Vanadium-Containing Sources And Processing Technologies: A Comprehensive Review

Sultan Yulussov[1], Omirserik Baigenzhenov[1*], Alibek Khabiyev[2], Bigamila Torsykbayeva[3], and Yerik Merkibayev[1]

[1] *Department of Metallurgical Engineering, Satbayev university, Almaty, Kazakhstan*
[2] *Department of Chemical and Biochemical Engineering, Satbayev university, Almaty, Kazakhstan*
[3] *Department of Pharmaceutical Disciplines, Astana Medical University, Astana, Kazakhstan*
[*] *Corresponding author. E-mail: o.baigenzhenov@satbayev.university*

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The article presents an overview of the basic technologies employed for the processing of these vanadium-containing materials. These technologies encompass a range of extraction methods, including roasting, leaching, solvent extraction, and precipitation. The specific techniques employed for each source material are discussed in detail, highlighting their advantages and limitations. Black shale ore, a significant source of vanadium, is explored for its extraction potential. Vanadium-containing titanium magnetite ores, known with their abundant vanadium content, are investigated as another prominent source. Additionally, spent vanadium catalysts, which are commonly utilized in several industrial processes, are examined as a potential source for vanadium extraction. Furthermore, vanadium-containing bauxite raw materials, oil, and steel production slags are evaluated for their vanadium extraction capabilities. Overall, this article provides a comprehensive understanding of the various sources of vanadium and the technologies employed for their extraction. The insights presented here will aid researchers and industry professionals in developing efficient and sustainable processes for vanadium extraction, ensuring a stable supply of this valuable transition metal for various applications.

Keywords: Vanadium-Containing Sources, black shale ore, titanium magnetite ores, spent vanadium catalysts, bauxite residues, oil residues.

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1. Introduction

Vanadium, a transition metal with atomic number 23 and symbol V, is a crucial element that finds extensive applications in various industries, including steel production [1], energy storage [2], and catalysis [3]. Its unique properties, such as high strength, excellent corrosion resistance, and the ability to form stable compounds, make it indispensable in these sectors [4]. Therefore, the extraction and processing of vanadium from different sources have gained significant attention in recent years. As the demand for vanadium continues to rise, the efficient processing of vanadium ores and industrial waste becomes paramount for ensuring a sustainable supply chain of this important resource [5, 6].

The main technological sources of vanadium considered in this study include black shale ore [7], vanadium-containing titanium magnetite ores [8], spent vanadium catalysts [9], vanadium-containing bauxite raw materials [10], oil [11], and steel production slags [12]. Each of these sources possesses varying concentrations of vanadium and requires distinct techniques for efficient extraction.

As it known, vanadium-containing ores and materials are processed using a combination of hydrometallurgical

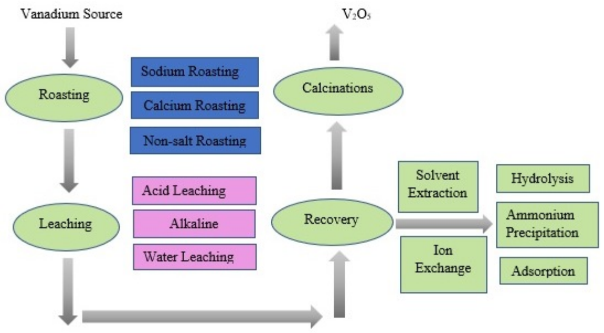

Fig. 1. Flowsheet of recovery of vanadium from vanadium source to V_2O_5 [12].

and pyrometallurgical methods to extract and refine vanadium. These processes are aimed at separating vanadium from other minerals and impurities, and producing high-purity vanadium compounds.

Hydrometallurgical processes involve the use of aqueous solutions to extract vanadium [13]. One common method is known as acid leaching, where the ore or material is treated with sulfuric acid or another suitable acid (Fig. 1). This process dissolves the vanadium minerals and forms a solution containing vanadium ions. The solution is then purified and subjected to various chemical reactions to separate vanadium from other impurities. Solvent extraction and ion exchange techniques are often employed to isolate and concentrate vanadium. Finally, the vanadium is precipitated as a compound, typically ammonium metavanadate or vanadium pentoxide, through the addition of suitable reagents [14].

