




Biosorption technique using water hyacinth plant as an effective and sustainable approach for treating oil refinery waste: Vanadium element as a case study

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ABSTRACT

This study aims to investigate the use of water hyacinth (*Eichhornia crassipes*) leaves as an adsorbent for vanadium removal from petroleum industry waste. Additionally, it seeks to identify the optimal conditions for maximizing the recovery efficiency of vanadium, a toxic heavy metal. The adsorption performance was evaluated using simulated aqueous solutions with a high concentration of vanadium, a metal released as waste from oil refineries, in a batch adsorption system. The treatment efficiency was studied at different values of acidity, temperature, agitation speed, contact time, and adsorbent dosage, and at 10 ppm concentration of vanadium. The ranges of the studied variables were 1–8, 20–50 °C, 100–500 rpm, 10–150 min, 1–12 g, respectively. The obtained results indicated that the maximum percentage removal was 76.16% and the removal was inversely proportional to temperature and directly proportional to other variables. The morphological test results indicated that vanadium adsorption onto the surface of water hyacinth (*Eichhornia crassipes*) caused an 89% reduction in the surface area of the untreated plant. Additionally, FT-IR and EFSEM analyses revealed significant structural modifications in the adsorption surface, leading to the depletion of most active sites. Furthermore, The Langmuir model best described the obtained data, exhibiting a 99% correlation coefficient. In comparison, the Freundlich and Temkin models had correlation coefficients of 98.56% and 96.44%, respectively. Kinetically, the intra-particle diffusion and pseudo-first-order models provided the most accurate representation of the data among the tested kinetic models, with the intra-particle diffusion model having a slight edge. Based on the thermodynamic function values, the adsorption process was spontaneous, exothermic, and exhibited a decrease in randomness across all examined temperature range.

Keywords: adsorption, batch unit, oil refinery waste, removal, water hyacinth and vanadium.

INTRODUCTION

Water hyacinth is a genus of plants belonging to the *Pontederia* family of the *Commelinales* order, and its scientific name is *Eichhornia crassipes*. The scientific name was coined by the German botanist Carl Sigismund Kunth in honor of the Prussian Minister of Culture 1840–1848, Johann Albrecht Friedrich Eichhorn (Hashem et al., 2021). *Eichhornia crassipes* is a seasonal plant that grows and floats on fresh water. Its original habitat is the Amazon River Basin and the tropical regions of South America, from where it spread to many countries of the world. This plant

was introduced to Iraq in the mid-eighties of the last century as an ornamental plant due to its purple flowers and large, bright green leaves, and also as a shade plant in fish tanks (Ali and Abbas, 2020). Overtime, it has been observed that it spreads rapidly and provides minimal benefits compared to its numerous and significant negative impacts on aquatic ecosystems, including surface water in rivers, tributaries, irrigation channels, and even drainage systems (Khaleel et al., 2022). Due to their rapid growth, these organisms impact fish and other aquatic life by obstructing sunlight from reaching other species, particularly phytoplankton. Phytoplankton form

the foundational base of the aquatic ecosystem and serve as the primary food source for zooplankton and fish, disrupting the delicate balance of the food web. Additionally, they consume significant amounts of water, with each plant requiring between 1 to 5 liters per day, while also depleting dissolved oxygen levels in the water. This reduction in oxygen alters the taste and odor of the water, making it unpleasant. (Priya and Selvan, 2017). Due to its roots extending deep into the water, it significantly disrupts irrigation operations by blocking and hindering the flow of irrigation water in channels, as well as clogging irrigation and drainage pumps. This presents substantial risks to water resources and can lead to the depletion of water supplies (Nega et al., 2023). The negative impact of this plant is not limited to fish wealth and water resources, but its impact extends to the infrastructure, as it weakens the surrounding structures, as one hundred square meters of “water hyacinth” weighs more than five tons, causing enormous pressure on the foundations of bridges and the structural structures of dams, in addition to its ability to impede navigation, by forming dense areas of tangled and crowded plants, in addition to many other environmental damages (Harun et al., 2021). Several methods have been developed to address the management of this invasive plant, with the manual approach being one of the most prominent. This method is considered simple and traditional, typically used in small-scale areas such as ponds, narrow canals, or locations that are inaccessible to machinery. It relies on human labor and the use of hand tools, including sickles, shovels, nets, and hooks, to remove the plants from the water. While this method has its advantages, it also presents several limitations. It is inefficient for large-scale applications and is not effective for completely eradicating the plant (Ajithram et al., 2023). Additionally, this method is time-consuming and labor-intensive. The mechanical approach involves the use of specialized tools, equipment, and machinery, such as mechanical cranes, trammels or manual nets, excavators, and weed harvesters, to remove large quantities of water hyacinth from aquatic environments. However, this method requires repeated removal efforts, as the plant regrows and spreads rapidly (Nega et al., 2023). The third procedure is biological control, which depends on the utilize of specialized living organisms, such as the fungus (*Cercospora piaropi*), or the grass carp fish, the water beetle (*Neochetina*

eichhorniae and *Neochetina bruchi*), which act to minimize the intensity of the plant grow or prohibit its spread without negatively affecting the close environment. However, this active method is too slowness comparing with other methods, in addition to the unknown risks may be happen when losing the control to reproduction of these living organisms (Gupta and Yadav, 2020). Chemical control is one of the most widely used methods for eliminating *Eichhornia crassipes* from aquatic environments. This approach involves the application of specific herbicides, such as 2,4-D (dichlorophenoxyacetic acid) and glyphosate, which effectively target the plant without harming other organisms. The primary advantages of this method are its relatively short treatment time and low cost compared to other techniques. However, the potential for contamination remains a significant drawback of this approach (Ajithram et al., 2021). The other method to get ride water hyacinth is to convert it from harmful plant to benefit matter by recycling (Hashem et al., 2021). Water hyacinth plant can be used in the production of organic fertilizer and biofuel, in the paper industry, and as animal feed after processing, and in the production of building materials after converting the plant into compressed wood panels used in construction or furniture manufacturing (Nahar and Sunny, 2024). One of the important applications of water hyacinth is its ability to treat contaminated or wastewater by acting as an adsorbent for heavy metals and organic pollutants. Adsorption is a process, either physical or chemical, in which molecules of a substance (such as a gas or liquid) accumulate on the surface of a solid or liquid known as an adsorbent (Ali and Abbas, 2020). This process takes place at the interface between the adsorption medium and the adsorbate, where the adsorbed particles are associated with the adsorbent surface through either weak physical interactions (such as van der Waals forces) or strong chemical bonds (Alsarayreh et al., 2025a). Adsorption technology is one of the promising technologies in the industrial, environmental and medical fields, as it is used to remove pollutants from environmental elements (water, air and soil) (Abbas and Abbas, 2013a). It has applications in separating and purifying various chemical compounds, and its role in the production of medicines and drug delivery systems, due to its simplicity, efficiency and low cost compared to other technologies (Abbas and Alalwan, 2019). The most

famous adsorption materials are activated carbon (Maddodi et al., 2020), alumina (Shadhan et al., 2024), zeolite (Khudair et al., 2024), and nanomaterials (Ali et al., 2024a). These materials have demonstrated their effectiveness in removing various types of pollutants across different concentrations. However, their high production costs, the need for continuous regeneration, and the loss of a portion of their mass with each cycle have prompted researchers to explore more cost-effective and suitable alternatives (Alsarayreh et al., 2024). One of these substitutional is bio-based materials such as agricultural and industrial waste, such as pomegranate peels (Ali et al., 2024b), eggshells (Abbas and Ibrahim, 2020), almond peels (Hameed et al., 2025), tangerine peels (Gadooda et al., 2025), watermelon rinds (Abbas and Nussrat, 2020), banana peels (Abdullah et al., 2023), rice husks (Abbas and Abbas, 2013b), orange peels (Hasan et al., 2021), lemon peels (Al-Hermizy et al., 2022), waste tea leaves (Al-Ali et al., 2023), aluminum foil (Ghulam et al., 2020), sunflower hulls (Abdulkareem et al., 2023), algae (Abbas et al., 2019a), water hyacinth (Ali and Abbas, 2020), and others. These materials offer several benefits, including their extremely low toxicity and year-round availability. Furthermore, they are not valuable resources and require disposal, as their accumulation in large quantities poses a significant environmental burden (Abbas and Abbas, 2013c). Over the past three decades, these materials have proven to be remarkably efficient in treating polluted environments, and have the ability to remove various types of pollutants such as dyes (Alwan et al., 2021), acids (Abbas and Abbas, 2014), water hardness (Ibrahim et al., 2021), organic materials (Alalwan et al., 2021), eutrophication elements (Abbas, 2015), inorganic toxins (Alalwan et al., 2020), pesticides (Abd Ali et al., 2024), drug residues (Ibrahim et al., 2020a), pharmaceuticals (Ibrahim et al., 2020b), and heavy metals (Abbas et al., 2020) of all kinds, from water (Alalwan et al., 2018), soil (Abbas et al., 2019b), and crude oil (Ali et al., 2021). Although these substances accumulate as toxic residues after the treatment process is completed, the concept of a zero-residue level has led to the development of various methods to repurpose them as valuable materials such as converting them into acetone (Abbas et al., 2022a) or promoted biofuel (Hamdi et al., 2024), or into concrete additives as reinforcement materials (Rajaa et al., 2023), or as radiation barrier materials when

constructing X-ray rooms in hospitals (Abbas et al., 2022b), or as catalyst (Abbas et al., 2021) or nanomaterials (Alminshid et al., 2021) as an effective pesticide for rodents, such as rabbits (Al-Latif et al., 2023) and rats (Abd Ali et al., 2018), or as an organic fertilizer for the soil (Abbas, 2015). The aim of the present study is to use water hyacinth (*Eichhornia crassipes*) leaves as an adsorption medium for vanadium resulting from petroleum industry waste, and to determine the optimum conditions that achieve the highest recovery efficiency for vanadium as one of the toxic heavy elements. Moreover, characterized the adsorption medium using BET surface area, FT-IR, and FESEM to detect the effect of vanadium adsorption. Furthermore, investigate the adsorption behavior through isothermal, kinetics, and thermodynamic studies and determine the governing model responsible for adsorption process.

