Article

Vanadium removal from water and wastewater by different technologies: A review study

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Abstract
Vanadium (V) contamination is a growing environmental hazard worldwide. Elimination of vanadium from water and wastewater is necessary due to its potential harm to the ecosystem and human health. This study aims to present different technologies used for vanadium elimination from water and wastewater. Various treatment techniques used for vanadium elimination, including adsorption, phytoremediation, bioremediation, chemical precipitation**,** electro-oxidation, membrane filtration, and photocatalysis process, have been considered widely by researchers and revealed acceptable findings. The focus of this review is on adsorption and biological remediation for vanadium elimination from aqueous environments. Based on the findings of this study, vanadium elimination via the adsorption method with a removal performance of 1.61-1428.57 mg/g is very effective. The highest vanadium level of 13980 µg/L was achieved in China and the lowest level of 21 µg/L was found in the USA in different waters. This study prepares a basis for the development of high-performance vanadium removal techniques that are appropriate for actual applications.

Keywords adsorption; bioremediation; wastewater; water treatment; vanadium removal.

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1 Introduction

Vanadium (V) is the fifth most plentiful transition element in Earth's crust (Aihemaiti et al., 2020). Vanadium is toxic and highly soluble, while V (IV) is less toxic and exists in solid phases at neutral pH. Vanadium ingestion can lead to adverse health effects, including pulmonary tumors and melanoma (Chen and Liu, 2017). Vanadium's low concentration is beneficial for growing plants, whereas a high concentration in the food chain increases the risk of functional lesions in the spleen, bones, liver, kidneys and nervous system (Li et al., 2007). The presence of vanadium in the ecosystem is related to the activity of volcanoes, ocean evaporation, forest fires, wastewater discharge, rock erosion or soil-forming processes (Gustafsson, 2019). However, the air, water, and soil pollution of anthropogenic origin is the greatest source of vanadium in the environment (Kończyk et al., 2022). Anthropogenic activities include industrial wastewater, such as the steel industry (approximately 85% of the global vanadium consumption is associated with steel production); glass, textile, ceramic, and photographic industries; metallurgical, mining, and ore processing activities; nuclear industry, industrial production, and fossil fuel burning. The use of fertilizers and pesticides, and recycling of domestic waste have also resulted in high levels of vanadium in soils and natural waters (Zhang, 2018; Fadaei, 2021; Liu et al., 2022). The world's whole vanadium production estimated in the form of metal vanadium was 15,235 kt in 2018 (Fig 1)(Gao et al., 2022). The mean level of vanadium was 97 mg/kg in the Earth's crust, 90 mg/kg in soil, and 30-199 mg/L in industrial wastewater (Liu et al., 2020). Vanadium concentration in wastewater ranges from 50 to 200 mg/L in China (Peng et al., 2022), and about 0.71 and 1.8 μg/L in the surface waters for rivers and oceans, respectively (Huang et al., 2015). Dissolved vanadium levels usually range from 0.5 to 2.4 μg/L in surface waters due to natural weathering of geologic materials (Vessey and Lindsay, 2020). Vanadium removal from waters and wastewaters is thus one of the most necessary problems to be taken care of in view of environmental protection and conservation.

Some techniques enabling the removal of vanadium ions from the aqueous solutions are as follows: adsorption (Salehi et al., 2020), chemical precipitation (Zhang et al., 2017), phytoremediation (Gan et al., 2021), solvent extraction (Barik et al., 2014), photocatalytic process (Sturini et al., 2013; Taie et al., 2021), electrokinetic (da Cruz Deniz et al., 2018), ion exchange (Keränen et al., 2015), nanofiltration (Shang et al., 2014), and oxidation roasting process (Kologrieva et al., 2021). Therefore, vanadium-containing wastewater needs to be treated before being discharged (Peng et al., 2022).

Four conventional techniques are used for vanadium-containing wastewater treatment, including physical, chemical, physic-chemical and biological techniques. However, the high salinity and low biodegradability of vanadium-containing wastewater restrict the removal performance of these techniques (He et al., 2018).