Pyrometallurgical processes involve high-temperature operations to extract vanadium from ores and materials [15]. One common method is known as the roast-leach process. In this process, the ore or material is first roasted at high temperatures to convert vanadium minerals into water-soluble compounds. The roasted material is then leached with an appropriate solution to dissolve the vanadium compounds. The resulting solution is further processed to remove impurities and recover vanadium. This may involve precipitation, filtration, and other separation techniques. The vanadium is eventually obtained as a high-purity compound, such as vanadium pentoxide [16, 17]. It is important to emphasize that the water leaching is always preceded by the roasting step, which convert the vanadium-containing mineral into a soluble form. The roasting process involves heating the mineral, causing a chemical change that makes vanadium easier to dissolve in water. It is important to note that depending on the desired product, additional reagents may be added during roasting. For example, if a chloride solution is desired, chloride-containing reagents are used, and a chemical reaction occurs during roasting, resulting in the formation of easily soluble chloride products. Alternatively, acid or alkaline teaching can be applied directly to vanadium-containing minerals without roasting, as they have the ability to extract vanadium without pre-treatment.

In addition to these primary methods, there are also secondary processes used to recycle and recover vanadium from various waste materials, such as spent catalysts [18, 19] and fly ash from coal combustion [20, 21]. These processes typically involve a combination of hydrometallurgical and pyrometallurgical techniques to extract vanadium from these secondary sources. The treatment of industrial waste, such as spent catalysts, fly ash, and slag containing vanadium, offers a promising source for vanadium recovery. Consequently, exploring effective methods to treat these waste streams for vanadium extraction not only has economic benefits but also contributes to reducing environmental contamination. By summing existing literature and incorporating the latest findings, this review article aims to provide a comprehensive understanding of the methods of processing vanadium ores and industrial waste. Moreover, we will delve into the challenges and limitations associated with these methods, highlighting the need for further research and development to enhance the efficiency and sustainability of vanadium processing. This knowledge can serve as a valuable resource for researchers, engineers, and industry professionals involved in vanadium production, as well as contribute to the overall understanding of sustainable resource management.

2. Processing of black shale ores

2.1. Methods of vanadium recovery from black shale ores using acid-based technologies

The acid leaching method is a widely used process for the extraction of valuable metals from black shale ores [22]. Black shale ores are sedimentary rocks containing high concentrations of various minerals including base metals, precious metals, and rare earth elements [23]. The acid leaching method involves the use of strong acids to dissolve and extract these valuable metals from the ore Fig. 2.

The first step in the acid leaching process is the preparation of the ore. The black shale ore is typically crushed and ground into fine particles to increase the surface area for better contact with the acid. This is followed by a series of pre-treatment steps such as roasting or calcination to remove any impurities or organic matter that may interfere with the leaching process. Once the ore is properly prepared, it is then subjected to the acid leaching process.

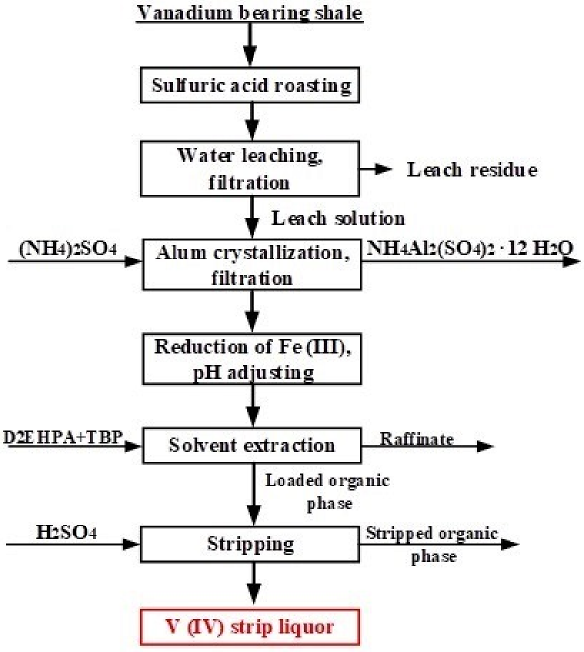

Fig. 2. Technological scheme of processing vanadium-containing shale ores by acid method [21].