EXPERIMENTAL WORK

Chemicals and equipment used

The main material used in this study was vanadium sulphate, of the chemical formula VOSO_4 , supplied by the English company BDH Limited Poole in the form of a blue powder. The study required secondary materials to accomplish it, which are hydrochloric acid (HCl) of 35% concentration, purchased by Laboratory Reagent company-Indian, and sodium hydroxide (NaOH) and a molecular weight of 40 g/mol and 97% purity, supplied by the Indian company HIMEDIA. As for the distilled water, it was obtained from a laboratory distillation device, type GFL-2008, Germany, with a capacity of 4 liters per hour. It is worth noting that all the glassware used in this study is of the type (borosilicate glass) and purchased from Eisco Labs, USA.

Samples of refinery wastewater

The real samples were collected from Baiji oil refinery, at 200 km north of Baghdad, during the period from February to September 2024. The collection process was carried out according to the method described by (Abbawi and Hassan, 1990) Using 0.5 L flasks. The samples were collected in clean, sterile, amber glass bottles from the wastewater discharge site in the oil refinery, then tightly locked and wraps with a stratum of aluminum foil to protect them from any possible effect of light,

before the details of samples were recorded. The collected samples were promptly transferred to the laboratory for analysis and component identification. Three types of tests were performed on the samples: the physical tests are presented in Table 1, and the results of the chemical tests are shown in Table 2. The concentrations of ions and heavy metals in the wastewater samples are measured using UV-Vis spectrophotometer, UV-1280 (Shimadzu-Japan) and atomic absorption spectrophotometer, AA-7800 (Shimadzu-Japan), listed in Tables 3 and 4, respectively.

Stock solution of vanadium heavy metal

As described in Ali et al. (2020a), 3.2 g of vanadium oxide sulfate was accurately weighed using a sensitive balance (NB A-400 NANBEI, China) in an appropriate amount of distilled water in 100 ml beaker, and the dissolution process was completed using a magnetic stirrer (CH-2093, Australia) at a speed of 150 rpm and at room temperature. After ensuring that all the used quantity was dissolved, the entire mixture was transferred to a volumetric flask (volumetric flask, 1000 ml of tolerance ± 0.40 ml – interchangeable, 24/29 polypropylene stopper) and the volume was completed with distilled water

to exactly 1000 ml. Thus, a stock solution with a concentration of 1000 mg/L was prepared, i.e. every 1 cm³ of the resulting solution has 0.001 g of vanadium.

Calibration curve

The calibration curve for the atomic absorption spectrophotometer to measure vanadium concentration is prepared by following precise methodological steps to ensure the accuracy of the results. The preparation begins by preparing series of standard solutions with known and increasing concentrations of vanadium, using the stock solution diluted in specific proportions to prepare the standard solutions. After adjusting the wavelength to 318.5 nm, the absorbance of each standard solution is measured, and the results are recorded in the form of instrument response signals (i.e. absorbance) against the known concentration of each solution. After collecting the data, the calibration curve is plotted, with the horizontal axis representing the standard concentrations and the vertical axis representing the absorbance. In most cases, the curve is assumed to be linear, and then the straight-line equation ($y = mx + c$) is applied to determine the relationship between absorbance and concentration. This curve is later used

Table 1. Physical tests of wastewater samples

Parameter	Unit	Value	Measuring device
Conductivity	µmho/cm	320–750	High range TDS and conductivity meter - HI99301 (Hanna-USA)
Density at 20 °C	g/cm ³	1.08–1.16	AU-300SL specific gravity tester (Guangdong Hongtuo instrument technology Co., Ltd., China)
pH	–	5.62–10.39	Portable pH meter, HI-83141-1 (Hanna, USA)
Surface tension	dyne/cm	40–61	Tensiometer, LMEC-10 (Labor scientific instrument Co., Ltd., China)
Turbidity	NTU	183–276	Portable turbidity meter, HI93703 (Hanna, USA)
Viscosity	cp	1.05–1.21	Rotary viscometer, NDJ-5S (Guangdong Kejian Instrument Co., Ltd., China)

Table 2. Chemical tests of wastewater samples

Parameter	Value, (ppm)	Measuring device
Biological oxygen demand (BOD)	945–1205	Biochemical oxygen demand instrument, LH-BOD606 (Lianhua, China)
Chemical oxygen demand (COD)	3110–3760	Chemical oxygen demand analyzer, LH-T3COD (Lianhua, China)
Dissolved oxygen (DO)	7.55–8.49	Portable optical dissolved oxygen meter, LH-DO2M (Lianhua, China)
Total dissolved solid (TDS)	191.270–417.000	Portable DiST 1 waterproof TDS tester, HI98301 (Hanna, USA)
Total organic carbon (TOC)	730–1023	Total organic carbon analyzer, LTOC1000 (Labman, England)
Total petroleum hydrocarbons (TPH)	54–73	Petroleum testing, HI932 (Hanna, USA)
Total suspended solid (TSS)	1085–15620	Portable TSS meter, LH-SS2M (Lianhua, China)

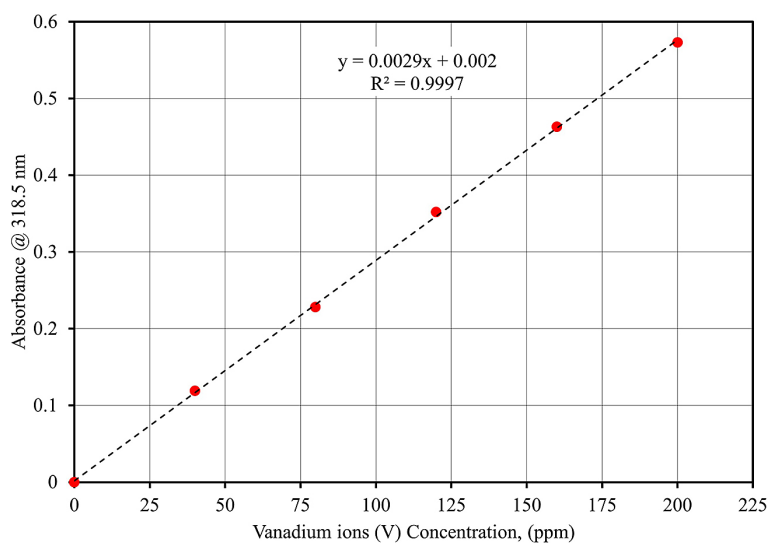
Table 3. Anions of wastewater used in this study

Anions	Concentration, (ppm)
Sulfite (SO_3^{2-})	1–8
Sulfate (SO_4^{2-})	55.3–69.38
Phosphate (PO_4^{3-})	84–196
Metasilicate (SiO_3^{2-})	17–30
Fluoride (F ⁻)	1–3
Nitrate (NO_3^-)	0.403–1.423
Chloride (Cl ⁻)	10,250–14,330
Bicarbonate (HCO_3^-)	966–1482
Ammonia (NH_4^-N)	0.25–1.50

Table 4. Heavy metals in refinery wastewater used in this study

Metal	Concentration, (ppm)
Vanadium (V)	2.332–8.627
Nickel (Ni)	0.953–2.084
Chromium (Cr)	0.247–0.502
Iron (Fe)	0.158–0.832
Copper (Cu)	0.102–0.375
Cadmium (Cd)	0.05–0.62
Lead (Pb)	0.024–1.072
Zinc (Zn)	2.4–4.05
Aluminum (Al)	16–52

to analyze samples of unknown concentration by measuring their absorbance and matching these values with the correction curve to determine the vanadium concentration (Ali et al., 2020b). Figure 1 shows the calibration curve for vanadium using an atomic absorption spectrophotometer.

**Figure 1.** AAS calibration curve of vanadium

Adsorbent material (leaves of water hyacinth)

Water hyacinth is a rapid-growing aquatic plant, known of its negative environmental impact due to its closure of waterways and high consumption of oxygen and water. However, it can be exploited as a non-valuable and sustainable adsorption material to remove vanadium from simulated aqueous solutions, achieving the aim of this study. The process of collecting the water hyacinth from the banks of the Tigris River began manually using nets and shovels in the Tikrit area during November, 2024. After collecting the plant, it is washed well using an excess of tap water to remove silt, dirt, and impurities suspended on the surface, with repeated washing several times to ensure the cleaning of the plant parts. After ensuring the cleanliness of the plant, it is washed with distilled water. The plant is cut into the basic plant parts (roots, stems, or leaves), where the leaves were chosen as the most effective part in adsorption, as they contain a large surface area rich in functional groups. In this study, the leaves of the *Eichhornia crassipes* plant were used as is without any additional treatment. The clean leaves were cut in a small piece and dried naturally, by spreading them out in the open air for several days, and then dried at 65 °C by drying oven (Laboratory Drying Oven-99200-3, Stanhope-Seta-UK) to remove all moisture, as moisture may reduce the adsorption efficiency.