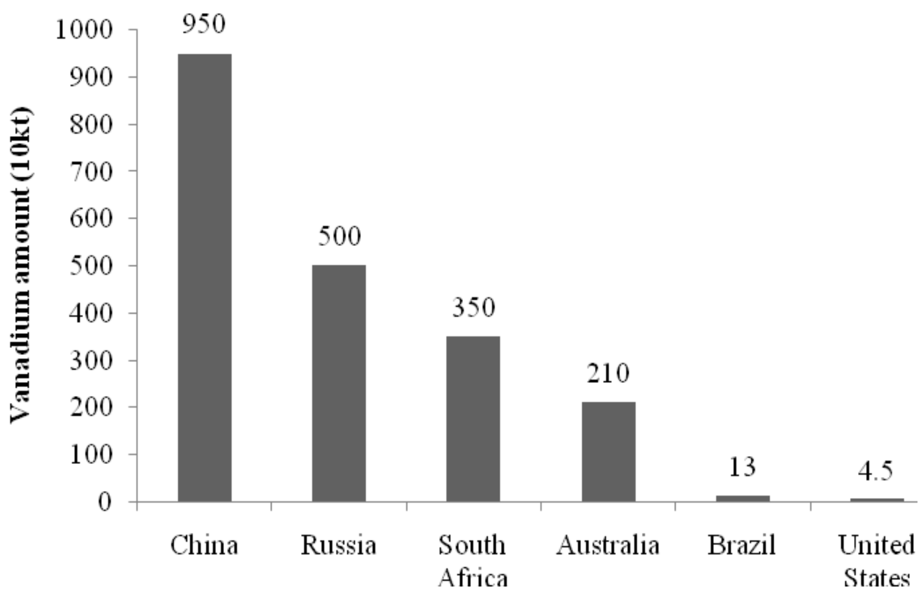

Fig. 1 World vanadium ore reserve calculated by metallic vanadium in 2018 (10 kt).

In this study, different vanadium elimination technologies are summarized. The most important issues addressed in this paper are: a comprehensive summary of various methods and the abilities for vanadium elimination with a focus on adsorption and biological remediation, and the suggestion of potential techniques for vanadium removal with high simplicity and performance. The purpose of this study is to present different technologies used for the removal of vanadium from water and wastewater.

2 Elimination Technologies

2.1 Adsorption

Adsorption is one of the techniques that has been recommended for the elimination of elements that exist in water and waste water (El Haouti et al., 2019; Peng and Guo, 2020). Currently, adsorption has exhibited rapid development and great potential for application in industrial wastewater processing owing to the strengths of high treatment performance, low energy use, and being eco-friendly (Li et al., 2021).

The reduction of vanadium in water and wastewater by various microorganisms has attracted a lot of attention over recent years. Bioremediation is a method used to eliminate environmental pollutants from the ecosystem. The basic principles of bioremediation include reducing the solubility of these media pollutants by changing pH, the redox reactions, and the adsorption of pollutants from contaminated media (Ojuederie and Babalola, 2017). Various living organisms, such as algae, bacteria, yeast, fungi, or plants, contribute to vanadium removal. The mechanisms of the microbial remediation of vanadium-polluted soil chiefly include bio-reduction and precipitation. The effects of various parameters, including initial concentration, temperature, reaction time and pH, have been studied (Liu et al., 2022). The advantages of this technique include high economic efficiency, and disadvantages include the sludge production, slow process, being easily influenced by environmental factors (Hao et al., 2021).

2.2 Chemical precipitation

Chemical precipitation is a process in which ferric chloride, hydrated iron (III), lime, and ammonium chloride are used to eliminate metals like vanadium. The strengths of this technique are method simplicity and inexpensive cost. Its limitations include chemical consumption, low selectivity, and inability to eliminate the element ions at low levels (Hao et al., 2021).

2.3 Electrocoagulation

This process is one of the advanced oxidation processes (AOPs) and one of the most promising techniques for purification of organic pollutants and heavy metals, including electrokinetic, electrodialysis, electro-coagulation, electro-flotation, anodic oxidation, and electrochemical reduction (Chen et al., 2013; Su et al., 2014). Among the electrochemical techniques, the most effective one is electrocoagulation. It is the electrochemical generation of destabilization agents from sacrificial anodes (e.g., Al, Fe) for removing heavy metals, pollutants, and pathogens (Moersidik et al., 2020). Electrokinetic remediation is based on employing a low electrical potential difference or a direct current of low intensity through electrodes in the material to be purified (Mangini et al., 2020). The strengths of this technique include high efficiency, ease of operation, less waste production, and less usage of chemical reagents. High energy consumption and low mass transfer performance are among the disadvantages of this method (Mangini et al., 2020).

2.4 Photocatalysis process

In this process, the heavy metals are reduced by receptive oxygen species generated on photocatalysts under UV or visible light. Among the strengths of this technique are the easy design, inexpensive-cost operation, flash- degradation, and no sludge production (Crini and Lichtfouse, 2019).

2.5 Membrane filtration

Membrane techniques are used in the treatment of water and wastewater due to their simple separation technique. Among the strengths of this technique are high efficiency, low sludge production, space- saving while clogging and fouling of membrane, and high costs are among the limitations of this method (Karimi-Maleh et al., 2021). Membrane techniques are divided into six kinds: microfiltration, ultrafiltration, nanofiltration, reverse osmosis, forward osmosis and electrodialysis (Semghouni et al., 2020).

2.6 Other elimination technologies

2.6.1 Solvent extraction

This process is based on the separation of mixtures between two mutually immiscible solvents(Ye et al., 2018). However, tracking the extraction of a metal from its pure solution can be valuable for the assessment of its extractability in various states (Razavi et al., 2017). The strengths of this technique include its simple usage in combination with other methods, high performance, safety, and simple operation, while low selectivity, and high influence of pH are among the limitations of this technique (Crini and Lichtfouse, 2019).