Sulfuric acid is the most commonly used acid for this purpose due to its availability and effectiveness in dissolving a wide range of metals. The acid is typically added to the ore in a controlled manner to ensure efficient leaching while minimizing acid consumption.

During the leaching process, the acid reacts with the minerals in the ore, dissolving the valuable metals into solution. The leaching conditions, such as temperature, pressure, and acid concentration, are carefully controlled to optimize the leaching efficiency. Increasing the temperature and acid concentration can enhance the dissolution kinetics, but excessive conditions may also lead to unwanted side reactions or the formation of insoluble compounds. The leach solution, which contains the dissolved metals, is then separated from the remaining solid residue through a series of solid-liquid separation techniques such as filtration or sedimentation. The solid residue, also known as the leach residue or tailings, may still contain traces of valuable metals and can be further processed to recover any remaining metals.

The next step in the acid leaching process is the recovery of the dissolved metals from the leach solution. This is typically achieved through sorption, precipitation or solvent extraction techniques [24]. Precipitation involves the addition of a suitable reagent to the leach solution, causing the metals to form insoluble precipitates that can be easily separated. Solvent extraction, on the other hand, involves the use of an organic solvent that selectively extracts the desired metals from the leach solution. The recovered metals can then be further purified and processed to obtain the final product. Depending on the specific metals of interest, additional refining steps such as electrowinning or smelting may be required. These steps aim to remove impurities and enhance the purity and quality of the final metal product. The acid leaching method offers several advantages for the processing of black shale ores [25]. Firstly, it allows for the extraction of a wide range of valuable metals from the ore, including base metals such as copper and zinc, precious metals such as gold and silver, and rare earth elements. This makes it a versatile and economically viable method for the recovery of multiple metals from a single ore source.

Secondly, the acid leaching process is relatively simple and straightforward, requiring minimal equipment and infrastructure compared to other extraction methods. This makes it a cost-effective option for both small-scale and large-scale mining operations. Furthermore, the acid leaching method is environmentally friendly compared to traditional mining and extraction methods. It reduces the need for extensive mining operations, which can cause significant environmental damage and disturbance. Additionally, the use of acids in the leaching process can be optimized to minimize acid consumption and waste generation. However, the acid leaching method also has some limitations and challenges. One of the main challenges is the presence of impurities in the ore, such as organic matter or refractory minerals, which can interfere with the leaching process and reduce the overall extraction efficiency. Pre-treatment steps, such as roasting or calcination, are often necessary to remove these impurities and improve the leaching performance.

Another challenge is the management of the leach residue or tailings. These residues may contain residual metals or other contaminants that require proper disposal or treatment to prevent environmental contamination. Efforts are being made to develop sustainable and environmentally friendly solutions for the management of these residues, such as recycling or reprocessing technologies.

Acid leaching method offers a cost-effective and environmentally friendly approach for the extraction of valuable metals from these complex ores. With ongoing advancements in technology and process optimization, the acid leaching method continues to be a promising option for the mining industry.

2.2. Methods of vanadium recovery from black shale ores using alkaline-based technologies

The alkaline leaching process involves the use of alkaline solutions, typically sodium hydroxide (NaOH) or ammonium hydroxide (NH4OH), to dissolve the metals present in the ore. The leaching is typically carried out at elevated temperatures and pressures to enhance the dissolution kinetics. The alkaline solution acts as a leaching agent by breaking down the mineral structure and releasing the metals into the solution [26].

One of the key advantages of the alkaline leaching method is its ability to selectively dissolve certain metals while leaving others untouched. This selectivity is achieved by controlling the pH and the composition of the leaching solution. For example, in the case of black shale ores, the alkaline leaching method can be used to selectively extract valuable metals such as vanadium, uranium, and REE, while leaving the unwanted components, such as iron and silicon, in the residue.

The alkaline leaching process is influenced by several factors, including the particle size of the ore, the concentration of the leaching solution, the leaching time, and the temperature and pressure conditions. The particle size of the ore plays a crucial role in determining the leaching efficiency, as smaller particles offer a larger surface area for the leaching solution to come into contact with the ore. The concentration of the leaching solution affects the rate of metal dissolution, with higher concentrations generally resulting in faster leaching kinetics. The leaching time, temperature, and pressure conditions are optimized to achieve the desired metal recovery while minimizing the consumption of reagents and energy [27].