The drying process of the leaves continued until the weight was stable. The dried leaves were stored in dry places away from light in amber, tightly closed glass jars, protected from moisture

and direct light, to ensure their chemical and physical stability. The water hyacinth plant used in this study is shown in Figure 2.

Batch adsorption unit

A batch adsorption unit was used to conduct the experiments of vanadium adsorption using water hyacinth leaves as a non-valuable adsorbent. The adsorption unit of batch mode is considered the essential equipment for studying adsorption processes and evaluating their efficiency under specific experimental conditions. The unit used in this study consists of a water bath shaker (Thermo-Fisher SHKE7000 MaxQ 7000), which is the main component in the process, as it is used to provide constant temperature and stable vibration motion. The water bath shaker ensures thermal equilibrium between the solution and the adsorbent, in addition to enhancing the contact between them, which contributes to achieving the best adsorption efficiency. At a specific pH, the experimental flasks are placed inside the water bath shaker, which contain the contaminated solution at a certain concentration, in addition to the adsorbent, and are wrapped by a layer of aluminum foil to protect the samples from any possible effect of light. The operational parameters studied in this process were temperature, contact time, amount of water hyacinth leaves as adsorbent, pH, and agitation speed. The ranges of these factors were 20–50 °C, 10–150 min, 0.5–12 g, 1–8, 100–500 rpm, respectively, at initial concentration of 10 ppm of vanadium. After adjusting the shaking and temperature parameters of the batch unit, the experiment was beginning and continued until the desired time period was over, after which the unit was stopped and the samples were carefully extracted and filtered using Whitmann® 41 filter paper



Figure 2. Water hyacinth leaves used in this study

to remove the water lily leaves, and then the solution was examined after treatment to determine the adsorption efficiency and capacity through Equations 1 and 2 (Alhamd et al., 2024a), respectively:

$$q_e = \frac{V(C_o - C_f)}{m} \quad (1)$$

$$\%R = 1 - \frac{C_e}{C_o} \quad (2)$$

where: q_e – the uptake of vanadium ions at equilibrium, ($\text{mg}\cdot\text{g}^{-1}$), C_o , and C_f – initial, and ultimate concentrations of vanadium ion, respectively, (ppm), V – Solution’s volume of, (liter), m – amount of water hyacinth leaves used in experiment, (g), %R – removal percentage of vanadium ions, (-).

RESULTS AND DISCUSSION

Morphological tests

Specific surface area

The surface area of the water hyacinth leaves’, which were used as an adsorbent for vanadium ions, was investigated before and after adsorption, as shown in Figure 3, which shows the adsorption-desorption isotherm of the leaves.

This important property was measured for the prepared activated carbon using Quantachrome, Qsurf 9600 Thermo Finnegan Co., USA device, depending on physical adsorption-desorption for nitrogen gas at constant temperature which were the boiling point of liquid N_2 (-77K). The results obtained showed that the virgin leaves of the water hyacinth plant had a surface area of $18.63 \text{ m}^2\cdot\text{g}^{-1}$. The presence of this surface area by the adsorbent in this study can be attributed to several factors, including the cellular composition, porous structure, chemical components and microfibrers, in addition to the physical properties resulting from the complex structure of the leaves. It is clear that the surface area of the water hyacinth plant decreased due to adsorption of vanadium ions by more than 89%, as it lowered from $18.63 \text{ m}^2\cdot\text{g}^{-1}$ to $2.04 \text{ m}^2\cdot\text{g}^{-1}$. This means that the active sites were fully occupied, and the functional groups were gradually and continuously consumed, which caused a significant decline in the ability of the plant to adsorb the target metal ions. Other possible explanation for this result is that the continuous accumulation of vanadium ions inside the pores and surface cavities, automatically reduced the surface area of

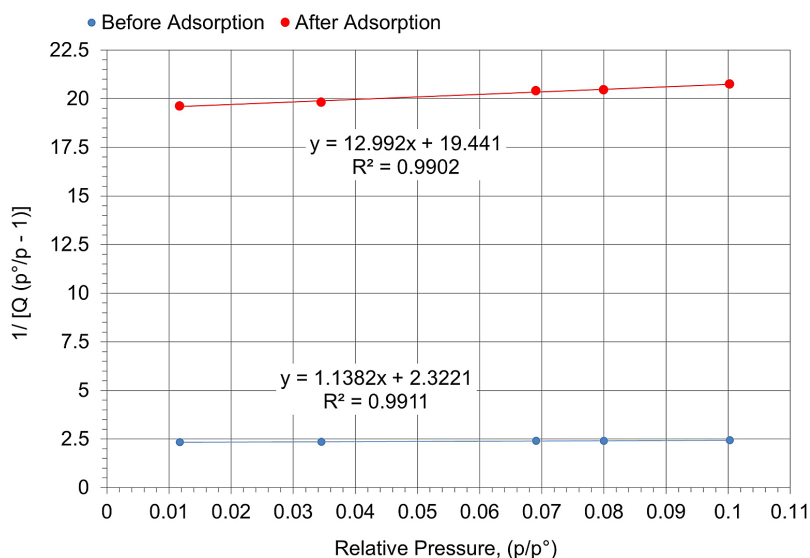


Figure 3. Adsorption-desorption curve

the *Eichhornia crassipes* leaves as an adsorbent. By this result, water hyacinth proved its high and notable ability to treat heavy metals polluting the aquatic media, as it is an efficient and effective adsorption medium (Alhamd et al., 2024a).

Fourier transform infrared spectroscopy analysis

FTIR analysis represents a detailed study of the effect of vanadium adsorption using water hyacinth leaves by comparing the changes in functional groups before- (red line) and after- adsorption (black line), as in Figure 4. The red line shows peaks representing the active functional groups existent on the surface of the water hyacinth leaves

before adsorption, while the black line reflects the modifications that took place to these functional groups due to the interaction with vanadium ions. FTIR analysis was measured using (IRPrestige-2, Shimadzu, Japan) device. Before adsorption, a distinct peak appears at 3404.36 cm⁻¹, representing the stretching vibrations of hydroxyl groups (O-H) on the adsorption surface or adsorbed water. While after adsorption, the intensity of this peak decreases and shifts slightly (as shown in the spectrum of black color), indicating that the O-H groups are associated with vanadium ions via hydrogen bonds or coordination interactions. The peaks at 2922.29 cm⁻¹ and 2852.49 cm⁻¹ indicate the stretching vibrations of the methylene group

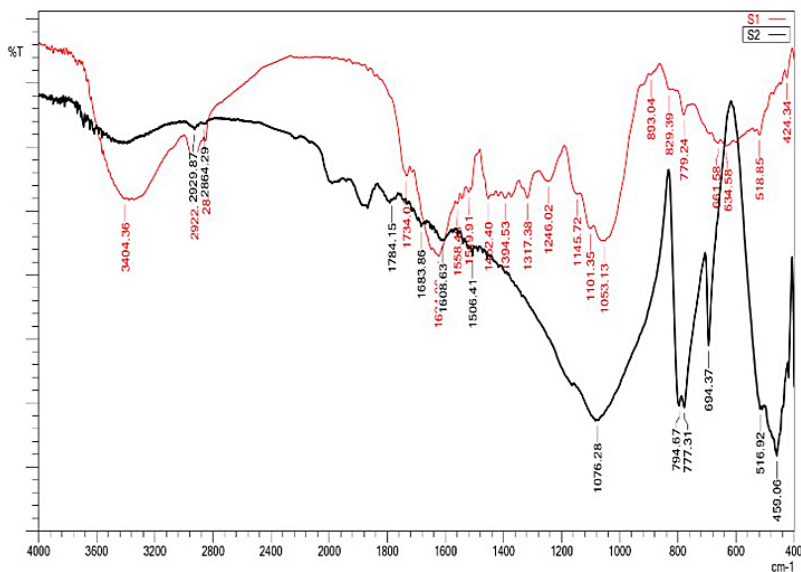


Figure 4. FT-IR spectra of water hyacinth

(C-H), which are related to the hydrocarbon chains in the water hyacinth leaves. The density of these peaks can be noted to decrease after adsorption, which means that these groups were influenced by the connecting of vanadium to them in addition to alterations in the surface framework. The peak at 1741.5 cm^{-1} before adsorption refers the stretching vibrations of the carbonyl group (C=O), which is one of the important functional groups on the surface of adsorbent medium. After adsorption, this peak shifts to 1683.86 cm^{-1} , showing an immediate chemical interaction between the carbonyl group and the vanadium ions (Alhamd et al., 2024b). This shift indicates the ability of the producing of coordination complexes between these groups and the vanadium ions. The peaks at 1633.13 cm^{-1} and 1506.41 cm^{-1} represent the vibrations of the carbon-carbon double bond (C=C) in the aromatic rings or amino groups (N-H), which explain a decline or shift in their location at ending of adsorption. These shifts demonstrate the changes of these groups due to relating with vanadium ions, via coordination changes in the near bond environment. The peaks in the range 1371.38 cm^{-1} to 1101.15 cm^{-1} elucidate the vibrations of the carbon-oxygen bond (C-O) or carbon-nitrogen bond (C-N) connected with the carboxylic or amino groups on the surface of the water hyacinth leaves, which varied their density and location at the end of adsorption, as in the former peaks. These alterations refer that these groups played an essential function in the linked process with vanadium ions, by donating electrons to form coordination bonds (57). In the minimum range between 1063.13 cm^{-1} and 694.37 cm^{-1} , the peaks indicate the bending vibrations of (Si-O) or (Fe-O)

bonds or any identical bonds, which may be established in the surface texture of water hyacinth leaves. Clear changes are observed in this range after adsorption, reflecting the interaction of the surface groups with the adsorbed vanadium ions. Finally, the peaks at 424.34 cm^{-1} and 459.06 cm^{-1} in the red spectrum represent vibrations of metal bonds or new functional groups formed due to the binding of vanadium to the surface of water hyacinth leaves. These new peaks indicate the formation of stable chemical bonds between the surface and the target heavy metal in the adsorption process. The spectral changes in the intensity and locations of peaks on the surface of water hyacinth leaves, as a result of processing with polluted vanadium solutions, and detected by FTIR analysis, indicate that the basic functional groups, such as hydroxyl, carbonyl, carboxyl, and amino groups, etc., directly participated in the adsorption process, and are responsible for the performance of water hyacinth leaves as an efficient and effective adsorption medium. It can be said that these changes indicate that the adsorption occurred through chemical reactions (such as the formation of coordination bonds) in addition to physical interactions (such as hydrogen bonds) (Hameed and Abbas, 2024).

