singh, 2021) with only hydrogen peroxide and with mixture of hydrogen peroxide and sulfuric acid. About 95% pyritic sulfur and 25% organic sulfur could remove. In this work the leaching was performed in three necked bottom flask(Usto et al., 2022). The reaction parameters was 45°C, pressure was 1 atm, the hydrogen peroxide concentration was 25% kept constant and sulfuric acid concentration was increased form from 1 to 3 normality(Usto & Memon, 2024). It was noted that Sulfur removing rate was increased with decreased in the size of particle and increased in reaction temperature and amount of sulfuric acid. Citrus and acetic acids have been used to eliminate ash from coal. These acids have a remarkable ability to operate as chelating agents, and by doing so, they might actually create coordination complexes with the inorganic mineral matter of coal, minimizing the amount of ash in the coal in the operationAside from the inorganic components, the utilization of oxidizing specialists like H2O2 Hydrogen peroxide, potassiumchromate, sodiumhypochlorate, fericsulfate, have been used for desulfurization and demineralization of coal (Behin, Akbari, Mahmoudi, & Khajeh, 2017; Krystynik, 2021) (Steel & Patrick, 2001). Several researchers have demonstrated successful desulfurization over the long term while also reducing amount of ash. (Cheng et al., 2003).

Oxidative alkali leaching

A very efficient technique for demineralizing and desulfurizing coal is oxidative alkali leaching. In order to remove both pyritic and organic sulphur at the same time, it combines the advantages of alkali treatment with oxidative agents such as hydrogen peroxide or nitric acid. Oxidative alkali leaching is more effective and selective than acid or alkali treatments alone. Furthermore, it permits the use of safe and ecologically acceptable chemicals that may remove ash and metals without compromising the structure of coal, such as EDTA and natural acids. That makes it a process that has the potential to produce cleaner coal with less of an impact on the environment.

Oxidative alkali leaching is same as acid alkali leaching, because acid acts as oxidative agent, but here we are discussing separately. Baluchistan coal from much was treated by Faisal Mushtaq with NaOH and HNO3(Mushtaq et al., 2021). The maximum sulfur reduction rate was 45% when treated with Nitric acid. While only 24% sulfur could be reduced when treated with sodium hydroxide. The reaction was carried out in glass ware, the solution was agitated with magnetic stirrer, the leaching time was 30 min and temperature was 90oC and particle size was 6 Mesh. It was found that increasing the solvent concentration enhanced the rate of desulfurization. While it decreased with larger coal particles size.

In a thermochemical investigation, Mukherjee and Srivastava treated Indian coals with 0.1 N sulfuric acid and hydrogen peroxide. It is thought that sulfuric acid serves as a catalyst to successfully desulfurize the coals by combining pyrtic sulfur and oxygen(Andrés et al., 1996). Other oxidising agents, including K2Cr2O7, have also removed 24% sulphur and 61% mineral matter from one type of Indian coal (ledo). Sodium hypochlorate leaching followed by basic treatment with sodium hydroxide has likewise been attempted by Li and Cho With 0.4 M hypochlorite and 0.4 M NaOH at 90oC, it was possible to remove almost 70% of pyritic sulphur and 37.8% of organic sulphur from Pittsburg coal. The ability of mineral acids to change the coal structure and its morphological surface features is the main disadvantage of using them.(Liu, Zhang, Choi, & Lu, 2018). So various reagents have been attempted. Ohki (Ohki, Nakajima, Yamashita, Iwashita, & Takanashi, 2004) have investigated the impact of different reageents at various concentrations on the successful removal of metals.

Various treatments with Nitric acid and EDTA was performed and Ca, Mg and Mn could be totally removed form the ash of coal . Citrus extract and pyroligneous acid have been used to remove the ash from coal, where these acids have a high capacity to act as adsorbing agents and can thus successfully build coordination structures with the inorganic mineral matter of coal, reducing the ash levels.(Huang, Liu, Wang, Zhao, & Xu, 2019). The chemical demineralisation at room temperature utilizing EDTA alongside various natural acids have likewise been performed by Manoj(Manoj, 2012) Citrus acid and EDTA leaching were used to reduce the ash content of an Indian coal to 2% and 1.8%, respectively. Aluminium, silica, and calcium could be completely removed from coal by combining acidic, citrus, and gluconic acids with EDTA. Citrus extract contains three COOH groups that can form carboxylates with metal cations.