2.6.2 Microwave irradiation roasting

This process has been suggested to extract costly elements from minerals. The major strengths of this process used in the metallurgical field are rapid heat transfer, volumetric and selective heating, higher thermal performance, and green chemistry that allows convenient automatization and process control (Gao et al., 2020). This process has been reported to be used for vanadium extraction from stone coal (Zhang et al., 2011).

2.6.3 Oxidation roasting process

This process is the most important step in the processing of vanadium-containing raw materials for more extraction of vanadium (Kologrieva et al., 2021). Different oxidation roasting techniques (e.g., slag oxidation roasting with MgO and oxidation roasting of vanadium slag with sodium salts) used to treat sludge have been investigated for increasing the vanadium extraction into the solution.

3 Methods

This review is principally focused on methods and processes used for vanadium removal. Databases like Google Scholar, Science Direct, PubMed, Cochrane Scopus, and Web of Science were employed to retrieve several papers on the topic. Keywords like phytoremediation, electrochemical, photocatalysis, wastewater, bioremediation, vanadium removal, adsorption, drinking water , water treatment, and groundwater were added to the above mentioned methods to retrieve appropriate papers. After a thorough search and removing articles with no direct association with water vanadium removal, a total of 129 original papers were primarily included in the context of the review. This excludes various review articles providing an understanding of the different mechanisms of each treatment.

The retrieved articles used various methods, such as adsorption (23), biological techniques (16) (i.e. bioremediation, microbial reduction, phytoremediation), chemical precipitation (5), electrochemical processes (3), photocatalysis processes (2), and other techniques (10) (i.e. reverse osmosis, nanofiltration, ion-exchange, microwave irradiation roasting, oxidation roasting process, and solvent extraction) (Tables 1,2,3,4,5)

4 Results and Discussion

4.1 Adsorption

Based on the obtained results from this study, the maximum elimination performance of vanadium by melamine adsorbent was 1428.57 mg/g, and the lowest removal performance was 1.61 mg/g for wet distiller grains derived adsorbent (Table 1). According to this study, the most appropriate adsorption isotherms of vanadium fit the Langmuir isotherm model (about 44%). Although vanadium elimination by adsorption has been widely studied and also a few research studies have investigated the elimination of vanadium from actual industrial waters, most of these studies are limited to pilot scale (Bahr et al., 2022; Cadaval Jr et al., 2016; Gan et al., 2020). A study by Kajjumba et al. demonstrated the maximum vanadium adsorption capacity by natural shale and waste coal was 67.57 and 59.88, mg/g, respectively at pH value of 3, temperature of 25°C and initial level of 100 mg/L (Kajjumba et al., 2018). In a study, Yang et al. indicated that maximum vanadium adsorption capacity was about 712.4 mg/g at pH 7, temperature of 25°C and initial level of 100 mg/L after a removal time of 24h from aqueous environments by using colloidal kaolinite. Moreover, the recovery rate of the colloidal kaolinite at pH 7 and 9 was 2.0 and 2.1 times that at pH 5, respectively(Meng et al., 2020). In a study, Zhu et al. reported the maximum vanadium adsorption capacity of weak-base resin D314 for vanadium removal from aqueous environments to be about 18.08 mg/g at pH 3, and an initial level of 127 mg/L (Zhu et al., 2018). In a study, Oyewo et al. reported that maximum vanadium adsorption capacity was about 40 mg/g at pH 4.2-5.2, and an initial level of 100-200 mg/L for vanadium removal from water by using montmorillonite (Oyewo et al., 2017). Zhang and Leivisk used Pine bark modified with quaternary ammonium groups for vanadium removal from water and reported the maximum vanadium adsorption capacity to be about 35 mg/g at pH 4, and an initial level of 10-591 mg/L after 24 h (Zhang and Leiviskä, 2020). Using Nanosized ZnO, Yin et al. removed vanadium from aqueous environments and found the maximum vanadium adsorption capacity to be about 369 mg/g at pH 6.5, and an initial level of 3-800 mg/L after 30 min(Yin et al., 2018). In a study, Ghanim et al. used sawdust biochar modified with red mud for vanadium removal from aqueous environments and reported that maximum vanadium adsorption capacity was about 16.45 mg/g at pH 3.5-5.5, and an initial level of 100 mg/L after 60 min (Ghanim et al., 2020). Using amino modified with derived ceramics for vanadium removal from wastewater, He et al. reported that maximum vanadium removal efficiency was about 99.8% at pH 4, and an initial level 50 mg/L with 800 g adsorbent (He et al., 2018). In a study by Kaczala et al., sawdust was used for vanadium removal from real wastewater. The obtained results indicated that maximum vanadium removal efficiency was about 95% at pH 4, and an initial level 50 mg/L with 800 g adsorbent (Kaczala et al., 2009).

Table 1 Adsorption specific of vanadium on different adsorbents.

