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Experimental Analysis of rGO-V_2O_5 Nanocomposites for Sustainable Water Remediation Completed with Bibliometric Analysis Toward Achieving Sustainable Development Goals (SDGs)

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ABSTRACT

This work integrates bibliometric analysis with laboratory experiments to develop nanotechnology-based water treatment technologies, aligning with Sustainable Development Goals (SDGs) on providing clean water and sanitation. A high-adsorption nanomaterial composed of reduced graphene oxide (rGO) doped with vanadium pentoxide (V_2O_5) was prepared using thermal doping and analyzed using XRD, FESEM, and FTIR techniques. This composite demonstrated the ability to remove 68.98% of methyl orange dye in just 30 minutes. Kinetic and adsorption studies showed conformed to a quasi-second-order kinetic model and a Langmuir single-layer adsorption model, indicating strong chemisorption and surface homogeneity. This high performance is attributed to the synergistic effect between V_2O_5 and rGO in contributing high surface area, improving electron transport, and enhancing effective sites for capturing dye molecules. This nanocomposite is a sustainable and economical option for supporting the smart architecture of urban water systems, contributing to SDGs.

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1. INTRODUCTION

The development of nanomaterials has become a major trend in materials science and environmental engineering. These structures come in a variety of shapes, such as rods, spheres, sheets, wires, and nanocomposites, each with unique physicochemical properties that influence adsorption, catalysis, and electronic characteristics. These morphological variations allow for precise control of surface area, porosity, and charge distribution. These are the key factors for enhancing the interaction between the adsorbent and pollutant particles. Consequently, interest in these materials has accelerated as researchers strive to produce versatile, efficient, and environmentally friendly nanomaterials for pollution treatment (Kolya & Kang, 2024; Homaeigohar, 2020). It is also closely associated with Sustainable Development Goals (SDGs), especially SDG number 6, that emphasise on the availability of safe drinking water and sanitation and the advancement of technology to ensure the quality of water. Although digital sensor-based automatic water monitoring systems are prevalent at present, the efficiency is the result of nanomaterials with strong adhesion, as well as accurate pollutant assessment (Kolya & Kang, 2024). Growing industries play a significant role in increasing water pollution due to the unregulated discharge of synthetic dyes. These dyes are chemically stable, have strong colors, and are toxic to aquatic life (Deletic & Wang, 2019; Homaeigohar, 2020). Methyl orange (MO) is one of the most prevalent dyes, persisting in wastewater for extended periods due to its resistance to natural degradation. It is also widely used in the textile, paper, and plastics industries. Exposure to MO at concentrations exceeding 50 mg/kg can lead to serious health problems (Homaeigohar, 2020; Juzsakova *et al*., 2023).

Traditional wastewater treatment methods, such as biodegradation (Gong *et al*., 2013), biosorption (Ramutshatsha-Makhwedzha *et al*., 2022), membrane separation, and acoustic treatment (Nguyen *et al*., 2018), face difficulties in achieving complete pollutant removal due to operational limitations (Lv *et al*., 2019). In contrast, adsorption is an efficient, simple, and low-cost option, making it a preferred method for industrial wastewater treatment (Ramutshatsha-Makhwedzha *et al*., 2022; Lv *et al*., 2019). Among the nanomaterials used as adsorbents, metal oxides such as vanadium pentoxide (V_2O_5), aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), and iron oxide (Fe_2O_3) have demonstrated remarkable adsorption capacity and catalytic activity (Ezzatfar *et al*., 2022; Hien *et al*., 2021; Xie *et al*., 2021; Jaseela *et al*., 2019; Chaukura *et al*., 2017). V_2O_5 is characterized by broad oxidizing capabilities, high catalytic efficiency, and excellent stability across a wide range of pH values, which confirms its strength and effectiveness in environmental applications (Abdul-Zahra & Rasheed, 2023). Graphene-based materials, particularly reduced graphene oxide (rGO), offer a large surface area of approximately 2600 m^2/g, along with high electrical conductivity and functional groups that enable π-π interactions and hydrogen bonding (Shi *et al*., 2022; Sharma *et al*., 2013).

This research presents the synthesis and characterization of a vanadium pentoxide-reduced graphene oxide (rGO-V_2O_5) nanocomposite using thermal grafting. This composite combines the oxidizing power of V_2O_5 with the large surface area and conductivity of rGO, resulting in a synergistic structure that enhances adsorption, electron transfer, and chemical stability. These properties are expected to contribute to faster and more efficient dye removal via chemisorption mechanisms.

The novelty of this work lies in the integration of vanadium-based metal oxide with graphene nanosheets to form a multifunctional hybrid structure optimized for sustainable and smart urban water remediation. Furthermore, the research is supported by bibliometric

analysis, which identifies growing global attention toward graphene–metal oxide nanostructures for wastewater treatment, validating the relevance and timeliness of this study within current scientific trends.