Field emission scanning electron microscopy (FESEM)

Figures 5a and 5b show the FESEM images of the surface of the water hyacinth leaves, measured by FEI Nova Nano SEM-450, Thermo Fisher Scientific, USA, before and after adsorption of vanadium ions, respectively. It is noted from the

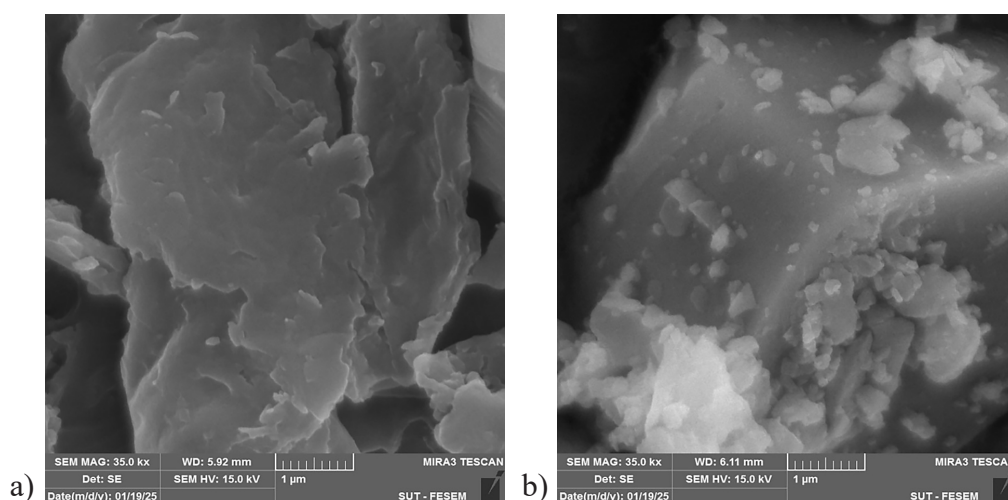


Figure 5. a) SEM image of water hyacinth before adsorption of vanadium, b) SEM image of water hyacinth after adsorption of vanadium

above figures that there is a clear difference in the structure of the leaves, reflecting the physical changes that occurred on the surface of the adsorbent material as a result of the adsorption process of vanadium from the contaminated aqueous solutions. In Figure 5a, the surface appears in clear details with high porosity, and it shows the pores, gaps, and active sites that represent the areas where the target metal ions can bind. This open porous structure is ideal for the adsorption process, because it provides a suitable surface area and a high capacity to retain the adsorbed ions (58). In contrast, Figure 5b shows clear changes on the surface of the water hyacinth leaves after adsorption, where the clarity of the surface details decreases and most of the pores appear to be covered or closed, indicating that the vanadium ions have occupied most or all of the available active sites. This change could be due to electrostatic interactions between heavy metal ions on the surface of the adsorbent, or as a result of accumulation of vanadium ions as a layer that completely covers the surface, reducing the apparent porosity (Alhamd et al., 2024a). Moreover, the change in surface morphology could be attributed to the accumulation of ions inside the micropores, leading to their blockage, or to structural changes caused by the effect of vanadium, such as rearrangement of chemical bonds or compression of the surface material. The decrease in surface roughness after adsorption could be due to the accumulation of the adsorbed metal ions in a homogeneous layer covering the entire surface. These results show that the water hyacinth leaves were very effective as an adsorption medium, as most of its pores and active sites were

used to trap vanadium ions, which explains the decrease in effective surface area and the emergence of a smoother and less porous surface (Hameed and Abbas, 2024). This structural change confirms the success of the adsorption process and supports the feasibility of using this plant - which represents a real environmental issue - as an efficient adsorption medium to treat the pollution of aqueous solutions with heavy metals (vanadium in particular).

Operating factors of adsorption process of vanadium metal

Impact of acidity on vanadium adsorption

The acidity change on vanadium adsorption was studied using the leaves of water hyacinth plant in a range of 1 to 8, keeping other operating variables are constant at 400 rpm, 10 ppm, 10 g, 150 min, 20 °C for each of the agitation speed, initial concentration of vanadium, adsorbent dose, contact time, temperature, respectively, as shown in Figure 6. The results show that the vanadium removal efficiency is greatly affected by the pH of the solution, starting very low at pH = 1 at 7.37% and gradually increasing with increasing pH until it reaches a peak of 74% at pH = 6, with relative stability at pH = 7 and 8. This change reflects the effect of the interaction between the nature of the adsorbent surface and the solution on the adsorption process. At very low pH values (1 to 3), the concentration of hydrogen ions (H^+) is very high, which leads to their intense competition with vanadium ions for the active sites on the adsorbent surface. This competition reduces

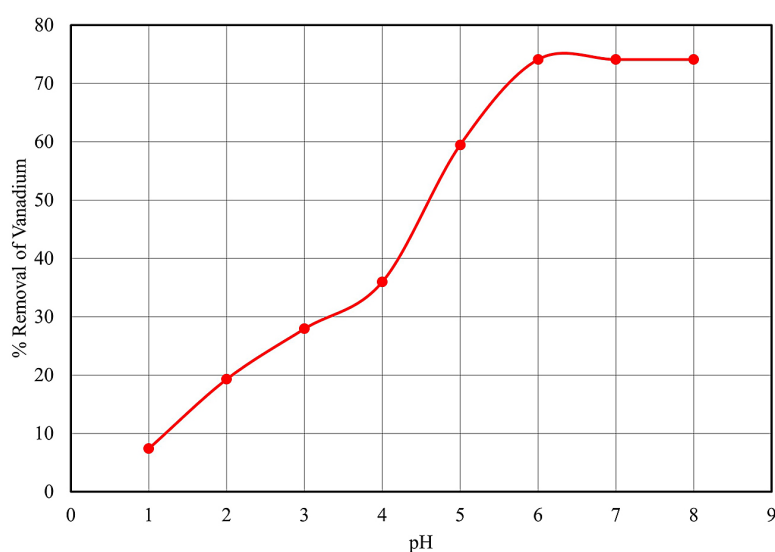


Figure 6. pH effect on vanadium adsorption using water hyacinth

the ability of the surface to bind with metal ions, and the surface becomes positively charged due to the adsorption of hydrogen ions, which causes repulsion with the positive vanadium ions, thus decreasing the adsorption efficiency. As pH increases to the intermediate range $\text{pH} = 4\text{--}6$, the concentration of hydrogen ions decreases, allowing more opportunity for the surface sites to bind to vanadium ions. Deprotonation of the adsorbent surface under these conditions results in a relative negative charge on the surface, which enhances the electrostatic attraction between the surface and the positive ions, thus greatly improving the adsorption efficiency. At $\text{pH} = 6$, the optimal conditions for surface-solution interaction are achieved, where there is a balance between the surface charge and the number of available active sites, resulting in the highest removal efficiency.

As the pH continues increasing to the basic zone, $\text{pH} = 7\text{--}8$, the removal efficiency stabilizes at about 74%, indicating that the system has reached a dynamic equilibrium where there is no significant increase in usable active sites or adsorbed vanadium ions (Alhamd et al., 2024d). Therefore, the optimum pH value required for the removal of vanadium ions using the leaves of the water hyacinth plant is 6.

Impact of agitation speed on vanadium adsorption

The change in the agitation speed on vanadium adsorption using the leaves of the water hyacinth plant, was studied in the range of 100–500

rpm, keeping other variables are constant at 6, 10 ppm, 10 g, 150 min, 20 °C for each of the pH, initial concentration of vanadium, adsorbent dose, contact time, and temperature, respectively, as shown in Figure 7. The results showed a clear effect of changing the agitation speed on the vanadium percentage removal, as the efficiency increased from 14.67% at 100 rpm to 74% at 400 rpm. This remarkable improvement reflects the important role of the agitation speed in enhancing the adsorption process by improving the transport of vanadium from the solution to the surface of the leaves of the water hyacinth plant. At low speeds, mixing is limited, resulting in a static boundary layer around the adsorbent surface that acts as a barrier to the access of ions to the active sites, and thus the adsorption efficiency is low. It's obvious that the increasing of agitation speed is directly related to increasing the adsorption efficiency of vanadium ions, and this may be due to the fact that increasing the shaking of adsorption unit leads to improve the distribution of the pollutant in the solution (Alalwan et al., 2018). Furthermore, the increasing the shaking leads to enhancing the possibility of the target metal ions reaching the active sites spread on the surface of the water hyacinth leaves, which contributes to increasing the adsorption efficiency. Another thing related to this result is that increasing the shaking works to break the boundary layer formed on the surface of the water hyacinth leaves, which leads to facilitating the access of vanadium ions to the functional groups in the pores of the adsorbent medium (Ghulam et al., 2020).