In addition to the leaching parameters, the alkaline leaching method is also influenced by the mineralogical composition of the ore. The presence of sulphide minerals, can significantly affect the leaching process. These minerals can react with the alkaline solution, leading to the consumption of reagents and the formation of undesired by-products. Therefore, a thorough understanding of the ore's mineralogy is essential for the successful implementation of the alkaline leaching method.

The alkaline leaching method has been successfully applied to various black shale ores around the world. Several studies have reported high metal recoveries using this method. For example, a study conducted on a black shale ore from the Zechstein deposit in Poland reported vanadium recoveries of up to 90% using a sodium hydroxide leaching solution. Another study on a black shale ore from the Kupferschiefer deposit in Germany achieved vanadium recoveries of over 95% using an ammonium hydroxide leaching solution [28].

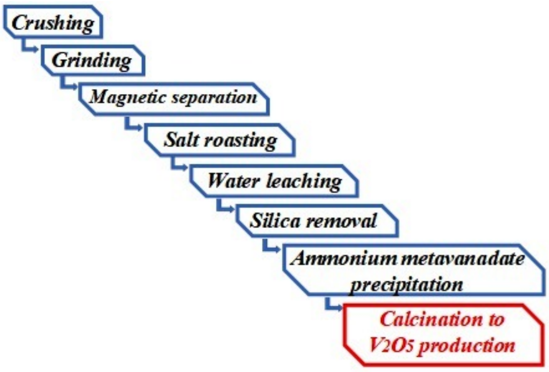

Fig. 3. Generic vanadium production flowsheet from titanomagnetites, based on several industrial examples [29].

Apart from metal recovery, the alkaline leaching method also offers the advantage of environmental sustainability. By selectively extracting metals from the ore, the method reduces the need for traditional mining and processing techniques, which often generate large amounts of waste and have a significant environmental impact. Furthermore, the alkaline leaching method can also be combined with other extraction techniques, such as solvent extraction and electrowinning, to further enhance the metal recovery efficiency and minimize the environmental footprint.

As we see, the alkaline leaching method is a competent and scientific approach for the processing of black shale ores. It offers the advantages of selective metal recovery, high metal yields, and environmental sustainability. However, successful implementation of the alkaline leaching method requires a thorough understanding of the ore's mineralogy and the optimization of leaching parameters. Further research and development in this field are necessary to improve the efficiency and cost-effectiveness of the alkaline leaching method for the processing of black shale ores.

3. Methods of vanadium recovery from vanadium-bearing magnetite ores

The processing of vanadium-bearing magnetite ores is a complex and multi-step procedure that involves various methods and techniques. These ores typically contain a significant amount of iron and vanadium, making them valuable resources for the production of steel and other alloys. The extraction of vanadium from these ores involves several stages, including crushing, grinding, magnetic separation, and smelting Fig. 3 [29].

The first step in processing Vanadium-bearing magnetite ores is the crushing and grinding of the ore to reduce its size. This is typically done using jaw crushers and ball mills, which break the ore into smaller particles. The purpose of this step is to increase the surface area of the ore, allowing for better contact with the chemicals used in subsequent processes. Once the ore is crushed and ground, it undergoes magnetic separation to separate the magnetite from the other minerals. This is achieved using magnetic separators, which utilize the magnetic properties of the magnetite to attract and separate it from the non-magnetic minerals. The magnetite concentrate obtained from this process is rich in iron and vanadium. The next step in the processing of Vanadium-bearing magnetite ores is the smelting of the magnetite concentrate. Smelting involves heating the concentrate in a furnace to high temperatures, typically above 1200°C. This process aims to separate the iron and vanadium from the other impurities present in the concentrate. During smelting, the magnetite concentrate is mixed with fluxes, such as limestone and silica, which help remove impurities and facilitate the formation of a molten slag. The slag, which contains most of the impurities, is then removed from the furnace, while the molten metal, consisting mainly of iron and vanadium, is tapped and collected. After smelting, the molten metal is further processed to obtain pure vanadium. One common method is the vanadium extraction from the molten metal using an oxygen blowing process. This involves blowing oxygen through the molten metal, which reacts with the vanadium to form vanadium pentoxide (V_2O_5). The V_2O_5 can then be further processed to obtain various vanadium compounds or converted into ferrovanadium, a popular alloy used in the steel industry [30].