2. METHODS

2.1. Materials

Ammonium-metavanadate (NH_4VO_5, 99.99%)., cetyltrimethylammonium bromide (CTAB, $C_{19}H_{42}BrN$, 99%)., and ethanol (99.8% purity) were obtained from Merck Kft., Budapest, Hungary., Sodium hydroxide (NaOH) from Merck Kft., Hydrochloric acid (HCl), from Merck Kft., Reduced graphene oxides nanosheet was purchased from USA, and used for the experiments in the present research.

2.2. Preparation of vanadium pentoxide nanoparticles

Vanadium pentoxide nanoparticles were prepared using the hydrothermal method. In this process, 0.1 g ammonium metavanadate and 0.1 g cetyltrimethylammonium bromide (CTAB) were dissolved in the mixed solvent of 7:3 ratios of ethanol and water to 100 mL. The resulting acid extract was carefully neutralized with nitric acid, and the pH was adjusted to 2.5. The reaction mixture was refluxed at 80 °C for 6 h. The formed precipitate was orange and washed ten times with distilled water and then with ethyl alcohol. The product was dried in an oven at 90 °C for nearly 1 h and calcined at 500 °C for 2 h The formation of vanadium pentoxide is shown in Equation (1) (Sharma *et al*., 2013):

$$2NH_4VO_3 + 2HNO_3 + nH_2O \xrightarrow{Ethanol/CTAB} V_2O_5nH_2O + 2NH_4NO_3 + H_2O \quad (1)$$

2.3. Synthesis of vanadium pentoxide modified (Juzsakova *et al*., 2023) nanosheet

The nanocomposite was prepared by doping vanadium pentoxide (V_2O_5) onto reduced graphene oxide (Juzsakova *et al*., 2023). 5 wt% V_2O was introduced into the reduced graphene surface, and the resulting mixture was blended using sonication for 15 min. The mixture was carefully moved to a stainless-steel Teflon autoclave reactor and cured at 200 °C in a muffle furnace.

2.4. Characterization of prepared samples

Characterization of prepared samples techniques X-ray diffraction (XRD) Patterns were recorded on a Shimadzu X-ray 6100 produced in Japan with a Cu-Kα (λ = 0.14506 nm) radiation source at 35 kV and 10 mA. The surface morphology of the nanoparticle was investigated by a Field Emission Scanning Electron Microscope (FESEM) Instrument, FEI Company product made in Poland.

2.5. Dye adsorption experiments

The absorbance at its maximum of methyl orange dissolved in water at a concentration of 20 mg/L was measured using a UV-Visible spectrophotometer (FEI Company, Poland) within the wavelength range of 400 to 700 nm. Detailed information regarding the adsorption experiment is explained elsewhere (Ragadhita & Nandiyanto, 2021; Nandiyanto *et al*., 2023a; Nandiyanto *et al*., 2023b).

The peak absorbance (λ max) was found at 464 nm. The stock solution was subsequently employed to prepare calibration standards for UV-Vis analysis at various concentrations of methyl orange (Obayomi *et al*., 2023; Shankar *et al*., 2024). The depollution experiments for

methyl orange were conducted in batch mode as previously described (Obayomi *et al*., 2023; Shankar *et al*., 2024). The stock solutions of methyl orange were diluted with distilled water, and the pH value of the dye solution was adjusted to pH = 7 by 0.1 N NaOH or 0.1 N HCl. In each experiment, 20 mg of metal oxides modified rGO was mixed with 30 mL of dye solution (20 mg/L). The adsorption of methyl orange was studied by investigating the contact time. The adsorption process was stopped, and samples were taken for separation using a centrifuge. A UV-Visible spectrometer was employed to measure the dye concentration in the supernatant. The absorbance determined the equilibrium adsorption capacity of removal at 464 nm. Removal efficiency (RE%) of methyl orange was computed by comparing the initial and final concentrations as shown in Equation (2) (Obayomi *et al*., 2023; Shankar *et al*., 2024):

$$RE = \left(\frac{C_0 - C_t}{C_0}\right) \cdot 100\ \% \quad (2)$$

where C_0 is the initial concentration (mg/L) of MO, (Khan *et al*., 2022) is the concentration in mg/L of MO at time *t*, and qt is the MO adsorbed, calculated from Equation (3) (Obayomi *et al*., 2023; Shankar *et al*., 2024):

$$q_t = \frac{(C_\circ - C_t)}{m} \cdot V \quad (3)$$

where *V* was the volume of the solution (L), m was the mass of the prepared vanadia-modified graphene (g), and qt denoted the adsorption amount of MO at time *t* (mg/g). Triplicates were carried out under the same conditions, and averages were determined and illustrated in the paper. **Figure 1** explains the processes of the lead ions removal from aqueous solution.