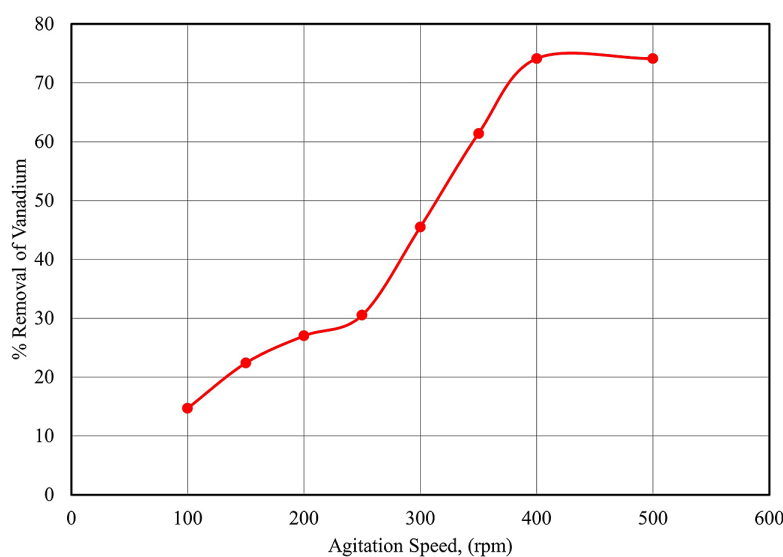


Figure 7. Agitation speed effect on vanadium adsorption using water hyacinth

Moreover, it is noted that increasing the agitation speed beyond 350 rpm does not lead to any increase in the percentage removal of vanadium adsorption, and this can be explained by the fact that the water hyacinth leaves have reached the saturation level and cannot receive any further amount of the adsorbate (i.e. vanadium ions), or that the adsorption rate is equal to the desorption rate, which makes the adsorbent in a dynamic equilibrium, which does not enable it to enhance the removal efficiency (Hameed et al. 2025). Therefore, the optimum value of agitation speed that achieves the maximum removal efficiency of vanadium ions from the contaminated solution is 350 rpm. Moreover, at these speeds, it can be assumed that the hydrodynamic distribution of the material in the solution has become completely homogeneous, ensuring maximum utilization of the adsorbent surface (Gadooda et al. 2025). These results show that increasing the agitation speed plays a pivotal role in improving the adsorption performance up to the optimum speed, while any further increase may not be effective in terms of energy or practical efficiency.

Impact of adsorbent dosage on vanadium adsorption

The variation of the amount of water hyacinth leaves as an adsorbent for the recovery of vanadium from aqueous solutions was studied over a range of 0.5–12 g, keeping other variables constant at 6, 10 ppm, 400 rpm, 150 min, 20 °C for each of the pH, initial vanadium concentration, agitation

speed, contact time, and temperature, respectively, as shown in Figure 8. The results showed that increasing the adsorbent dosage gradually improved the vanadium removal efficiency, increasing from 9.5% at 0.5 g to 76% at 11 g, with a stable efficiency at higher dosages. This behavior can be explained by the effect of the adsorption dosage on providing more active sites on the surface of water hyacinth leaves with increasing dosage. At low doses, the amount of adsorbent is limited, so the number of available active sites decreases, resulting in low adsorption efficiency. As the dose increases, the number of active sites increases, which enhances the possibility of capturing vanadium ions, thus significantly increasing the percentage removal. However, at high doses (greater than 9 g), the efficiency gradually starts to stabilize, which can be explained by reaching saturation. In this case, most of the vanadium ions available in the solution have already been adsorbed on the surface of the water hyacinth leaves, and the remaining concentration of ions in the solution becomes very low (Khudair et al., 2024). At this point, even with increasing the active sites by adding more adsorbent, the number of remaining ions is not sufficient to fill the additional sites, limiting any significant increase in efficiency. Furthermore, other factors may play a role in the stability of the efficiency at high doses, such as the hydrodynamic effect resulting from aggregation or interference between adsorbent molecules, which reduces the effective surface area available for capturing ions. Increasing the dose may also increase the thickness of the adsorbent layer, limiting the ease with which ions can reach the internal sites

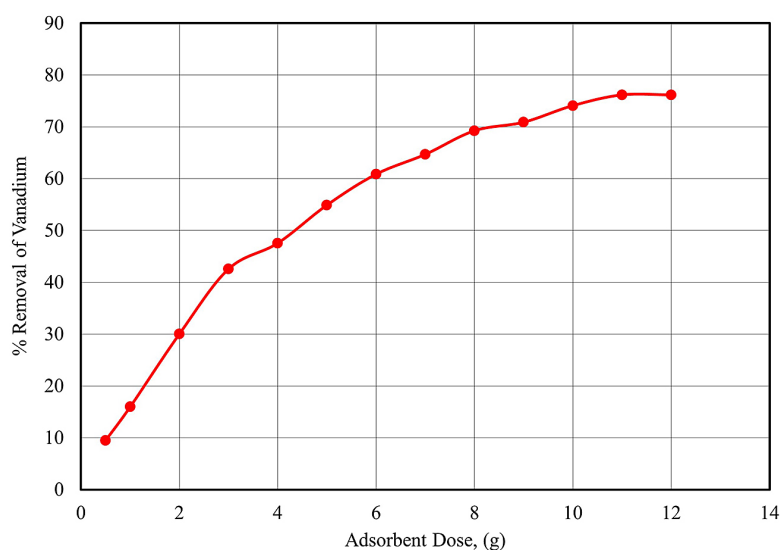


Figure 8. Adsorbent dose effect on vanadium adsorption using water hyacinth

on the surface of the adsorbent (Ali et al., 2024a). This stability in efficiency suggests that there is a certain threshold for the adsorption capacity of the water hyacinth leaves, making the optimal dose 11 g, as higher doses may not be beneficial at this level until the adsorbent reaches saturation.

Impact of contact time on vanadium adsorption

The varying of contact time on the adsorption of vanadium using the leaves of water hyacinth was studied within a range of 10–150 minutes, keeping other variables are constant at 6, 10 ppm, 400 rpm, 11 g, 20 °C for each of the pH, initial concentration of vanadium, agitation speed, adsorption dose, and temperature, respectively, as shown in Figure 9. The results showed a significant effect of the contact time variable on the vanadium percentage removal, as increased from 8% after 10 minutes to 76% at 120 minutes, with the efficiency remaining stable at this level despite increasing the time to 150 minutes. This behavior reflects the importance of contact time in improving the adsorption process during the early stages of the reaction, where the active sites on the surface of the adsorbent are unoccupied, allowing vanadium ions to quickly interact with the surface via physical or chemical adsorption mechanisms (Abdullah et al., 2023). During this stage, a high percentage removal is observed due to the large concentration gradient between the solution and the adsorbent surface, which drives the ions towards the surface more effectively. As time progresses, the adsorption gradually decreases (as evidenced by the slowdown in the increase in efficiency after 90 min), due to

the active sites on the surface being filled and the remaining vanadium ions in the solution having difficulty reaching those sites due to interference between the ions or the weak concentration gradient (Hasan et al., 2021). At 120 min, the system reaches a state of dynamic equilibrium, where the adsorption and removal from the surface become equal, which explains the stable efficiency at this point. Other influencing factors such as intra-particle diffusion within the pores of the adsorbent may have become the main limiting factor after the early stages of adsorption. In this case, vanadium ions need longer time to reach the internal sites of the adsorbent, which explains the continued increase in efficiency up to the equilibrium time. However, beyond the equilibrium time (120 min), no further improvement is observed because the active sites are either completely consumed or the remaining ions in the solution are no longer sufficient to increase the efficiency (Ibrahim et al., 2021). These results suggest that 120 min is the optimal time to achieve the maximum percentage removal, taking into account that increasing the contact time beyond this point does not provide any additional benefit in terms of efficiency, but rather leads to additional time consumption that is not justified from an operational point of view.