Compression

In the table below the compression of all leching methods is given and it was observed that Oxidative alkali leaching produces ultra-clean coal by sequentially targeting all impurities

Table 1.Compression of leching types

Leaching Type	Advantages	disadvantages
Acid Leaching	1. HCL Reduces Ash minerals significantly 2. Strong Acid like Nitric acid and hydro Chloric Acid can remove inorganic and organic sulfur up to 90% 3. Rapid reaction 4. Sequential or combined acid treatments can nearly eliminate mineral particles, making coal for advanced applications.	1. Single acid leaching can not remove all minerals of coal 2. Intensive usage of strong acids like HNO_3 can alter coal's structure and physical characteristics. 3. Managing potent acids (HF, HNO_3, HI) presents safety hazards and necessitates specific apparatus. 4. West of acid disposal can be hazardous
Alkali leaching	1. Alkali solutions convert silicates and alumina into soluble molecules that acids cannot efficiently dissolve. This greatly decreases the ash concentration in coal. 2. Alkali leaching enhances the calorific value of coal by eliminating mineral matter, hence improving its combustion efficiency. 3. Under optimum conditions, alkali leaching can attain up to 83% demineralization and 47% sulfur reduction in lignite coal. 4. Strong caustic solutions can eliminate all tyoes of sulfur like pyritic, organic, and sulfate sulfur,	1. Increased alkali concentrations results in the formation of sodium aluminosilicates, hence decreasing the efficacy of demineralization and desulfurization processes. 2. Efficient alkali leaching typically requires elevated temperatures (200–300°C) and pressure, hence increasing operational complexity and expense. 3. Limited sulfur removal as compared to acid leaching
Acid alkali combine leaching	1. Sequential treatment demineralizes more than acid or alkali leaching because it dissolves unreacted minerals and residual chemicals. 2. After alkali leaching, acid treatment eliminates precipitated residues that obstruct demineralization, providing cleaner coal. 3. Under ideal circumstances, studies show up to 70–85% ash removal and a notable reduction in alumina and silica. 4. efficient for high-ash and low-grade coals where single-step leaching is inadequate	1. Multiple phases, thorough parameter control, and longer reaction times than single-stage leaching. 2. Sequential treatments require more chemicals and equipment, increasing cost.

Oxidative Alkali leaching	1. Oxidative alkali leaching removes mineral debris and sulfur faster than standard procedures, making it suited for ultra-clean coal. 2. Oxidation and alkali treatment improve reaction kinetics and selectivity, removing metals and ash without damaging coal structure. 3. Suitable for high-sulfur and high-ash coals where single-step leaching fails. 4. Eliminating sulfur and ash through oxidative alkali leaching leads to cleaner energy and less environmental impact by minimizing SO_2 emissions during combustion.	1. Exact control of temperature, pressure, reagent concentration, and particle size is needed for optimal results. 2. Using oxidizing agents like H_2O_2, nitric acid, or hypochlorite requires additional reagents and equipment, making it more costly than single-step acid or alkali leaching.

Conclusion

- Coal remains essential in global energy, but its mineral and sulfur content poses significant environmental challenges.
- Chemical leaching improves coal quality by reducing ash and sulfur while maintaining calorific value.
- Acid leaching effectively dissolves ash-forming minerals and removes sulfur, with acids like
- HCl, HF, HNO_3, and HI being particularly effective for certain impurities.
- Alkali leaching targets silicates and alumina, while acid-alkali combinations enhance demineralization by sequentially removing residual compounds.
- Oxidative leaching and oxidative alkali treatments boost the removal of pyritic and organic sulfur for ultra-clean coal.
- Optimizing process parameters (temperature, pressure, reagent concentration) can achieve high desulfurization and demineralization levels.
- Advanced techniques such as microwave-assisted and high-pressure leaching enhance reaction rates and efficiency.
- Existing challenges include minimizing coal structural changes and ensuring economic feasibility for large-scale applications.
- Future research should focus on environmentally friendly reagents, recovery systems, and hybrid processes for sustainable coal beneficiation.
- These strategies aim to help the coal industry shift towards cleaner energy production with a lower environmental impact.

REFERENCES

Adeleke, A., Ibitoye, S., Afonja, A., & Chagga, M. (2011). MULTISTAGE CAUSTIC LEACHING DE-ASHING OF NIGERIAN LAFIA-OBI COAL. *Petroleum & coal, 53*(4).

Aditya, A., Suresh, A., Sriramoju, S., Dash, P., Pati, S., & Padmanabhan, N. (2018). Optimization study of sodium hydroxide consumption in the coal demineralization process. *Mineral Processing and Extractive Metallurgy Review, 39*(4), 250-257.