Another method for vanadium extraction from the molten metal is the ammonium metavanadate (NH_4VO_3) precipitation process. In this method, ammonium metavanadate is precipitated from the molten metal by adding ammonium chloride or ammonium carbonate. The precipitated ammonium metavanadate can be further processed to obtain vanadium compounds or converted into ferrovanadium [31].

In recent years, there has been increasing interest in hydrometallurgical methods for the processing of vanadium-bearing magnetite ores. These methods involve the use of chemical solutions to extract vanadium from the ore. One such method is the acid leaching process, which involves leaching the crushed and ground ore with sulfuric acid or hydrochloric acid. The leach solution is then treated to remove impurities and recover vanadium as a vanadium compound.

Another hydrometallurgical method is the alkaline leaching process, which uses alkaline solutions, such as sodium hydroxide or sodium carbonate, to extract vanadium from the ore. The leach solution is then treated to remove impurities and recover vanadium as a vanadium compound. The processing of vanadium-bearing magnetite ores involves a combination of physical and chemical methods, including crushing, grinding, magnetic separation, smelting, and hydrometallurgical processes. Each step in the process is crucial for the efficient extraction of vanadium from the ore. The choice of processing method depends on various factors, such as the ore composition, desired vanadium product, and economic considerations.

4. Methods of vanadium recovery from bauxite residue

Bauxite residue, also known as red mud, is a byproduct of the aluminum production process and is generated from the digestion of bauxite ore with sodium hydroxide. It is estimated that around 150 million tons of bauxite residue are produced annually worldwide. This residue is primarily composed of iron oxide, titanium oxide, and alumina, but it also contains several other valuable metals, including vanadium [32].

The recovery of vanadium from bauxite residue has gained significant attention in recent years due to the increasing demand for this metal in various industries, such as steel production, energy storage, and catalysis. Several methods have been investigated for the extraction and recovery of vanadium from bauxite residue, including physical separation, leaching, and precipitation techniques.

Physical separation methods involve the separation of vanadium-bearing phases from the rest of the bauxite residue matrix. This can be achieved through techniques such as magnetic separation, gravity separation, and froth flotation. Magnetic separation relies on the magnetic properties of vanadium-bearing minerals to separate them from the non-magnetic components. Gravity separation utilizes the differences in density between the vanadium-bearing minerals and the rest of the bauxite residue to achieve separation. Froth flotation, on the other hand, exploits the differences in surface properties between the vanadium-bearing minerals and the gangue minerals in the bauxite residue.

Leaching methods involve the dissolution of vanadium from the bauxite residue matrix using various chemical reagents. Acid leaching is one of the commonly used techniques, where sulfuric acid is often employed to dissolve the vanadium oxide minerals. The leachate containing vanadium is then subjected to further processing to recover the metal. Alkaline leaching, using sodium hydroxide or sodium carbonate, has also been investigated as an alternative method for vanadium recovery. This method offers the advantage of selective leaching, where vanadium is preferentially dissolved while leaving other valuable metals, such as iron and titanium, behind in the residue [33].

Precipitation techniques are used to recover vanadium from the leachate obtained through leaching methods. One of the commonly employed techniques is solvent extraction, where an organic solvent is used to selectively extract vanadium from the leachate. The extracted vanadium is then stripped from the organic phase using an appropriate stripping agent to obtain a concentrated vanadium solution. Another precipitation method involves the use of chemical precipitants, such as ammonium metavanadate or sodium metavanadate, to selectively precipitate vanadium from the leachate. The precipitated vanadium can then be further processed to obtain vanadium compounds or metal [34].

In recent years, there has been growing interest in the development of innovative and sustainable methods for vanadium recovery from bauxite residue. This includes the exploration of bioleaching techniques, where microorganisms are used to selectively dissolve vanadium from the residue matrix. These microorganisms produce organic acids that can effectively leach vanadium, offering a potentially cost-effective and environmentally friendly approach. The recovery of vanadium from bauxite residue is a complex process that requires the implementation of various methods, including physical separation, leaching, and precipitation techniques. Each method has its advantages and limitations, and the selection of an appropriate method depends on factors such as the composition of the bauxite residue, the desired purity of the vanadium product, and the economic viability of the process. Further research and development efforts are needed to optimize and improve the efficiency of these methods to ensure sustainable and economically viable vanadium recovery from bauxite residue.