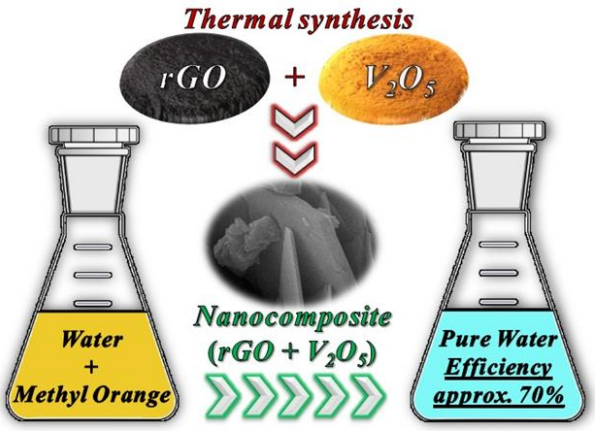

Figure 1. The nano sorbent process for lead ion removal from aqueous solution.

3. RESULTS AND DISCUSSION

3.1. XRD Results

The X-ray diffraction (XRD) technique identifies and understands the crystalline structure and growth characteristics of reduced graphene oxides (Juzsakova *et al*., 2023). The XRD pattern of the samples, depicted in **Figure 2**, shows a typical diffraction peak that corresponds to the (002) plane, which is highly indicative of reduced graphene oxide (Juzsakova *et al*., 2023; Rasheed *et al*., 2021). This peak usually appears around 26° (2θ), suggesting partial restoration of the graphitic structure after the reduction process. This peak corresponds to the highly ordered layered structure exhibiting an interlayer spacing of 0.33 nm along the (002) orientation, confirming the presence of a well-organized hexagonal lattice. The presence of the (002) peak in the reduced graphene oxide samples suggests that the reduction process has successfully reintroduced some degree of graphitic ordering. However,

residual defects and oxygen groups may still exist. This partial restoration is characteristic of rGO, where the hexagonal structure is reformed but not to the same extent as in pristine graphite. **Figure 2** illustrates the primary diffraction peaks of V_2O_5 as prepared at 90 °C, with 2θ values of 15.62, 31.4, 40.9, 50.5, and 58.8°. These peaks match the characteristic diffraction patterns of the (200), (110), (310), (002), and (611) planes of V_2O_5, respectively (Aldabagh *et al*., 2024).

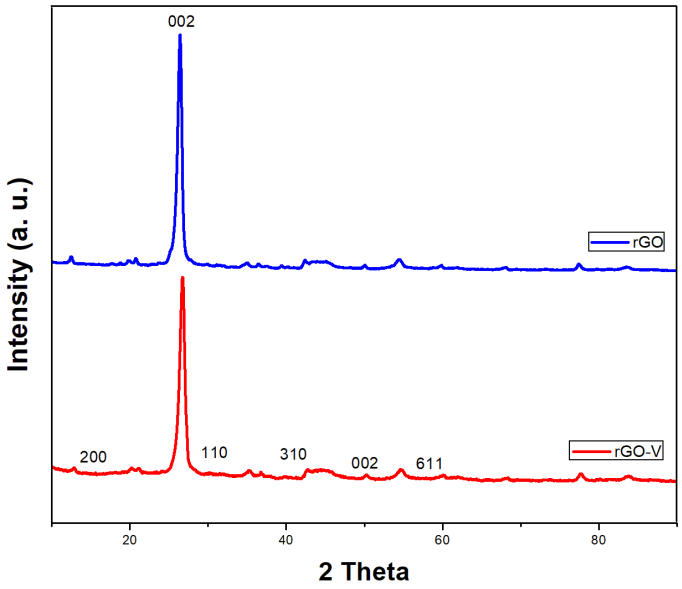

Figure 2. The XRD analysis of rGO and V_2O_5 modified rGO.

3.2. FESEM and EDX results

Figure 3 illustrates the morphology of a few-layer reduced graphene oxide (Juzsakova *et al*., 2023) nanosheet before oxidation, representing a thin, homogeneous layer of reduced graphene oxide film. **Figure 3a** is the low magnification of the SEM image, whereas **Figures 3b and 3c** are the high magnification of the SEM images. The images also show that the few-layer reduced graphene oxide material contains multiple layers arranged on each other in a paper-like structure, with wavy folded sheets. Moreover, this material has a sharp edge, indicating the successful reduction process while maintaining a layered morphology. These figures show images of reduced graphene oxide nanosheets with more stacked layers, with larger folds and wrinkles. This indicates that the reduction process significantly influences the structural arrangement, increasing interlayer spacing and forming thicker multilayered structures.