Technique	**Media**	**Temperature**	**pH**	**Initial concentration**	**Time**	**Adsorption models**	**Removal efficiency**	**Ref**
Zirconium modified Chitosan-zeolite	Aqueous solution	25°C	5	250 mg/L	30 min	Langmuir	277.75 mg/kg	(Salehi et al., 2020)
Iron sorbents	Wastewater	25°C	3-9	58.2 mg/L	15-60 min	Langmuir	4.7-5.1 mg/kg	(Leiviskä et al., 2017)
Chitosan films	Aqueous solution	35°C	6	200 mg/L	24 h	BET	251.4(50.3)mg/kg	(Cadaval Jr et al., 2016)
Nano zero-valent iron stabilized by biochar	Water	25°C	2-10	Below 25 mg/L	120 min	-	48.5(98%) mg/kg	(Fan et al., 2020)
Silica	Water	25°C	3-5	29.1 mg/L	600 min	Langmuir and Freundlich	82.7 mg/kg	(Gan et al., 2020)

Activated carbon	Wastewater	20–23˚C	7	40–50 mg/L	24 h	-	48.9 mg/kg	(Keränen et al., 2015)
Trioctyl methyl ammonium chloride-impregnated resins	Aqueous solution	25 ◦C	1.8	1500 mg/L	4 h	Langmuir	78.65 mg/kg	(Peng et al., 2021b)
Wet distiller grains derived	Aqueous solution	25 ◦C	3	50 mg/L	240 min	Freundlich	1.61 mg/kg	(Kończyk et al., 2022)
Fe-nanoparticle-activated carbon	Aqueous solution	25 ◦C	4.5	60 mg/L	200 min	FPSDM	119.01 mg/kg	(Sharififard and Soleimani, 2017)
Agricultural soils	Environment	25 ◦C	7	50 mg/L	60-120	Freundlich	748.6-1124.6 mg/kg	(Jiang et al., 2019)
CsCl-modified biochar (Cs-BC), Zn(II)-modified biochar (Zn-BC), Zr(IV)-modified biochar (Zr-BC	Aqueous solution and groundwater	25 ◦C	4-8	5-250 mg/L	4 h	Langmuir	(Cs-BC) 41.07, (Zn-BC) 28.46, (Zr-BC) 23.84 mg/kg	(Meng et al., 2018)
Magnetic chitosan nanoparticles	Aqueous solutions	20 ◦C	5	10 mg/L	2 h	Freundlich	186.6 (99.9%)mg/kg	(Omidinasab et al., 2018)
Humic Acid and Silica	Aqueous solutions	5-45◦C	2-4	83.6 mg/L	24 h	Freundlich	359.97 mg/kg	(Song et al., 2020)
Sawdust	Aqueous solutions	22◦C	4	19.1 mg/L	8 h	Langmuir	35 mg/g(96.2%)	(Gogoi et al., 2021)
Resin D302	Aqueous solutions	25◦C	4	100 mg/L	90 min	Redlich–Peterson	70.57 mg/g(	(Huang et al., 2020)
Melamine	aqueous solution	25-65◦C	1-4	10000 mg/L	10-40 min	Freundlich	1,428.57mg/g	(Peng et al., 2017)
Glutamic Acid	Aqueous solution	25◦C	1-7	0.05 mol/L	60 min	-	101.53 mg/g(91.66%)	(Peng et al., 2021b)
Liquid-phase polymer-based retention	Aqueous solution	20◦C	6	60 mg/L	-	-	520 mg/g (90%)	(Rivas et al., 2019)
Nano-hydroxyapatite	Aqueous solution	25◦C	About 7	300 mg/kg	60 d	-	4.92-39.75 mg/kg	(Song et al., 2020)
Zero-valent iron	Wastewater	25◦C	4.2	50 mg/L	24 h	-	Over 99%	(Vollprecht et al., 2019)

Functionalized biochars	Groundwater	30°C	4	50 mg/L	60 min	-	70 mg/kg	(Wu et al., 2021a)
Functionalized sawdust-derived cellulose	Aqueous solution	25-45°C	3-4	25-75 mg/L	0-280 min	Langmuir	37.9–47.2 mg/g	(Zulu et al., 2020)
Goethite and birnessite	Aqueous solution	15-35°C	4-8 and 2	25 mg/L	60 and 120 min	Langmuir	8.24 and 9.11 mg/kg	(Zhu et al., 2020)
Granular ferric hydroxide	Drinking water	-	7.6	30μg/L	175 d	-	92.85%	(Bahr et al., 2022)