5. Methods of vanadium recovery from fly ash and coal

Fly ash is a byproduct of coal combustion in thermal power plants. Fly ash and coal contain trace amounts of vanadium, making them potential sources for its recovery (Table 1).

Several methods have been developed and studied to extract vanadium from these sources, each with its own advantages and limitations. One of the most commonly employed methods for vanadium recovery from fly ash is acid leaching. This process involves treating fly ash with an acid solution, typically sulfuric acid, to dissolve the vanadium present. The leaching efficiency can be enhanced by factors such as temperature, acid concentration, and particle size. Numerous studies have investigated the effects of these parameters on the leaching process. For instance, Wang et al. [35] conducted experiments to optimize the acid leaching of vanadium from coal ash. They found that increasing the temperature and acid concentration significantly improved the vanadium extraction efficiency. Additionally, reducing the particle size of fly ash increased the surface area available for leaching, resulting in higher vanadium recovery rates.

Another method commonly used for vanadium recovery from fly ash is alkaline leaching. In this process, fly ash is treated with alkaline solutions, such as sodium hydroxide or ammonia, to extract vanadium. Alkaline leaching has been shown to be effective in recovering vanadium from fly ash with high alkaline content. However, the presence of other elements, such as calcium and magnesium, can interfere with the extraction process.

In a study by Font et al. [36], the authors investigated the alkaline leaching of vanadium from fly ash with a high calcium content. They found that the addition of a chelating agent, such as EDTA (ethylenediaminetetraacetic acid), improved the vanadium extraction efficiency by reducing the interference of calcium. The study concluded that alkaline leaching, combined with a chelating agent, could be a promising method for vanadium recovery from fly ash with high calcium content.

In a study by Masoum et al. [37], the authors investigated the acid leaching of vanadium from coal ash using hydrochloric acid. They found that the leaching efficiency was influenced by factors such as acid concentration, temperature, and leaching time. Increasing the acid concentration and temperature enhanced the vanadium extraction, while extending the leaching time had a diminishing effect. Roasting and smelting are alternative methods for vanadium recovery from coal. Roasting involves heating coal in the presence of air or oxygen, which oxidizes vanadium to a soluble form that can be leached. Smelting, on the other hand, involves the reduction of vanadium oxides in coal to metallic vanadium, which can then be separated and purified.

6. Methods of vanadium recovery from oil residue

Vanadium recovery from oil residue is an important area of research due to the increasing demand for vanadium. Oil residue, also known as petroleum coke or petcoke, is a byproduct of the oil refining process and contains significant amounts of vanadium [38–40]. One of the most common methods for vanadium recovery from oil residue is through hydrometallurgical processes. These processes

Table 1. Components of stone coal [35]

Chemical Composition	Content (%)	Chemical Composition	Content (%)
Quartz	38.05	Vanadate and vanadium oxide	2.28
Carbonaceous and clay materials	15.87	Feldspar	2.59
Loewite	9.64	Molybdenite	2.63
Carbonaceous matter	7.02	Nickel potassium	2.06
Spinel	4.26	Periclase	0.66
Roscoelite	6.81	Others	6.91

involve the use of chemical solutions to selectively extract vanadium from the petcoke. One such method is acid leaching, where the petcoke is treated with a strong acid, such as sulfuric acid or hydrochloric acid, to dissolve the vanadium. The resulting solution is then processed to recover the vanadium by sorption or extraction. Several studies have investigated the optimization of acid leaching parameters, such as acid concentration, temperature, and leaching time, to enhance vanadium recovery efficiency [41].

Another hydrometallurgical method involves the use of alkaline solutions for vanadium extraction (Fig. 4). In this process, the petcoke is treated with a strong alkali, such as sodium hydroxide or potassium hydroxide, to dissolve the vanadium [42]. The resulting solution is then subjected to various purification steps to isolate the vanadium (Fig. 4).