Figure 4 shows FESEM images of vanadia nanosize and a nanocomposite of reduced graphene oxide and vanadium pentoxide (V_2O_5) nanosheets. **Figure 4a** shows an FE-SEM image of vanadium pentoxides, which were prepared in small sheets with a nanoscale between 49 and 68 nm. **Figures 4b and c** illustrate the size and shape of the V_2O_5 nanoparticles intercalated with the reduced graphene oxide nanosheets. The average diameter of the V_2O_5 nanoparticles was determined to be 59 nm. Successful incorporation of V_2O_5 nanoparticles within the reduced graphene oxide matrix enhances the composite's structural stability and surface area, potentially improving its electrochemical performance.

EDX analysis confirmed the elemental composition of reduced graphene oxide (rGO, **Table 1**) and the vanadia-functionalized composite (rGO-V, **Table 2**). Following functionalization, the carbon content decreased from 90.9 to 78.3 wt%, while the oxygen content increased from 9.1 to 14.4 wt%. Furthermore, vanadium was

detected in the composite at 4.3 wt%. These compositional changes indicate the successful integration of vanadia species onto the rGO surface.

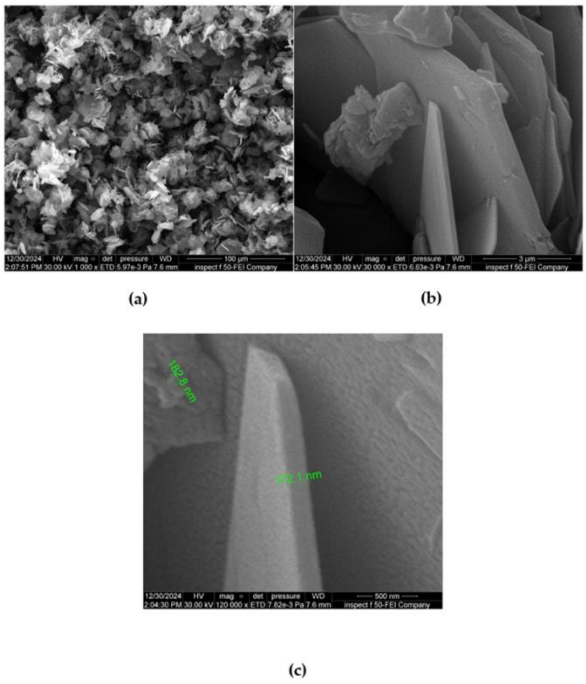

Figure 3. FESEM images of rGO nanosheet at several magnifications of (a) 100 µm, (b) 3 µm, and (c) 500 nm.

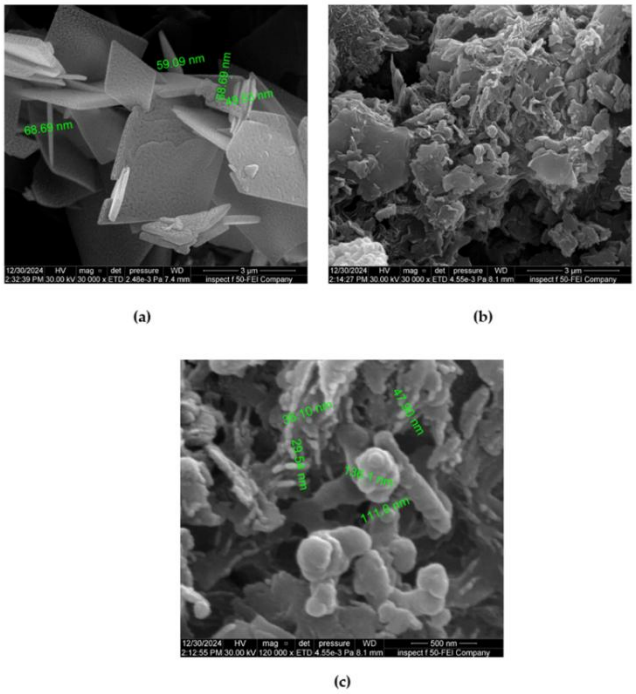

Figure 4. FESEM image of vanadium pentoxide nanosize (a) FE-SEM images of V_2O_5-rGO nanocomposite at several magnifications of 3 µm (b), and 500 nm (c).

Table 1. EDX results of rGO.

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	93.0	0.8	90.9	0.8
O	7.0	0.7	9.1	0.9

Table 2. EDX results of rGO-doped vanadium pentoxide.