4.2 Biological treatment

According to the findings of this study, the highest (100%) and the lowest (65.2%–98.7%) vanadium removal efficiency was observed for novosphingobium bacillus and hauera, respectively (Table 2). A study by Zhang et al. demonstrated that maximum vanadium removal efficiency was about 78% at 0.2 mM vanadate through the mechanism of reduction and precipitation of V(V) and ethanol as electron donor from synthetic groundwater by using pseudomonas, soehngenia, anaerolinea (Zhang et al., 2019a). Zhang et al. found that maximum efficiency of vanadium removal from synthetic groundwater using Geobacter, Spirochaeta was about 99.5% at 1 mM vanadate through the mechanism of reduction of V(V), elemental sulfur, and iron as electron donor (Zhu et al., 2018). A study by Wang et al. indicated that maximum efficiency of vanadium removal from groundwater by using aerolineaceae and Spirochaeta was about 91% at 1 mM vanadate through the mechanism of reduction of V(V); acetate as electron donor (Wang et al., 2018). In a study by Xu et al., the maximum efficiency of vanadium removal from groundwater through the mechanism of bio-reduction of V(V) and hydrogen gas as the electron donors was found to be about 95.5% at pH of 7.5-8 and temperature of 35-40- °C (Xu et al., 2015). In a study, He et al. reported that the maximum efficiency of vanadium removal from groundwater by using Thiobacillus was about 76.4% at 10 mg/L vanadate concentration after 150 d (He et al., 2021). Zhang et al. investigated vanadium removal from contaminated soil by using a canola plant and found that the maximum vanadium removal efficiency was about 14.64-61.53% through the mechanism of phytoremediation (*Brassica campestris* L.)(Zhang et al., 2018). Abeywardane studied vanadium removal from aqueous solution by using wheat with an initial level of 62.43 mg/L and showed that the maximum vanadium adsorption capacity by shoot and root was 648.45 and 6620.66 mg/kg, respectively (Abeywardane, 2019). Using the Slim amaranth plant in a study, Ameh et al. investigated vanadium removal from aqueous solution with an initial level of 63 mg/kg and found that the maximum vanadium adsorption capacity by shoot and root was 92 and 75 mg/kg, respectively (Ameh et al., 2019). Liao and Yang used a Chinese cabbage plant for vanadium removal from the environment with an initial level of 300 mg/kg. The results of their study indicated that the maximum vanadium adsorption capacity by shoot and root was 4.92 and 39.75 mg/kg, respectively (Song et al., 2020). In a study by Nawaz et al., vanadium with an initial level of 50 mg/L was removed from an aqueous solution by using watermelon grafted onto a bottle gourd and pumpkin rootstock. The results of their study indicated that maximum vanadium adsorption capacity by shoot and root was 0.3 and 1.3 mg/kg, respectively (Nawaz et al., 2018).

Table 2 Microbiological treatment of vanadium in water and wastewater.

Technique	**Media**	**pH**	**Operation time**	**Temperature**	**Initial concentration**	**Removal efficiency**	**Ref**
Bryobacter and Acidobacteriaceae	Groundwater	7	60 h	22 °C	75 mg/L	91-92%	(Hao et al., 2018)
Novosphingobium and Rhodobacter	Groundwater	7	181-210 d	-	10 mg/L	100%	(Chen et al., 2022)
Bryobacter and Acidobacteriaceae	Groundwater	7	60 h	22 °C	75 mg/L	92%	(Hao et al., 2018)
Thauera	Groundwater	-	10 d	25°C	75 mg/L	90.3%	(Hao et al., 2021)
Ecological floating beds(Acorus calamus L.)	Water	8.6	34 d	22 °C	300 **μg/L**	79.91%	(Lin et al., 2019)
Anaerolineaceae, Spirochaeta and Spirochaetaceae	Aqueous solution	7	72 h	22 °C	1 mM	97%	(Wang et al., 2018)
Shewanella loihica PV-4	Aqueous solution	7.4	27 d	-	50.6 mg/L(1mM)	71.3%	(Wang et al., 2017)
Phytoremediation (Cyperus papyrus)	Wastewater	6.45-6.61	30 d	28 °C	1 mg/L	90.2-92.2%	(Chen et al., 2021)
Phytoremediation(alfalfa, Milkvetch Root)	Aqueous solution	7	70 d	-	250 mg/kg	83.9%	(Gan et al., 2021)
Phytoremediation (Tobacco)	Aqueous solution	6-7	20 d	25°C	4 mg/L	272.5mg/kg	(Wu et al., 2021b)
mustard	Aqueous solution	7	60 d	22°C	100 mg/L	3000-5000mg/kg	(Imtiaz et al., 2018)
Pseudomonas putida and Halomonas mono	Aqueous solution	7-7.5 and 8.5-9	7 d	22 °C-25 °C	200 mg/L	69% and 85%	(Safonov et al., 2018)
Bacillus and Pseudomonas	Ground water		72 h	25 °C	5-20 mg/L	84.5%	(Shi et al., 2021)
Geobacter, Longilinea, Syntrophobacter, Spirochaeta and Anaerolinea	Groundwater	6-7	72 h	22 °C	-	90%	(Liu et al., 2017)
Bacillus, Thauera	Environment	-	30 d	22 °C	1.5 mM	65.2%–98.7%	(Zhang et al., 2019b)
Dechloromonas, Hydrogenophaga, Geobacter	Groundwater	-	7 d	-	1 mM	91%	(Jiang et al., 2018)