Ahmad, W., Ahmad, I., Ahmad, I., & Shah, A. A. (2023). Desulfurization and De-ashing of coal through catalytic oxidation using Fe (III) and Cu (II) catalysts loaded in different forms. *International Journal of Coal Preparation and Utilization, 43*(7), 1164-1184.

Ahmad, W., Ahmad, I., Ahmad, I., Yaseen, M., Muhammad, N., & Salman, M. (2022). Desulfurization and de-ashing of low-rank coal by catalytic oxidation using Sn as catalyst loaded in different forms. *International Journal of Coal Preparation and Utilization, 42*(8), 2260-2276.

Ahmad, W., Ahmad, I., Ahmad, R., Ullah, Z., & Ibrahim, M. (2022). Desulfurization of Lakhra coal by combined leaching and catalytic oxidation techniques. *International Journal of Coal Preparation and Utilization, 42*(2), 124-140.

Andrés, J. M., Ferrando, A. C., & Membrado, L. (1996). Chemical desulfurization of coal with hydroiodic acid. *Energy & fuels, 10*(2), 425-430.

Balaz, P., LaCount, R., Kern, D., & Turcaniova, L. (2001). Chemical treatment of coal by grinding and aqueous caustic leaching. *Fuel, 80*(5), 665-671.

Behera, S. K., Chakraborty, S., & Meikap, B. (2018). Demineralization mechanism and influence of parameters on high ash Indian coal by chemical leaching of acid and alkali solution. *International Journal of Coal Science & Technology, 5*(2), 142-155.

Behin, J., Akbari, A., Mahmoudi, M., & Khajeh, M. (2017). Sodium hypochlorite as an alternative to hydrogen peroxide in Fenton process for industrial scale. *Water research, 121*, 120-128.

Casetou-Gustafson, S.-C. (2019). From minerals to trees: Reducing uncertainty in estimating weathering rates for sustainable forest growth.

Chaudhary, M., Singh, R., Tyagi, I., Ahmed, J., Chaudhary, S., & Kushwaha, S. (2021). Microporous activated carbon as adsorbent for the removal of noxious anthraquinone acid dyes: Role of adsorbate functionalization. *Journal of Environmental Chemical Engineering, 9*(5), 106308.

Cheng, J., Zhou, J., Liu, J., Zhou, Z., Huang, Z., Cao, X., . . . Cen, K. (2003). Sulfur removal at high temperature during coal combustion in furnaces: a review. *Progress in energy and combustion science, 29*(5), 381-405.

Chuang, K.-C., Markuszewski, R., & Wheelock, T. (1983). Desulfurization of coal by oxidation in alkaline solutions. *Fuel Processing Technology, 7*(1), 43-57.

Dash, P., Lingam, R., Kumar, S. S., Suresh, A., Banerjee, P., & Ganguly, S. (2015). Effect of elevated temperature and pressure on the leaching characteristics of Indian coals. *Fuel, 140*, 302-308.

Dash, P. S., Kumar, S. S., Banerjee, P., & Ganguly, S. (2013). Chemical leaching of high-ash Indian coals for production of low-ash clean coal. *Mineral Processing and Extractive Metallurgy Review, 34*(4), 223-239.

Dash, P. S., Sriramoju, S., Kargupta, K., Banerjee, P., & Ganguly, S. (2015). Characterization of chemically beneficiated Indian coals. *International journal of coal preparation and utilization, 35*(5), 257-272.

Dhawan, H., & Sharma, D. K. (2019). Advances in the chemical leaching (inorgano-leaching), bio-leaching and desulphurisation of coals. *International Journal of Coal Science & Technology, 6*(2), 169-183.

Doymaz, I., Gulen, J., Piskin, S., & Toprak, S. (2007). The effect of aqueous caustic and various acid treatments on the removal of mineral matter in asphaltite. *Energy Sources, Part A, 29*(4), 337-346.

Duz, M., Hamamci, C., Erdoğan, S., Saydut, A., & Merdivan, M. (2008). Effect of molten caustic leaching on demineralization and desulfurization of asphaltite. *Energy Sources, Part A, 30*(17), 1637-1644.

Fu, Y., He, K., Zhou, C., & Mao, Y. (2021). *Improvement of Saline-Alkaline Soil via Flue Gas Desulfurization Gypsum and Safety Analysis of the Associated Heavy Metals.* Paper presented at the Journal of Physics: Conference Series.