Element	Atomic %	Atomic % Error	Weight %	Weight % Error
C	85.9	1.3	78.3	1.2
O	09.9	0.7	14.4	0.9
Mg	0.2	0.1	0.4	0.1
Al	0.0	0.0	0.1	0.1
Si	0.2	0.0	0.3	0.1
Cl	0.3	0.0	0.8	0.1
K	0.3	0.1	1.0	0.2
V	3.6	0.0	4.3	0.1
Ni	0.5	0.1	2.3	0.4

3.3. FTIR Spectra for rGO, rGO-V, and rGO-V after Methyl Orange Adsorption

The FTIR spectra of fresh reduced graphene oxide (Juzsakova *et al*., 2023), vanadia-loaded reduced graphene oxide (rGO–V), and the nanosorbent after MO adsorption (rGO–V+MO) (see **Figure 5**) provide compelling evidence for the successful synthesis of the hybrid nanomaterial and subsequent dye adsorption, while also elucidating the underlying chemical interactions. Detailed information on how to read FTIR is explained elsewhere (Nandiyanto *et al*., 2019; Nandiyanto *et al*., 2023c).

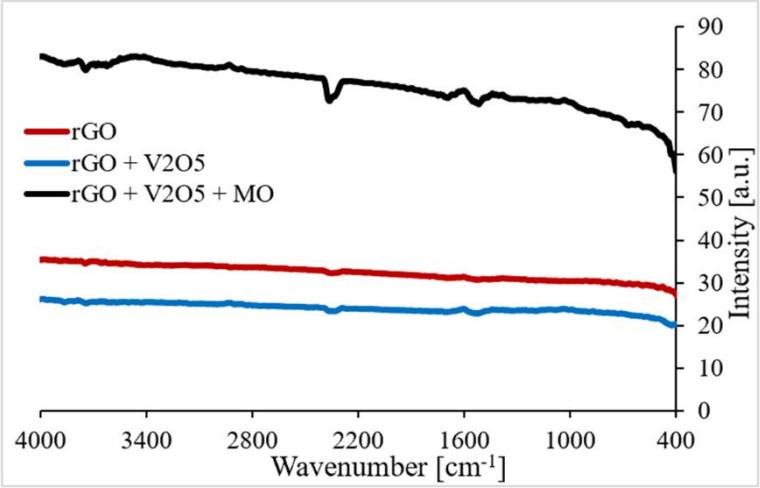

Figure 5. FTIR spectra of pristine rGO nanosheets, vanadia-modified rGO (rGO-V), and rGO-V after MO adsorption.

The transformation from the pristine rGO spectrum to that of rGO–V confirms two fundamental processes:

(i) Reduction of the graph- oxide: The impacts of oxygen-containing feature band strength are found in **Figure 5**. Some characteristic bands, such as that at 1720 cm^{-1}, being due to C=O stretching and the C–OH bending band of 1220 cm^{-1}, or finally the C–O stretch vibration from 1050 cm^{-1}, all either dropped radically in intensity or disappeared altogether (**Figure 5**). This clearly shows that GO has undergone efficient chemical reduction to rGO through treatment with V_2O_5; these changes are traceable in parallel with the load-carrying out procedure.

(ii) Species introduction: New characteristic vibration peaks arose after vanadia loading, indicating that products such as V_2O_5 were formed. A sharp, intense band beginning at 1020 cm^{-1} corresponds to the out-of-plane stretching mode of terminal V=O; additional

bands within a range of 600-800 cm^{-1} can all be attributed to V–O–V bridging vibrations between different oxide units in vanadialatis. Also, the O–H stretching band (3200- finally split into two parts: a broadly shaped part beginning from around 3200 cm^{-1} and extending up to 3400 cm^{-1}; a sharp band between these two ranges of values soon developed Its (**Figure 5**), clearly pointing out changes in shape and intensity that are characteristic of a V_2O_5 nanoparticle's interaction with edges of residual hydroxyl groupson rGO surface. Collectively, these spectral modifications confirm both the reduction of GO and the successful immobilization of V_2O_5 on the carbonaceous matrix.

(iii) The spectral changes after exposure to MO confirm successful adsorption and provide clues about the adsorption mechanism: The broadening of the O-H stretching peak suggests that hydrogen bonding between the dye and hydroxyl groups on the composite surface is also a contributing factor to the adsorption process. The spectrum of the rGO-V+MO composite shows new peaks characteristic of methyl orange. A peak in the range of 1550-1600 cm^{-1} can be assigned to the azo group (-N=N-) stretching vibration (though it may overlap with the C=C stretch from the carbon backbone). Peaks in the regions 1000-1100 and 1150-1250 cm^{-1} indicate the sulfonate group ($-SO_3^-$) vibrations. The most significant evidence is the shift and decrease in intensity of the vanadia peaks (V=O at 1020 cm^{-1} and V-O-V at 600-800 cm^{-1}). This indicates a strong chemical interaction, likely through coordination between the dye molecules (lone pairs of electrons on the azo group (-N=N-) and sulfonate group ($-SO_3^-$), which react as Lewis bases) and the vanadium (empty orbitals which react as Lewis acids) sites on the nanoparticle surface. The broadening of the O-H stretching peak suggests that hydrogen bonding between the dye and hydroxyl groups on the composite surface is also a contributing factor to the adsorption process (see **Figure 5**).