Impact of temperature on vanadium adsorption

The temperature change for the recovery of vanadium from aqueous solutions using the leaves of the water hyacinth plant as an adsorbent was studied within a range of 20–50 °C, keeping other variables constant at 6, 10 ppm,

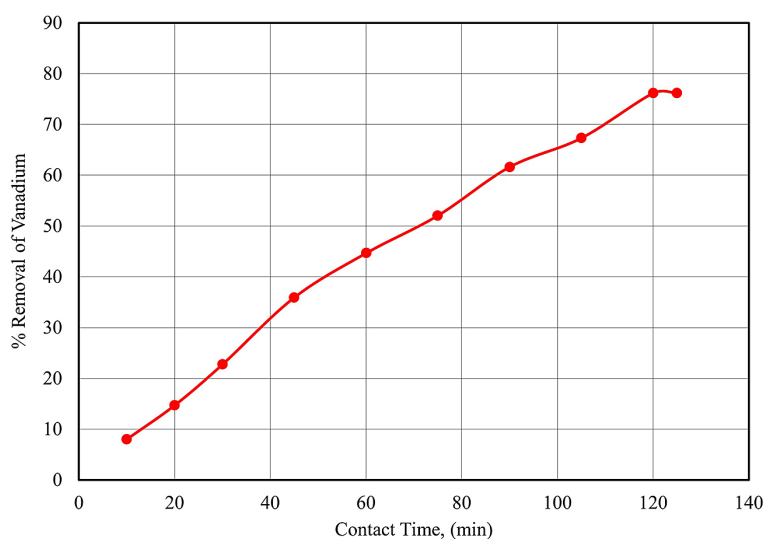


Figure 9. Contact time effect on vanadium adsorption using water hyacinth

400 rpm, 11 g, 120 min for each of the pH, initial vanadium concentration, agitation speed, adsorption dose, and contact time, respectively, as shown in Figure 10. The results obtained from temperature variation experiments show a significant decrease in the vanadium metal removal with increasing temperature, reflecting an important effect of temperature on the percentage removal. Initially, this result can be explained by the thermal effects on the physical and chemical interactions between adsorbed ions or molecules and the adsorbed surface (Gadooda et al., 2025). As the temperature raises, the transferring of ions in the solution raises too, which lowers the potential of their coalescence to the surface water hyacinth leaves, thus lowering the adsorption. High temperatures may also be the reason of increasing the energy of ions, which promotes the opposite processes that prevent the adsorption of vanadium on the adsorbent surface of the water hyacinth leaves (Hasan et al., 2021). Furthermore, raising temperatures may be led to defragment the adsorption surface of the adsorbent in different ways, such as impairment of pores or modulation in the chemical composition of the surface, which lowers the activity of adsorption process (Ibrahim et al., 2021). These modulates in the surface framework may result in diminishing the surface area available for adsorption process. These results may also refer to conversion from physical adsorption to chemical adsorption at high temperatures, as chemical reactions are less efficient under high-temperature conditions. In general, the results show that the adsorption of vanadium

ions is more active at low temperatures, and that the optimum temperature is room temperature, at which the maximum percentage removal of the required ions is performed.

Adsorption behavior

Adsorption thermodynamic

To calculate the basic parameters of thermodynamic study, the effect of temperature on the adsorption process must be known, and by applying the data obtained in the Van't Hoff Equation shown in Equation 3 (Alhamd et al., 2024a), the changes in free energy, enthalpy and entropy depending on temperature can be calculated after determining the adsorption equilibrium constant (k_d) via Equation 4 (Alhamd et al., 2024a), at several different temperatures.

$$\Delta G = \Delta H - T\Delta S \quad (3)$$

$$\ln k_d = -\frac{\Delta H}{R} \frac{1}{T} + \frac{\Delta S}{R} \quad (4)$$

where: k_d – Adsorption equilibrium coefficient (–); R – Universal gas constant (8.3144 J/mol·K); T – Absolute temperature (K); ΔH – Enthalpy change (kJ/mol); ΔS – Entropy change (J/mol·K); ΔG – Gibbs free energy (kJ/mol).

Figure 11 represents the results of applying Equations 3 and 4 to the results obtained from the adsorption of vanadium ions using the leaves of water hyacinth plant as an adsorbent, while Table 5 shows the values of the thermodynamic functions of the adsorption process. The results of the

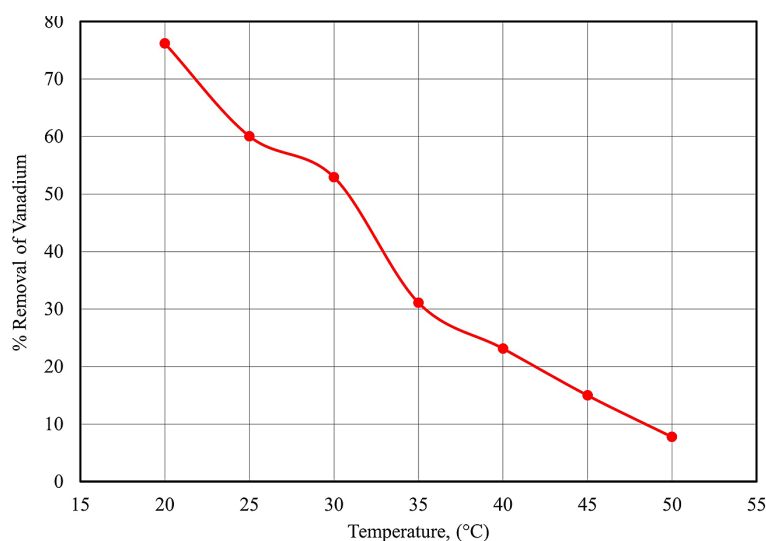


Figure 10. Temperature effect on vanadium adsorption using water hyacinth

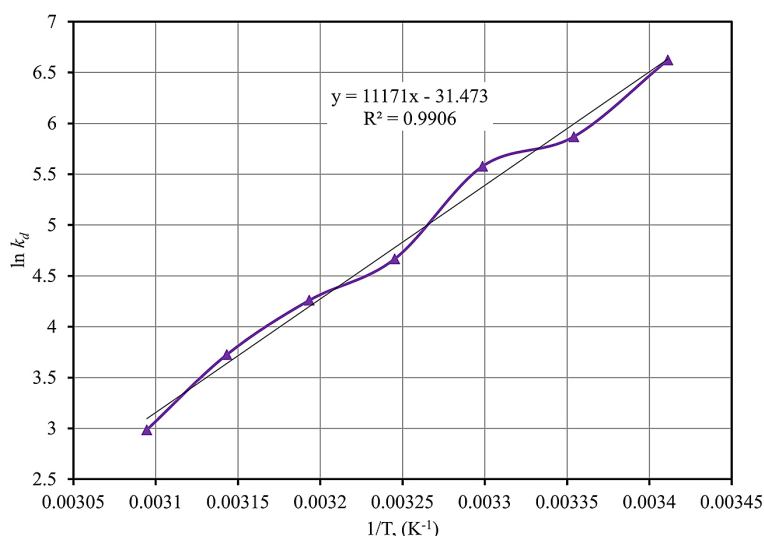


Figure 11. Thermodynamic behavior of vanadium adsorption using water hyacinth

Table 5. Thermodynamic functions of vanadium adsorption using leaves of water hyacinth plant

T(°C)	k_d	$\ln k_d$	ΔH (J/mol)	ΔS (J/mol.K)	ΔG (KJ/mol)
20	752.74	6.62	-92.88	-261.68	-16.16
25	353.83	5.87			-14.86
30	264.82	5.58			-13.55
35	106.35	4.67			-12.24
40	70.89	4.261			-10.93
45	41.53	3.73			-9.63
50	19.81	2.99			-8.32

thermodynamic study show the adsorption behavior over different temperatures, starting from 20 °C to 50 °C, where several important constants were calculated such as k_d , ΔH , ΔS , and ΔG , which provide information about the thermal energy, the change in entropy, and the Gibbs free energy change in the adsorption process (Alhamd et al., 2024b). The value of k_d , which represents the distribution constant of the adsorbent, shows a gradual decrease with increasing temperature, indicating a decrease in the ability of the adsorbent to absorb when the temperature rises. This decrease is consistent with the negative ΔH results at all temperatures, where ΔH is initially at -92.88 kJ/mol at 20 °C, and gradually decreases with increasing temperature, indicating that the process is exothermic and occurs in an endothermic reaction. ΔS , which represents the change in entropy, was negative in all cases, indicating that the process is directed towards a more orderly state upon adsorption, reflecting the decrease in disorder in the system after the reaction. As for the values of ΔG , which represents the free energy change of the Gibbs apparatus, they are all

negative, indicating that the adsorption process is spontaneous at all temperatures (Ali et al., 2023). It is also observed that ΔG becomes more negative with increasing temperature, indicating that the adsorption becomes more reactive at higher temperatures, reflecting the enhancement of the thermal reaction. Overall, these results indicate that adsorption is an endothermic, spontaneous process, and its efficiency decreases with increasing temperature (Ali et al., 2024a).

Adsorption isotherm

Three different model are used to describe adsorption isotherm, namely Langmuir isotherm model, Freundlich isotherm model and Temkin isotherm model. These models allow the identification of the most accurate mechanism for understanding the adsorption behavior in certain systems, which enhances the applications of environmental and industrial technology in removing pollutants from solutions. Table 6 shows the details of the isothermal models used in the current study.

Table 6. Details of isothermal models used in this study

Model	General form	Linear form	Slop	Intercept	Augmented parameter
Langmuir	$q_e = \frac{q_{max} \cdot K_L C_e}{1 + K_L C_e}$	$\frac{1}{q_e} = \frac{1}{q_{max} K_L C_e} + \frac{1}{q_{max}}$	$\frac{1}{q_{max} K_L}$	$\frac{1}{q_{max}}$	$R_L = \frac{1}{1 + K_L C_e}$
Freundlich	$q_e = K_F C_e^{\frac{1}{n}}$	$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e$	$\frac{1}{n}$	$\ln K_F$	–
Temkin	$q_e = \frac{RT}{b} \ln K_T C_e$	$q_e = \frac{RT}{b} \ln K_T + \frac{RT}{b} \ln C_e$	$\frac{RT}{b}$	$\frac{RT}{b} \ln K_T$	–

Note: q_e – equilibrium adsorption capacity of water hyacinth leaves (mg/g), C_e – vanadium adsorbed concentration at equilibrium (mg/g), q_{max} – constant of Langmuir model, represent maximum capacity (mg/g), K_L – constant of Langmuir model, represent the binding sites (L/mg), R_L – constant of Langmuir model, represent separation factor (-), K_F – constant of Freundlich model (mg/g)·(L/mg)^{1/n}, n – constant of Freundlich model, represent intensity of the adsorption (-), K_T – constant of Temkin model, represent equilibrium binding (L/mg), R – refer to ideal gas constant (8.3144 J/mol.K), b – constant of Temkin model (-), and T – refer to absolute temperature (K).