Hashmi, Z., Jatoi, A. S., Aziz, S., Soomro, S. A., Abbasi, S. A., Usto, M. A., . . . Usman, M. T. (2023). Bio-assisted treatment of hazardous spent wash via microbial fuel cell. Environmental friendly approach. *Biomass Conversion and Biorefinery, 13*(7), 5981-5989.

Huang, B., Liu, G., Wang, P., Zhao, X., & Xu, H. (2019). Effect of nitric acid modification on characteristics and adsorption properties of lignite. *Processes, 7*(3), 167.

Ismail, S., Kasim, N. N., Ali, S. N., Abdullah, M. F., Ishak, M. A. M., & Ahmad, R. (2023). An overview of the development of chemical desulfurization technology for organic sulfur coal. *Sci Lett, 17*, 39-55.

Jatoi, A. S., Abbasi, S. A., Hashmi, Z., Shah, A. K., Alam, M. S., Bhatti, Z. A., . . . Usto, M. A. (2023). Recent trends and future perspectives of lignocellulose biomass for biofuel production: a comprehensive review. *Biomass Conversion and Biorefinery, 13*(8), 6457-6469.

Kara, H., & Ceylan, R. (1988). Removal of sulphur from four Central Anatolian lignites by NaOH. *Fuel, 67*(2), 170-172.

Krystynik, P. (2021). Advanced Oxidation Processes (AOPs)–Utilization of Hydroxyl Radical and Singlet Oxygen.

Lei, M., Zhang, Y., Hong, D., & Ye, B. (2022). Characterization of nitrogen and sulfur migration during pressurized coal pyrolysis and oxy-fuel combustion. *Fuel, 317*, 123484.

Liu, Z., Zhang, Z., Choi, S. K., & Lu, Y. (2018). Surface properties and pore structure of anthracite, bituminous coal and lignite. *Energies, 11*(6), 1502.

Lolja, S. A. (1999). A model for alkaline removal of sulfur from a low-rank coal. *Fuel Processing Technology, 60*(3), 185-194.

Manoj, B. (2012). Chemical demineralization of high volatile Indian bituminous coal by carboxylic acid and characterization of the products by SEM/EDS. *Journal of environmental research and development*, 6(3A), 654-658.

Markuszewski, R., Chuang, K., & Wheelock, T. (1978). *Coal desulfurization by leaching with alkaline solutions containing oxygen*. Retrieved from

Meshram, P., Purohit, B. K., Sinha, M. K., Sahu, S., & Pandey, B. (2015). Demineralization of low grade coal–A review. *Renewable and Sustainable Energy Reviews, 41*, 745-761.

Mukherjee, S., & Borthakur, P. (2001). Chemical demineralization/desulphurization of high sulphur coal using sodium hydroxide and acid solutions. *Fuel, 80*(14), 2037-2040.

Mushtaq, F., Ullah, A., Khan, A., Waheed, A., Sultan, S. H., Kakar, G., . . . Abbasi, A. M. R. (2021). Desulfurization of Mach Coal of Balochistan by Leaching Method. *Journal of Applied and Emerging Sciences, 11*(1), pp 63-66.

Nabeel, A., Khan, T., & Sharma, D. (2009). Studies on the production of ultra-clean coal by alkali-acid leaching of low-grade coals. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 31*(7), 594-601.

Ohki, A., Nakajima, T., Yamashita, H., Iwashita, A., & Takanashi, H. (2004). Leaching of various metals from coal into aqueous solutions containing an acid or a chelating agent. *Fuel Processing Technology, 85*(8-10), 1089-1102.

Oyediran, I. A., & Olalusi, D. A. (2017). Hydraulic conductivity and leachate removal rate of genetically different compacted clays. *Innovative Infrastructure Solutions, 2*(1), 1-14.

Pantović Spajić, K., Marković, B., Pavlović, M., Sokić, M., Zildžović, S., Đorđević, N., & Stojanović, K. (2021). Deashing and desulfurization of subbituminous coal from the East field (Bogovina Basin, Serbia)–Insights from chemical leaching. *Journal of the Serbian Chemical Society, 86*(11), 1113-1126.

Saleem, A., Abbas, N., Dur-e-Shehwaar, T. S., Hassan, N., & Munawwar, M. (2021). Chemical Desulphurization of Coal using KOH as Oxidizing Agent in the Presence of Deep Eutectic Solvent. *Sch Int J Chem Mater Sci, 4*(7), 180-195.

Saydut, A., Duz, M., Erdogan, S., Tonbul, Y., & Hamamci, C. (2011). Chemical leaching on sulfur and mineral matter removal from asphaltite (Harbul, SE Anatolia, Turkey). *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 33*(5), 383-391.