Moreover, the broadening of the O–H stretching band (3200–3400 cm^{-1}) after adsorption supports the involvement of hydrogen bonding between the hydroxyl groups of the composite and functional moieties of the dye. This dual interaction—Lewis acid–base coordination and hydrogen bonding—facilitates adsorption and alters the local electron density around vanadium, thereby weakening the V=O bond. The resulting downshift and diminished intensity of the V=O stretching band completely agree with the observed spectral changes (**Figure 6**).

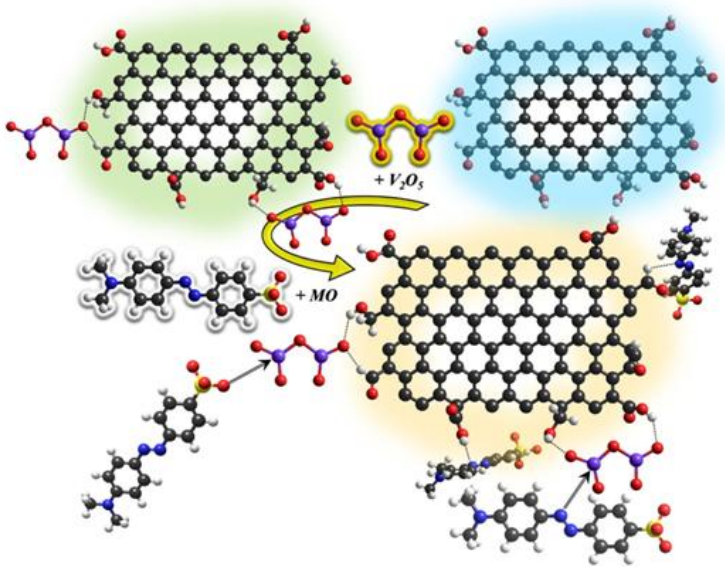

Figure 6. Proposed mechanism of MO adsorption over rGO-V.

3.4. Adsorption Results of MO removal using rGO and rGO-V

After preparing reduced graphene oxide (rGO) and a vanadium pentoxide-supported reduced graphene oxide composite (rGO-V), a study was conducted to evaluate their ability to remove methyl orange dye from water. Methyl orange is an organic dye that contributes to aquatic pollution and harms aquatic organisms. This dye is a common organic pollutant that increases water pollution levels and negatively impacts aquatic organisms, making its treatment essential to mitigating its environmental risks. The experiment was carried out using the following formulations: a 20 mg/L initial concentration of methyl orange dye and a 30 mL solution volume for each experiment. For a period of 50 minutes, absorption was monitored every ten minutes using a UV-Vis spectrophotometer. The experiments used an initial concentration of methyl orange of 20 mg/L, with a solution volume of 30 mL per experiment. The adsorption process was monitored for 50 minutes, with absorbance measured by UV-Vis spectroscopy every 10 minutes. The amount of nanomaterial used was 10 mg, and all tests were conducted at a constant temperature of 25 °C. These conditions were chosen to closely reflect practical applications in water treatment. The results shown in **Figures 7 and 8** and **Table 3** demonstrate the gradual decrease in methyl orange concentration over the adsorption time, reaching 9.48 mg/L after 30 minutes using rGO and 6.40 mg/L using rGO-V. Figure 8 also shows the increased removal efficiency after 30 minutes, reaching 53.09% for rGO and 62.20% for rGO-V, highlighting the superiority of the vanadium-doped compound in the adsorption process. This study confirms the efficiency of the nano-adsorbent in removing methyl orange dye, highlighting its potential for application in the treatment of dye-contaminated water. Note that doping V_2O_5 nanosize over rGO resulted in better methyl orange removal results from water compared to reduced graphene oxide.