4.3 Chemical Precipitation

Many researchers have focused on vanadium recovery from aqueous environments by using precipitation with different coagulants. According to findings of this study, vanadium elimination by chemical precipitation is very effective, with removal performances ranging from more than 80 to 99.85% (Table 3). A study by Wang et al. demonstrated that vanadium removal from crude $TiCl_4$ was 81.5% using NaOH leaching, ion exchange, and precipitation within 3 h and at the maximum temperature of 98 °C (Wang et al., 2011). Mahandra et al. found that vanadium removal from synthetic and actual leaching solution was 97.45% using HNO_3 leaching at a temperature of 25°C(Mahandra et al., 2020).A study by Navarro et al. demonstrated that vanadium removal from oil fly ash was 50-90% using precipitation by aluminum at pH 8 and ammonium chloride at pH 5 (Navarro et al., 2007). A study by Wen et al. indicated that vanadium elimination from acidic/alkaline environments was above 93% using precipitation by ammonium salts at pH 1.8-3 (Wen et al., 2019). A study by Ye et al. showed that vanadium removal from acid leaching solution was 97% using precipitation by NaOH within 4 h (Ye et al., 2012).

Table 3 Chemical precipitation process for vanadium removal from water and wastewater.

Technique	Media	pH	Time	Temperature	Initial concentration	Removal efficiency	Ref
Hydrated iron(III)	Wastewater	2-3	72 h	90 °C	29.23 g/L	98.5%	(Chen et al., 2011)
Calcium-based semi-dry flue gas desulfurization ash	Wastewater	7.5	15 min	25℃	86 mg/L	99.85%	(Fang et al., 2018)
Ferric chloride	Water	7.25	20 min	-	125 μg/L	Over 85%	(Roccaro and Vagliasindi, 2015)
Lime	Aqueous solution	-	60 min	60℃	0.21 g/L	More than 80%	(Zhao et al., 2012)
Ammonium chloride	Aqueous solution	5-7	16 h	-	1000 mg/L	97.29%	(Gharagozlou et al., 2021)

4.4 Electro/Coagulation/ Oxidation/Chemical

According to the findings of this study, vanadium elimination using electrochemical methods ranged from 22.99% to 99.64% (Table 4). Electro-oxidation is an environmentally friendly method (Peng et al., 2016). One study indicated that the vanadium removal was 99.7% from alkaline media at pH 13 by using an electrochemical advanced oxidation process (Xue et al., 2017). Another study indicated that vanadium elimination was 75.64% from an acidic environment at a temperature of 75℃ after 4h by using an electro-oxidation process (Liu et al., 2016). The vanadium removal from the aqueous solution was 22.99% with an initial vanadium level of 0.5 mol/L after 48 h by using electrokinetic remediation (da Cruz Deniz et al., 2018).

Table 4 Electrochemical process for vanadium removal from water and wastewater.

Technique	Media	pH	Initial concentration	Time	Removal efficiency	Ref
Electrokinetic	Aqueous solution	4	3283 mg/L	-	22.99%	(da Cruz Deniz et al., 2018)
Electrochemical	Aqueous solution	-	Current density of 750 A/m^2	6 h	95%	(Wang et al., 2015)
Electro-oxidation	Wastewater	-	Current density of 1000 A/m^2	30 min	95.64%	(Deng et al., 2019)

4.5 Photocatalysis process

Photocatalysis remediation is a quite novel method for water and wastewater treatment and a charming way to realize green chemistry. According to the findings of this study, the vanadium elimination by photocatalysis process ranged from 68.8% to 98% (Table 5). In a study, AbdelAziz et al. reported vanadium removal from the environment by using gamma irradiation at a dose of 1.5 Gy/S (150 rad/s) at 30^{o}C (AbdelAziz et al., 2014). A study by Holmes et al. indicated that the efficiency of Se removal from mine water was 99.6% at a TiO_2 dose of 0.2 g/L at pH 3, UV intensity of 11.03 mW/cm^2 by using photocatalysis (UV/TiO_2)(Holmes et al., 2022). A study by Xu et al. reported the efficiency of Cr(VI) elimination from an aqueous environment was 99.5% by using photocatalysis (UV/Bi_2WO_6-PNS), at a Bi_2WO_6 –PNS dose of 1.2 g/L, at pH 4, with initial Cr (VI) level of 10 mg/L, within 1.67 h (Xu et al., 2018). A study by Xu et al. indicated that the efficiency of Cr (VI) elimination from aqueous solution was 97% by using photocatalysis (UV/$CuFeO_2$), at a $CuFeO_2$ dose of 400 mg/L, pH 3, with an initial Cr(VI) level of 5 mg/L, within 60 min (Xu et al., 2017).

Table 5 Summary of other techniques for vanadium removal from water and wastewater.