Figures 12–14 represent the results of applying isothermal models to the results obtained from the adsorption of vanadium ions using the leaves of the water hyacinth as an adsorbent, while Table 7 shows the values of the constants of these models. The results of the isothermal study show the application of three main models: Langmuir, Freundlich, and Temkin, which provide multiple insights into the adsorption mechanism and the nature of the interaction between the adsorbent and the pollutant (Shadhan et al., 2024). For Langmuir model, which is based on the assumption that adsorption occurs on a homogeneous surface with equal energy sites, the value of q_{max} represents the maximum adsorption capacity, i.e. the maximum mass of vanadium that can be adsorbed by the adsorbent when all sites are saturated. K_L is the Langmuir constant that indicates the affinity of the contaminant to

the adsorbent surface; a low value here indicates a relatively weak interaction between the adsorbent and vanadium, indicating that the ions do not bind easily or strongly to the surface of the water hyacinth leaves. The separation coefficient R_L indicates the suitability of adsorption, with a value between 0 and 1, meaning that adsorption is of the preferred type (Khudair et al., 2024).

For Freundlich model, which assumes that the surface is heterogeneous and adsorption occurs across sites of varying energy, the value of K_F represents the ability of the adsorbent to adsorb at a given concentration, with a low value indicating limited adsorption capacity. The value of n is a nonlinear indicator reflecting the intensity of adsorption; being greater than 1 indicates that adsorption is favorable but follows a heterogeneous distribution across the adsorbed sites, indicating that the surface is not homogeneous and that there

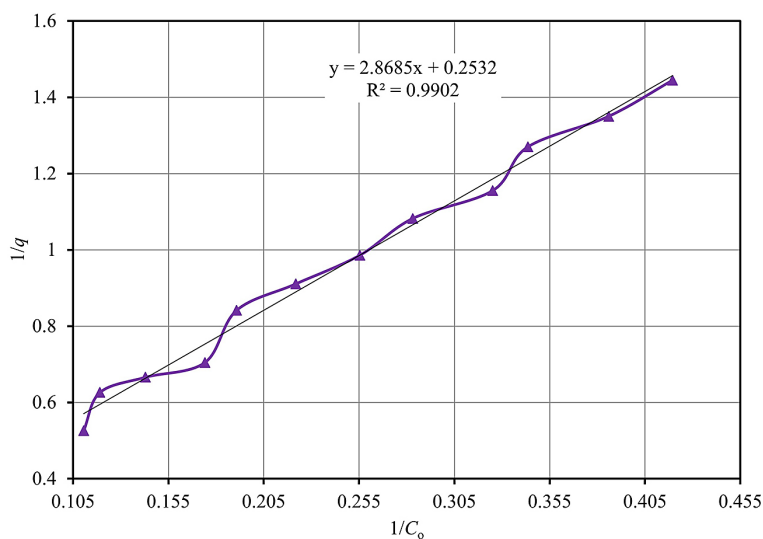


Figure 12. Langmuir isotherm model

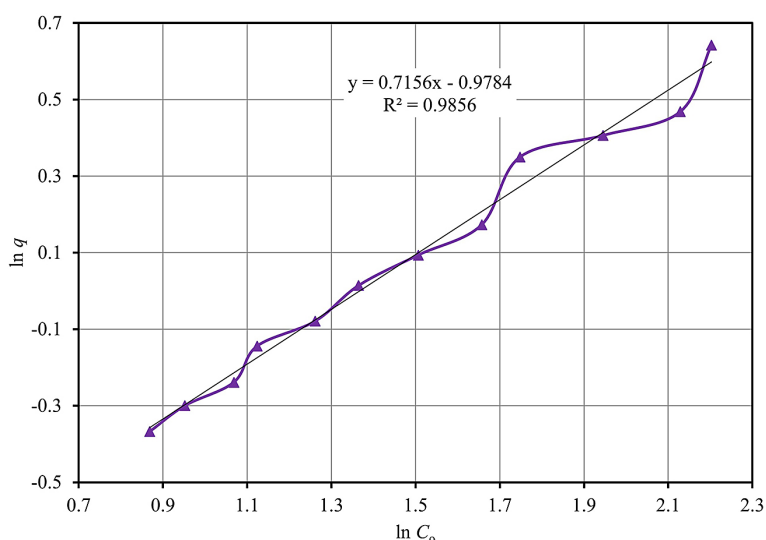


Figure 13. Freundlich isotherm model

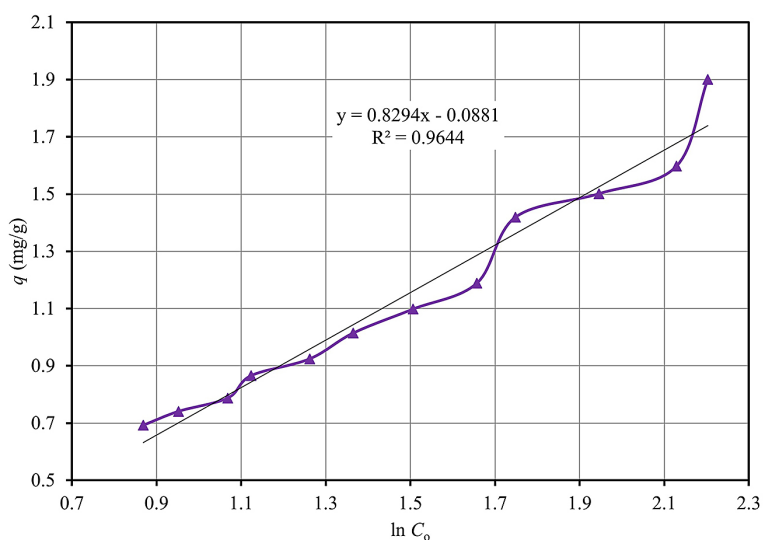


Figure 14. Temkin isotherm model

Table 7. Constants of isothermal models used in the current study

Langmuir				Freundlich			Temkin		
q_{max}	K_L	R_L	R^2	K_F	n	R^2	K_T	b	R^2
3.9494	0.0883	0.5312	0.9902	0.3759	1.3974	0.9856	0.8992	2.9387	0.9644

are sites with higher adsorption capacity than others (Ali et al., 2023). For the Temkin model, which takes into account the interactions between adsorbent molecules and thermal effects, the K_T value represents the interaction strength between the adsorbent and the pollutant, indicating relatively strong interactions. On the other hand, the b value reflects the thermal energy changes during adsorption, and indicates that the adsorption efficiency increases with the increase in the pollutant concentration, indicating a significant thermal effect on

the adsorption process. When comparing the models, the Langmuir model appears to best represent the data according to the high correlation coefficient value (0.9902), indicating that the adsorption process mainly occurs on a homogeneous surface with equally efficient sites. In contrast, the Freundlich model ($R^2 = 0.9856$) reflects the nature of a heterogeneous surface with diverse energy sites, while the Temkin model ($R^2 = 0.9644$) highlights the effects of thermal interactions, but they are less accurate in representing the data.

Adsorption kinetics

Four different models are used to describe adsorption kinetics, namely Pseudo first order model, Pseudo second order model, Elovich model and Intra-particle diffusion model. By using these kinetic models, the performance of adsorption processes can be developed more effectively in improving different applications. Table 8 shows the details of the kinetic models used in the current study. Figures 15–18 represent the results of applying kinetic models to the results obtained from the adsorption of vanadium ions using the leaves of the water hyacinth plant as an adsorbent, while Table 9 shows the values of the constants of these models. The results of the kinetic study show the application of four main models to analyze the adsorption behavior: the pseudo first order adsorption model, the pseudo second order adsorption model,

the Elovich model, and the intra-particle diffusion model. Firstly, in the pseudo first order model, k_1 represents the reaction rate at the onset of adsorption, while q_e represents the maximum adsorption capacity predicted by this model. According to the value of R^2 that does not exceed 0.78, this model is not suitable to represent the obtained experimental data isothermally. Also, the pseudo-second-order model, the values of both adsorption rate (k_2) and maximum adsorption capacity (q_e) at equilibrium are $0.0007 \text{ g}\cdot\text{mg}^{-1}\cdot\text{min}^{-1}$ and $3.1898 \text{ mg}\cdot\text{g}^{-1}$, respectively. Although the value of the R^2 of this model is 0.8241, which is higher than the previous model, the value is still low, so this model lack's reliability to describe the obtained data. On the other hand, it is clear that the Elovich model of 0.94 correlation coefficient and the intra-particle diffusion model of 0.99 correlation coefficient are the closest models to describe the obtained data, due to the closeness

Table 8. Details of kinetic models used in this study

Kinetic model	Differential form	Linear form	Slop	Intercept
Pseudo first order	$\frac{dq_t}{dt} = k_1(q_e - q_t)$	$\ln(q_e - q_t) = \ln q_e - k_1 t$	$-k_1$	$\ln q_e$
Pseudo second order	$\frac{dq_t}{dt} = k_2(q_e - q_t)^2$	$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t$	$\frac{1}{q_e}$	$\frac{1}{k_2 q_e^2}$
Elovich model	$\frac{dq_t}{dt} = \alpha e^{-\beta q_t}$	$q_t = \frac{1}{\beta} \ln t + \frac{1}{\beta} \ln \alpha \beta$	$\frac{1}{\beta}$	$\frac{1}{\beta} \ln \alpha \beta$
Intra-particle diffusion	–	$q_t = k_p t^{0.5} + C$	k_p	C

Note: q_e and q_t – adsorption capacity of water hyacinth leaves at equilibrium and any time, respectively (mg/g), k_1 – rate constant of pseudo first order kinetic model (1/min), k_2 – rate constant of pseudo second order kinetic model (g/mg·min), α – initial adsorption rate constant of Elovich kinetic model (mg/g.min), β – Desorption rate constant of Elovich kinetic model (g/mg), k_p – Rate constant of intra-particle diffusion model (mg/g·min^{0.5}), and C – boundary layer thickness.