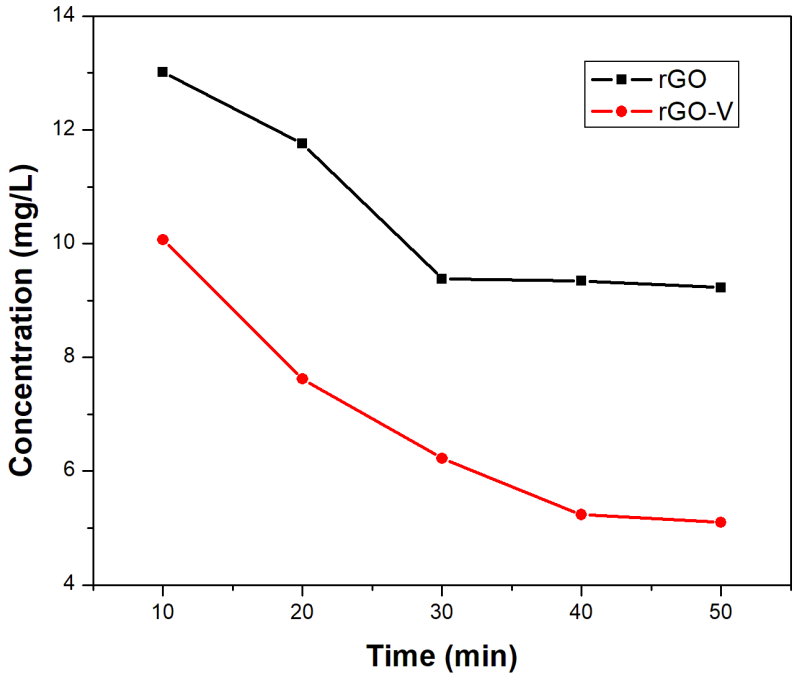

Figure 7. Change in MO concentration against time over rGO and rGO-V nanosheets.

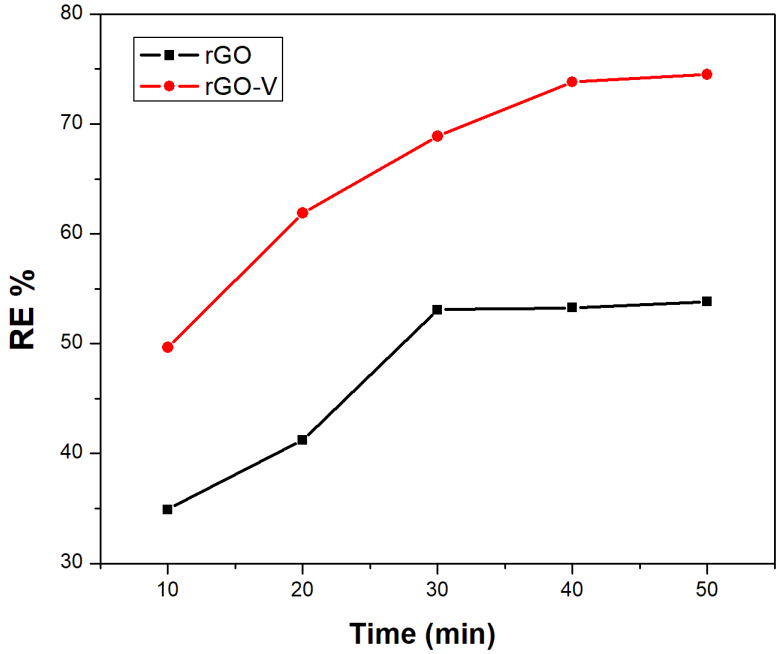

Figure 8. Time-Dependent Removal Efficiency (RE%) of MO from Water Using rGO and rGO-V nanosheets.

Table 3. MO removal efficiency and reduction in concentration using rGO and rGO-V.

	r-GO-V				**r-GO**		
T (min)	**C (mg/L)**	**RE %**	**qe mg/g**	**T (min)**	**C (mg/L)**	**RE %**	**qe mg/g**
10	10.11	49.40	29.64	10	13.61	31.91	19.15
20	7.65	61.71	37.02	20	11.31	43.41	26.046
30	6.40	67.95	40.77	30	9.48	52.59	31.55
40	6.13	69.33	41.59	40	9.256	53.71	32.22
50	5.12	74.39	44.63	50	9.15	54.21	32.52

Finally, the effect of pH on the removal efficiency of lead ions from aqueous solutions using the synthesized nano-adsorbent vanadia-doped graphene oxide was systematically investigated across a pH range of 3, 5, 7, 9, and 11, as shown in **Figure 9**. After statistical processing, how acidic conditions by the lead ion adsorption effect are best, appeared at pH 5 maximum removal efficiency is 82%, trumping that achieved at pH 3 with 78%. But under neutral and alkaline conditions (pH 7, 9, and 11), adsorption efficiencies were all relatively low. Specifically, the least removal was observed under pH 9 and 11. Therefore, it goes without saying that if one wishes to remove lead ions, then they should tune a synthesized nano-adsorbent toward moderate acidity. All these effects are the central issues around which this research has been built. This is because one of the most valuable features in lead remediation from polluted waters with powdered ash as sorbent material (hereafter, 'nano-adsorbent') comes from its increased surface charge interactions, facilitating absorption and adsorption of ions. Based on these findings, it is evident that the application of the nano-adsorbent must be put at each pH rather than using creation (for instance, at lower pH) to reach better lead removal from water polluted with real estate waste site effluents.