Technique	Media	Comment	Removal efficiency	Ref
Ion exchange	Wastewater	C_0=40-50 mg/L, pH=7-9,	92-98%	(Keränen et al., 2015)
Leaching	Aqueous solution	Time=180 min, T=90 °C, pH=1.8	99.8%	(Peng et al., 2019)
Oxidation process by Goethite	Aqueous solution	C_0=20 mg/L,T=25 °C, specific surface of Goethite 14.60 m^2 /g	pH=2: 25-30% and pH=4: 15-20%	(Hu et al., 2019)
Oxidation Roasting Process	Environment	1000 ◦C for CaCO3 and 900 ◦C for MgO	98.7%	(Kologrieva et al., 2021)
Oxidation−alkaline extraction	Environment	reaction temperature 90 ◦C, reaction time 90 min	97.24%	(Peng et al., 2021a)
Ultrasound-assisted leaching	Environment	ultrasound power: 159 W at 20 kHz in 2 h, T= 35◦C, hydrogen peroxide10%,	88.7%	(Rahimi et al., 2020)

		lemon juice 27.9%		
Fluidized bed reactor	Wastewater	C0=50 mg/L, pH=4.2-10	More than 90%	(Vollprecht et al., 2019)
Nanofiltration	Aqueous solution	C_0= 1.429 g/L, pH=6-6.5, room temperature, d operation pressure of 2069 kPa	95%	(Shang et al., 2014)
Solvent extraction	Aqueous solution	C_0=4.78 g/L,pH=1.8-2, extraction time =5 min	Above 98%	(Ye et al., 2018)
Microwave irradiation roasting	Environment	Power:2 KW, roasting time :1.5 h	98.29%	(Gao et al., 2020)
UVA/TiO_2	Wastewater	C_0=20 mg/L, pH=2.1, contact time =15 min, catalyst concentration=0.5 g/L	Up to 98%	(Sturini et al., 2013)
Solar light /ZnWO4	Wastewater	C_0=10 mg/L, contact time =180 min, catalyst concentration=50 mg/L	68.8%	(Zhao et al., 2016)

4.6 Other elimination technologies

Table 6 shows a summary of other techniques for vanadium removal from water and wastewater. Some other technologies, such as membrane filtration, ion-exchange, and solvent extraction, have also attracted much more attention in removing vanadium from water and wastewater.

4.7 Membrane filtration

The elimination of toxic elements from water and wastewater environments with high levels of salt has been a rising area for membrane separation. A study by Ricci et al. indicated that the rejection of metals from wastewater by using reverse osmosis was as follows: Cu= 99.3%, Ni= 94.8%, Co=98.2%, Al=97.4%, As=92.7%, Ca= 98.2%, Mg=95.7%,Fe=98.7%, Mn=98.8%with permeate flux 11.4 L/m^2 h at pH 2.5 (Ricci et al., 2015). A study by Ortega et al. demonstrated that the rejection of metals from contaminated soil by using nanofiltration was as follows: H= 36%, Al= 92%, Ca= 42%, Cu= 12%, K=0%, Mg=79%, Mn=66%, Na=-3%, Pb= 36%, SO4=89%, Si=3% (Ortega et al., 2008).

4.8 Ion exchange

In a study, Vinco et al. reported the use of ion- exchange for vanadium removal from an acid solution containing iron at pH 0.50–2.00, resin mass 0.055–9.000 g, and temperature 293–328 K (Vinco et al., 2022). The vanadium removal from vanadium molybdate solutions was 99.5% with an initial vanadium level of 10 mg/L, at pH=9.25, after 4 h (Zhu et al., 2017). Zeng et al. reported that the efficiency of vanadium removal from sulphuric acid leach solutions by using ion-exchange was 99% at pH 4, with an initial vanadium level of 2.06 g/L after 60 min(Zeng et al., 2009). In a study, Keranen et al. reported that the efficiency of vanadium removal from industrial wastewater by using anion exchange was 92-98% at pH 7-9, with an initial vanadium level of 40–50 mg/L (Keränen et al., 2015).

4.9 Solvent extraction

The extraction performance of vanadium from the leaching solution by solvent extraction was 99.5%, stripping efficiency was above 99.8%, and the purity of the V_2O_5 product was 99.22% (Ying et al., 2022). Razavi et al.

reported that the efficiency of vanadium extraction from aqueous environments by using solvent extraction was about 93% at pH 1.9- and extraction temperature of 60°C (Razavi et al., 2017). In a study, Mingyu et al. reported that the efficiency of vanadium extraction from aqueous environments by using solvent extraction was about 70% at pH 1-2, with an initial vanadium level of 2.20 g/L (Wang et al., 2009).

4.10 Comparison of different technologies used for vanadium removal

Generally, traditional water and wastewater treatment includes a mixture of physical, chemical and/or biological processes and operations to eliminate pollutants, including colloids, organic matter, nutrients, microorganisms, metal ions, organics, etc., from the environment (Crini and Lichtfouse, 2019). This section is assigned to the strengths and limitations of the techniques available (Table 6). Only a few are popularly used by the industrial sector for economic and technological reasons. Among these technologies, adsorption and biological purification have attracted the most intensive attention to understanding low energy use and high vanadium-binding capacities.

Table 6 Comparison of different technologies used for vanadium elimination.