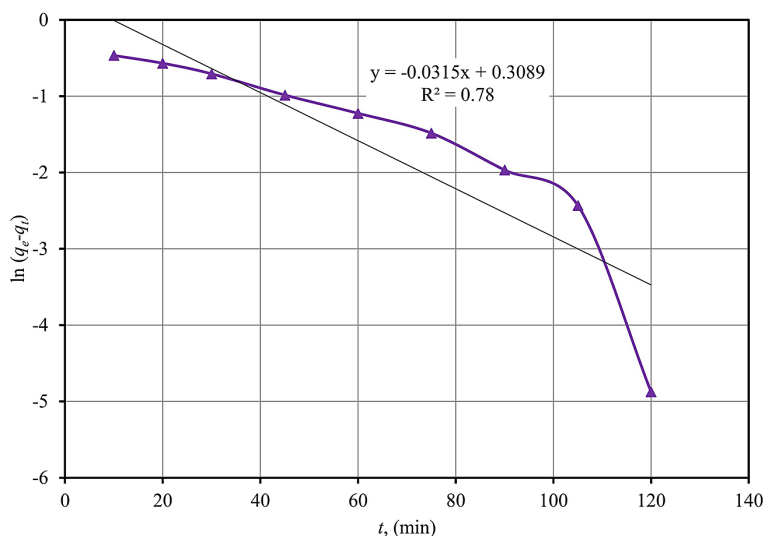


Figure 15. Pseudo-first-order kinetic model

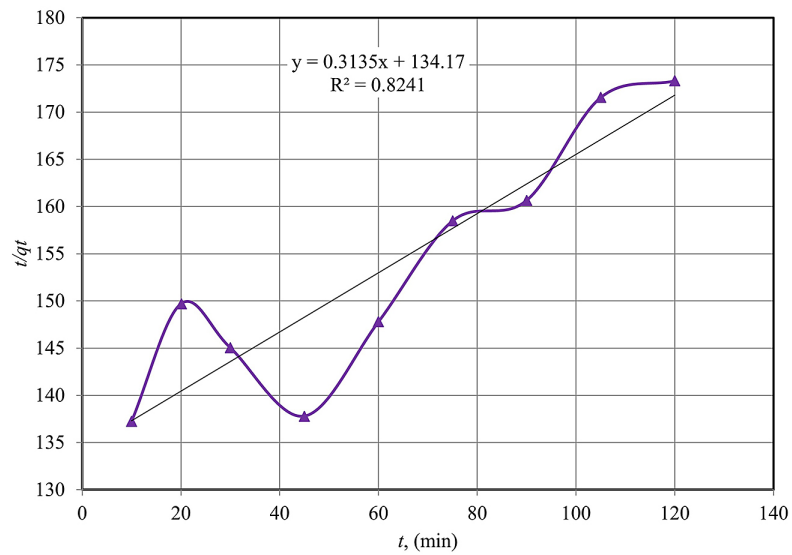


Figure 16. Pseudo-second-order kinetic model

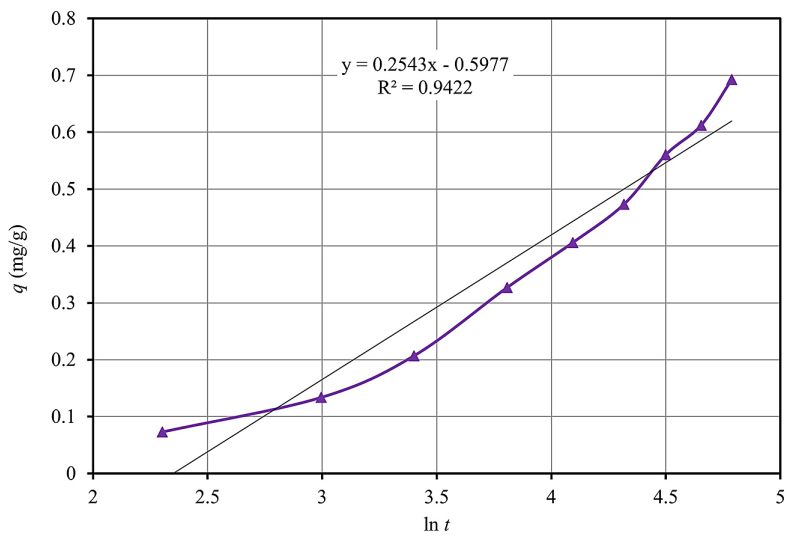


Figure 17. Elovich kinetic model

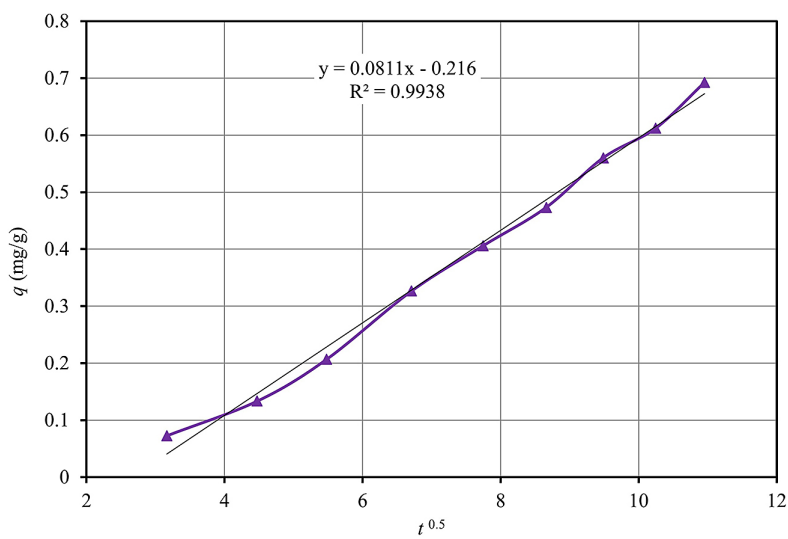


Figure 18. Intra-particle diffusion kinetic model

Table 9. Constants of kinetics models used in the current study

Intra-particle diffusion			Elovich model			Pseudo first order			Pseudo second order		
k_p	c	R^2	α	β	R^2	k_1	q_e	R^2	k_2	q_e	R^2
0.0811	- 0.216	0.9938	0.3749	0.2543	0.9422	0.0315	1.3619	0.78	7.3×10^{-4}	3.1898	0.8241

of the R^2 values to the ideal value (Alsarayreh et al., 2025b). It is noted that the values of the Elovich model constants, which represent the initial reaction rate (α) and the energy associated with the reaction (β) give the impression that the adsorption is of the chemical type and occurs at a balanced rate during the specified time period. As for the latter model, the value of the diffusion rate constant within the particles (k_p) and the value of the surface reaction (C) confirm that the adsorption is multi-stage, and that it does not start immediately at a high rate. Instead, there may be an initial delay or significant resistance to the transfer of vanadium ions to the surface of water hyacinth, indicating that the process may be governed by slow chemical reactions or that there is a repulsion between the adsorbed ions and the surface of the adsorbent in the initial stages of adsorption according to the negative value of the constant C . Thus, the best model that fit the obtained experimental data of vanadium adsorption using water hyacinth leaves is intra-particle diffusion model (Ali et al., 2023).

CONCLUSIONS

Although water hyacinth has adverse effects on aquatic organisms, the findings of the current study demonstrate that it can be utilized to purify the very water resources that it typically harms, offering a potential solution to the environmental challenges it causes. The leaves of water hyacinth (*Eichhornia crassipes*) demonstrated effectiveness and efficiency in removing vanadium ions, a toxic and harmful heavy metal, from polluted aqueous solutions. The adsorption experiments were carried out at a constant concentration of 10 ppm, and the maximum removal of vanadium ions using water hyacinth leaves was achieved, which exceeded 76%, at 6, 400 rpm, 11 g, 120 min, 20 °C for pH, agitation speed, water hyacinth leaf dosage, contact time, temperature, respectively. The adsorption exhibited an inverse relationship with temperature, while it was directly related to the other design parameters. Morphological analysis revealed that the surface area of the virgin water hyacinth leaves, which was 18.63 m²/g, was

largely occupied by the accumulation of vanadium ions on their surface. FTIR analysis revealed that the adsorbent contains multiple active groups capable of capturing and retaining the target element ions within its pores. Additionally, FESEM images indicated significant structural changes on the adsorption surface. The obtained results indicated that the Langmuir model was the best to represent the experimental data isothermally, while the intra-particle diffusion model was the best to describe the adsorption process of vanadium ions kinetically, according to the correlation coefficient values that exceeded 0.99 for both models. The adsorption process was found to be exothermic with low randomness, based on the obtained enthalpy and entropy values. Additionally, it was determined to be of a chemical nature and spontaneous across all studied temperatures. Consequently, positioning this plant near water bodies affected by oil refinery discharges would significantly contribute to the purification of contaminated water.

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