Researchers have explored different factors affecting the alkaline leaching process, including alkali concentration, reaction temperature, and leaching time, to maximize vanadium recovery In addition to hydrometallurgical methods, pyrometallurgical processes have also been investigated for vanadium recovery from oil residue. Pyrometallurgy involves the use of high temperatures to extract and separate metals from ores or other materials. One such method is the roasting of petcoke followed by leaching with an acid solution. The roasting process converts vanadium compounds present in the petcoke into a more soluble form, facilitating their extraction during the subsequent leaching step. Studies have examined the influence of roasting temperature, duration, and atmosphere on vanadium recovery efficiency [43].

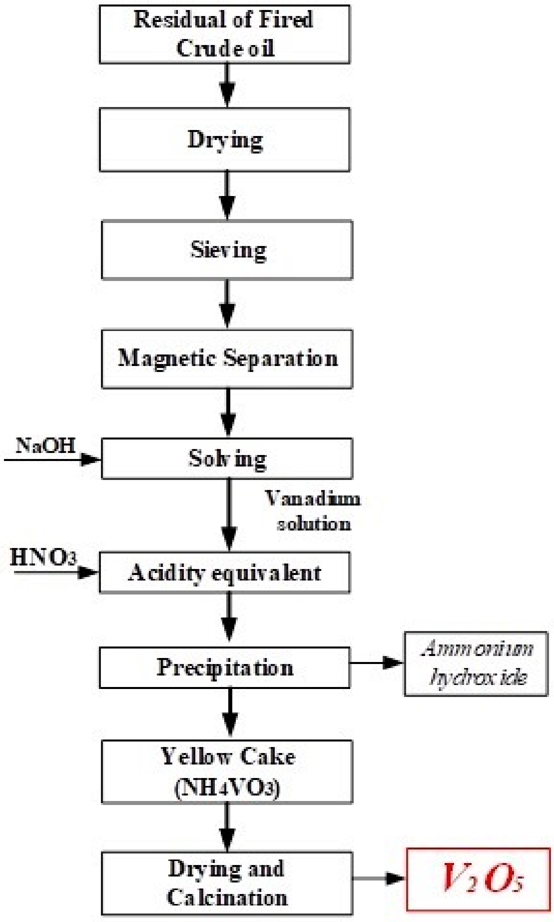

Fig. 4. technological scheme of crude oil processing by the alkaline method [42]

Furthermore, researchers have explored the possibility of using bioleaching techniques for vanadium recovery from oil residue. Bioleaching involves the use of microorganisms or their metabolic products to extract metals from ores or other materials. Several studies have reported the isolation and characterization of vanadium-tolerant bacteria capable of leaching vanadium from petcoke. These bacteria produce organic acids or enzymes that can solubilize vanadium, making it accessible for recovery. Optimization of bioleaching parameters, such as bacterial concentration, temperature, and pH, has been investigated to improve vanadium recovery efficiency [44].

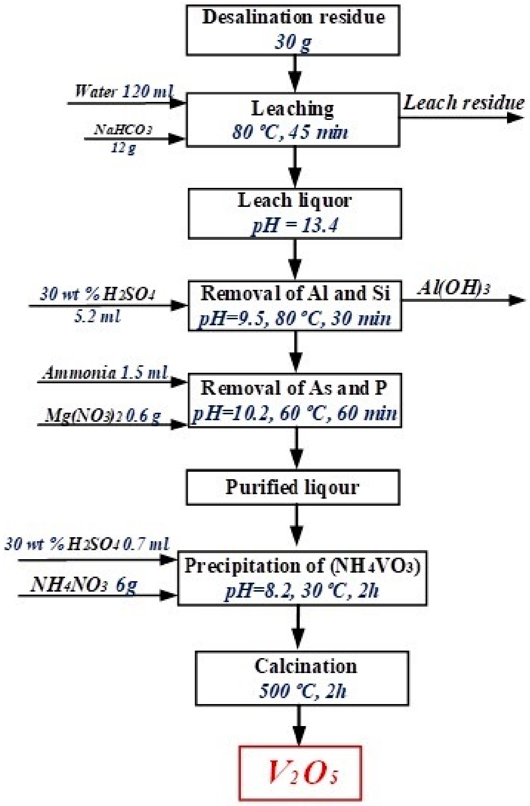

Fig. 5. Flow sheet for recovering vanadium from desalination residue [46].