Shah, A. A., Usto, M. A., Ahmed, T., Jatoi, A. S., Hashmi, Z., Chandio, Z. A., . . . Shah, A. K. (2023). Facile application of used engine oil in high sulfur coal briquetting to reduce the hazardous emission gases. *International Journal of Coal Preparation and Utilization, 43*(7), 1139-1151.

Sharma, D., & Gihar, S. (1991). Chemical cleaning of low grade coals through alkali-acid leaching employing mild conditions under ambient pressure. *Fuel, 70*(5), 663-665.

Singh, S. (2021). Oxidative Desulphurisation and Kinetics of Pyrite in Coal. *Annals of the Romanian Society for Cell Biology*, 20224-20230.

Song, G., Qi, X., Song, W., Yang, S., Lu, Q., & Nowak, W. (2016). Slagging behaviors of high alkali Zhundong coal during circulating fluidized bed gasification. *Fuel, 186*, 140-149.

Speight, J. G. (2012). *The chemistry and technology of coal*: CRC press.

Sriramoju, S. K., Dash, P. S., & Majumdar, S. (2022). Extraction of clean coal from washery rejects and its effect on coking properties: an approach toward sustainable development. *International Journal of Coal Preparation and Utilization, 42*(11), 3325-3347.

Sriramoju, S. K., Dash, P. S., Suresh, A., & Ray, T. (2021). Integrated process for coal chemical demineralization and spent caustic regeneration-A pilot scale study. *Journal of Cleaner Production, 327*, 129497.

Steel, K. M., & Patrick, J. W. (2001). The production of ultra clean coal by chemical demineralisation. *Fuel, 80*(14), 2019-2023.

Usto, M. A., Abbasi, S. A., Maitlo, G., Iqbal, A., Jatoi, A. S., Ahmed, S., . . . Shah, A. (2022). Desulfurization of thar lignite by oxidative alkali leaching under pressure. *International Journal of Coal Preparation and Utilization, 42*(11), 3430-3450.

Usto, M. A., Jarwar, A. I., Maitlo, G., Qureshi, S. A., Abbasi, S. A., Alam, S., . . . Jatoi, A. S. (2021). Desulfurization of Thar Lignite by Oxidative Alkali Leaching Under Pressure.

Usto, M. A., & Memon, A. R. (2024). Alkali leaching in dissolved oxygen for efficient desulphurization of low-grade Lakhra coal. *International Journal of Coal Preparation and Utilization, 44*(7), 811-822.

Usto, M. A., Solangi, Z., Shah, A. K., Qureshi, K. M., Sultan, S. H., Rajput, M. I., . . . Channa, F. H. (2023). Characterization and value-added addition of biomass for the reduction of emissions using coal as co-feed. *Biomass Conversion and Biorefinery*, 1-9.

Usto, M. A., Solangi, Z., Shah, A. K., Qureshi, K. M., Sultan, S. H., Rajput, M. I., . . . Channa, F. H. (2024). Characterization and value-added addition of biomass for the reduction of emissions using coal as co-feed. *Biomass Conversion and Biorefinery, 14*(14), 16189-16197.

Vogrin, J., Santini, T., Peng, H., & Vaughan, J. (2020). Influence of chloride on sodium aluminosilicate solubility in Bayer liquor. *Microporous and Mesoporous Materials, 299*, 110086.

Wahab, A., Nawaz, S., Shahzad, K., Akhtar, J., Kanwal, S., Munir, S., & Sheikh, N. (2015). Desulfurization and demineralization of Lakhra coal by molten caustic leaching. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 37*(11), 1219-1223.

Wang, J., & Tomita, A. (1998). Removal of mineral matter from some Australian coals by Ca (OH) 2/HCl leaching. *Fuel, 77*(15), 1747-1753.

Waugh, A., & Bowling, K. M. (1984). Removal of mineral matter from bituminous coals by aqueous chemical leaching. *Fuel Processing Technology, 9*(3), 217-233.

WIDYA, I., TOMMY, T., & WINDHU, N. (2024). DESULFURISASI BATUBARA DENGAN METODE LEACHING MENGGUNAKAN NAOH DAN HCL DI PT. ANUGERAH KRIDA UTAMA, KUTAI KARTANEGARA, KALIMANTAN TIMUR. *GLOBE, 2*(1), 100-116.

Wu, Z., & Steel, K. M. (2007). Demineralization of a UK bituminous coal using HF and ferric ions. *Fuel, 86*(14), 2194-2200.