Technology	Strengths	Limitations	Ref
Adsorption	Easy operation, wide range of adsorbents, eco-friendly, wide diversity of objective pollutants	The high price of regeneration, Non-selective methods	(Kończyk et al., 2022; Song et al., 2020)
Microbiological methods	Economically feasible, high performance	Slow process, waste production, essential to make an optimal condition for microorganisms	(Gan et al., 2021; Karimi-Maleh et al., 2021)
Chemical precipitation	Efficient and economical method, technically simple, integrated physicochemical process	Chemical use, high waste production, ineffective in the elimination of the metal ions at low value, transport and management of the coagulants	(Hao et al., 2021; Liu et al., 2022)
Electrochemical process	High efficiency, widely used in the mining industries, effectiveness of the technique for the recovery/recycling of costly metals	Requires post-treatment to remove high levels of iron and aluminum ions	(Crini and Lichtfouse, 2019; Mangini et al., 2020)
Photocatalytic methods	Rapid degradation, no waste production, simple design, low-cost operation, high stability and high removal efficiency	Economically non-viable for small and medium industries, technical limitations	(Crini and Lichtfouse, 2019; Liu et al., 2022)

4.11 Global perspectives toward vanadium

According to the results of this study, the highest vanadium level of 13980 µg/L was achieved in China and the lowest level of about 21 µg/L was found in the USA in different waters (Table 7). The EU and USA recommend that vanadium in potable water should not exceed 0.46 and 50 µg/L, respectively (Watt et al., 2018). Vanadium level in fresh water is significantly beyond that in seawater. Vanadium concentration in fresh water ranges from 0.2 µg/L to over 100 µg/L depending on the existence of effluents and leachates from human and/or natural sources entering the water table (Arena et al., 2015). Another study reported that vanadium levels of up to 200 µg/L were revealed in groundwater of volcanic areas worldwide (Dabizha et al., 2020).In a study, Härter et al. reported that high vanadium levels of up to 28 µg/l were observed in surface waters (spring) of the western Eifel volcanic area, Germany (Härter et al., 2020). Vanadium is present as a natural material in global groundwaters, e.g., the USA, Canada, China, and various European countries (Germany, Italy), depending on geological conditions (Bahr et al., 2022).

Table 7 Vanadium levels in surface and ground waters from different countries.

Regions/countries	Water sources	Vanadium concentration	Ref
USA (California)	Drinking water	Over 21 µg/L	(Chen and Liu, 2017)
USA (Colorado)	Ground- water	100 µM	(Jiang et al., 2018)
Spain (El Hierro)	Ground- water	288 µg/L	(Bello et al., 2019)
Argentina (Pampean)	Ground -water	2470 µg/L	(Fiorentino et al., 2007)
Italy (Mt. Etna)	Ground- water	201 µg/L	(Aiuppa et al., 2000)
Japan (Mt. Fuji)	Ground- water	58-99 µg/L	(Koshimizu and Tomura, 2000)
China(Panzhihua)	Ground- water	76-208 µg/L	(Yang et al., 2014)
China(Datong)	Ground- water	0.02-288 µg/L	(Chen et al., 2022)
China (Baguan River)	Surface- water	13.98mg/L	(Zhong et al., 2015)
China (Panzhihua)	Ground-water	94-285 µg/L	(Chen et al., 2022)
China (Hebei)	Ground-water	1-11 mg/L	(Jia et al., 2002)

5 Conclusions

This study aimed to prepare a complete evaluation of the major concepts and limitations of vanadium elimination from water and wastewater. Various techniques, such as adsorption, membrane filter, photocatalytic remediation, electrochemical process, and microbial techniques, have been widely evaluated to achieve more efficient and economical results. This study has attempted to review an extensive range of published articles on vanadium elimination from aqueous environments. The adsorption was found to be the most common, frequently adopted and effective technique with elevated elimination performances in the literature. We concluded that to eliminate vanadium totally and effectively, many techniques discussed above should be used together and also some new techniques needed to be developed. Most of the studies conducted for vanadium removal from water and wastewater were on pilot or lab-scale, for example, still a gap exists between pilot results and full-scale accomplishment of vanadium remediation techniques. It is thus vital to carry out large- scale studies. In the recent study on vanadium removal, the authors would like to focus on the following aspects:

- It is mainly important to select the suitable technique based on the real water and wastewater conditions. One technique has a high efficiency for vanadium under pilot study, but it may fail under large-scale.
- Currently, most studies have only discussed the effect of a single parameter. There is little discussion on the impact of two or more parameters acting together. Therefore, it is very important to carry out comprehensive studies in the future to explore the interactive parameters.
- The cost of different techniques and chemical reagents or materials should be investigated and compared.
-Adsorption remediation depends on a few factors, including environment pH, organic and inorganic ions, the dosage of adsorbents, type of adsorbents, reaction time, initial concentration of pollutant and temperature.
- Development and extension of bioremediation technique for V(V) removal from contaminated groundwater is important.
-Using the phytoremediation method with the assistance of soil improvements and microorganisms is a promising technique for vanadium removal from contaminated environments.

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