7. Methods of vanadium recovery from spent catalysts

One significant application of vanadium is its use as a catalyst in the production of sulfuric acid [45]. Spent vanadium catalysts from sulfuric acid production contain a considerable amount of vanadium, making their recovery an economically viable and environmentally sustainable process.

One of the primary methods used for vanadium recovery from spent catalysts is leaching (Fig. 5) [46].

Leaching involves the dissolution of the vanadium-containing material in a suitable solvent, followed by the separation and purification of the vanadium. Different leaching agents have been investigated, including sulfuric acid, hydrochloric acid, and alkaline solutions. The choice of leaching agent depends on factors such as the nature of the spent catalyst and the desired purity of the recovered vanadium.

Sulfuric acid leaching is commonly employed due to its compatibility with the spent vanadium catalysts used in sulfuric acid production. The leaching process involves the dissolution of the spent catalyst in a concentrated sulfuric acid solution, followed by the separation of impurities and precipitation of vanadium compounds. The vanadium content in spent catalysts can range from 5% to 25%, depending on the specific application and operational conditions. The leaching efficiency can be enhanced by adjusting factors such as temperature, acid concentration, and leaching time [47].

Hydrochloric acid leaching has also been explored as an alternative method for vanadium recovery. This method involves the dissolution of the spent catalyst in hydrochloric acid, followed by the separation and purification of vanadium compounds. Compared to sulfuric acid leaching, hydrochloric acid leaching offers the advantage of higher leaching efficiency and lower impurity content in the leachate. However, it requires additional steps for the removal of impurities such as iron and aluminum. Alkaline leaching methods, such as sodium hydroxide leaching, have been investigated for vanadium recovery from spent catalysts. Alkaline leaching offers the advantage of selective vanadium dissolution while minimizing the dissolution of impurities. The leaching process involves the dissolution of the spent catalyst in an alkaline solution, followed by the separation and purification of vanadium compounds. However, alkaline leaching methods often require higher temperatures and longer leaching times compared to acid leaching methods [48, 49].

After leaching, the vanadium needs to be separated and purified from the leachate. Various separation techniques have been employed, including solvent extraction, ion exchange, precipitation, and membrane separation.

8. Conclusions

In conclusion, this review article has comprehensively examined various vanadium-containing sources, including black shale ore, titanium magnetite ores, spent vanadium catalysts, bauxite residues, oil residues and their respective processing technologies. The research findings presented in this article demonstrate the potential of these sources as viable and sustainable alternatives for vanadium production.

Black shale ore, which is abundant in many regions, has been identified as a promising vanadium source due to its high vanadium content. The extraction and recovery of vanadium from black shale ore have been extensively studied, and various processing technologies, such as acid leaching and alkaline leaching, have been developed to achieve efficient vanadium recovery. These technologies have shown promising results in terms of high vanadium extraction rates and low environmental impact.

Titanium magnetite ores, another significant vanadium source, have been widely explored for their vanadium content. The extraction of vanadium from these ores involves a series of complex processes, including magnetic separation, roasting, and acid leaching. The development of advanced technologies, such as selective reduction and direct leaching, has further improved the efficiency of vanadium extraction from titanium magnetite ores.

Spent vanadium catalysts, which are generated as waste from various industrial processes, have also been recognized as potential sources of vanadium. Recycling these spent catalysts not only helps in vanadium recovery but also contributes to the reduction of environmental pollution. Different techniques, such as acid leaching, calcination, and solvent extraction, have been employed to recover vanadium from spent catalysts, achieving significant vanadium yields.

Bauxite and oil residues have emerged as unconventional sources of vanadium. The extraction of vanadium from bauxite residue, a waste generated from alumina production, has shown promise through different methods like roasting, leaching and precipitation. Similarly, the processing of oil residues, such as petroleum coke and heavy oil fly ash, has demonstrated the potential for vanadium recovery using techniques like direct leaching. In summary, the exploration and utilization of vanadium-containing sources discussed in this review article offer promising opportunities for sustainable vanadium production. Furthermore, the utilization of these sources not only addresses the growing demand for vanadium but also contributes to the reduction of waste generation and environmental pollution. Continued research and development in this field will undoubtedly lead to further advancements in vanadium production, making it more economically viable and environmentally sustainable.

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