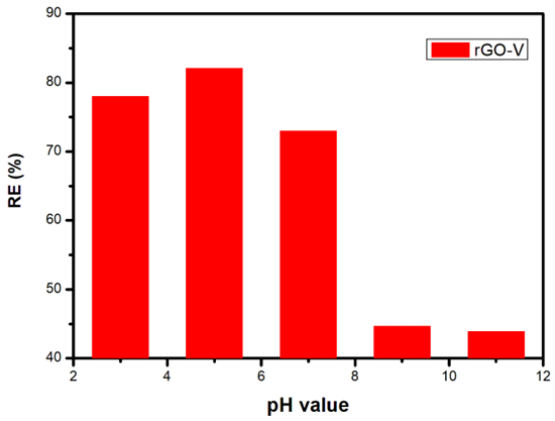

Figure 9. Influence of Solution pH on the Lead Ion Removal Efficiency Using rGO-V Nano-Adsorbent.

3.5. Reusability of the Nano-Adsorbent for Lead Ion Removal

This phase of the research aimed to accurately verify the reusability of the adsorbent nanomaterial through a series of regeneration steps that ensure its continued effectiveness in adsorption processes for extended periods. The regeneration process began by dispersing the nanoparticles in distilled water and subjecting them to rapid shaking, followed by centrifugation to separate them from the liquid. Repeating the washing process two or more times helped to efficiently remove any remaining impurities. Next, the nanomaterial was placed in a 0.1 M sodium hydroxide solution with continuous stirring to release the adsorbed lead ions. The particles were then collected again by centrifugation. To remove any remaining organic matter adhering to the surface, the particles were mixed with a 20% ethanol solution and thoroughly shaken before being subjected to another centrifugation. The washing step with distilled water was repeated to ensure the complete removal of any solvent residues. After washing, the regenerated adsorbent was dried in a 100 °C oven to restore its physical and chemical properties and prepare it for further adsorption cycles. These steps are an essential part of the repeated reactivation process that allows these materials to be used efficiently to remove lead ions from aqueous solutions (as shown in **Figure 10**). Tests involving four consecutive adsorption and release cycles showed that the nanomaterial retained approximately 74% of its original efficiency after regeneration, reflecting stable performance during the first three cycles, before a gradual decrease in efficiency began with repeated use.

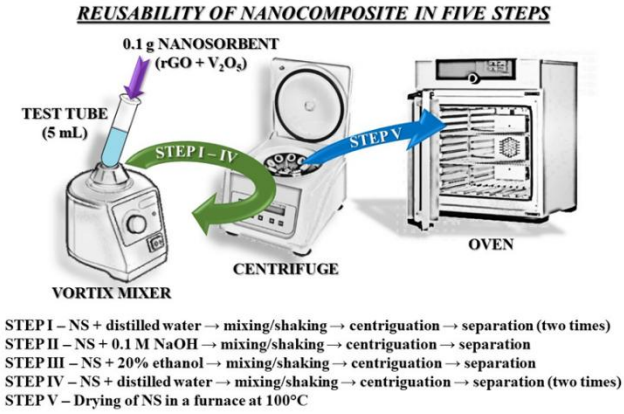

Figure 10. Regeneration procedure of the nanosorbent for repeated Lead ion removal from aqueous solutions.

3.6. Adsorption kinetics of MO removal using r-GO and r-GO-V.

The pseudo-first order reaction rate constant was determined using Equation (4) (Aldabagh *et al*., 2024):

$$\log(qe - qt) = \log qe - k_1 t / 2.303 \quad (4)$$

where *qe* (mg/g) and *qt*(mg/g) are the adsorption capacities of MO at the equilibrium and at time t(min), respectively, and k_1 is the first-order rate constant (min^{-1}). Slope and intercepts of plots of l*og(qe-qt)* and *t* were used to determine k_1 (Mashhour *et al*., 2024) for both r-GO and vanadia-modified r-GO (r-GO-V). As demonstrated in **Figure 11**, the pseudo-first order reaction for the r-GO and r-GO-V has the coefficient of determination R^2 of 0.8174 and 0.8995, respectively, as in **Figures 11 (a and b)**. The pseudo-second order equation, which depends on the equilibrium capacity adsorption, can be represented by Equation (5).

$$t/qt = 1/k_2 q^2 e + t/qe \quad (5)$$

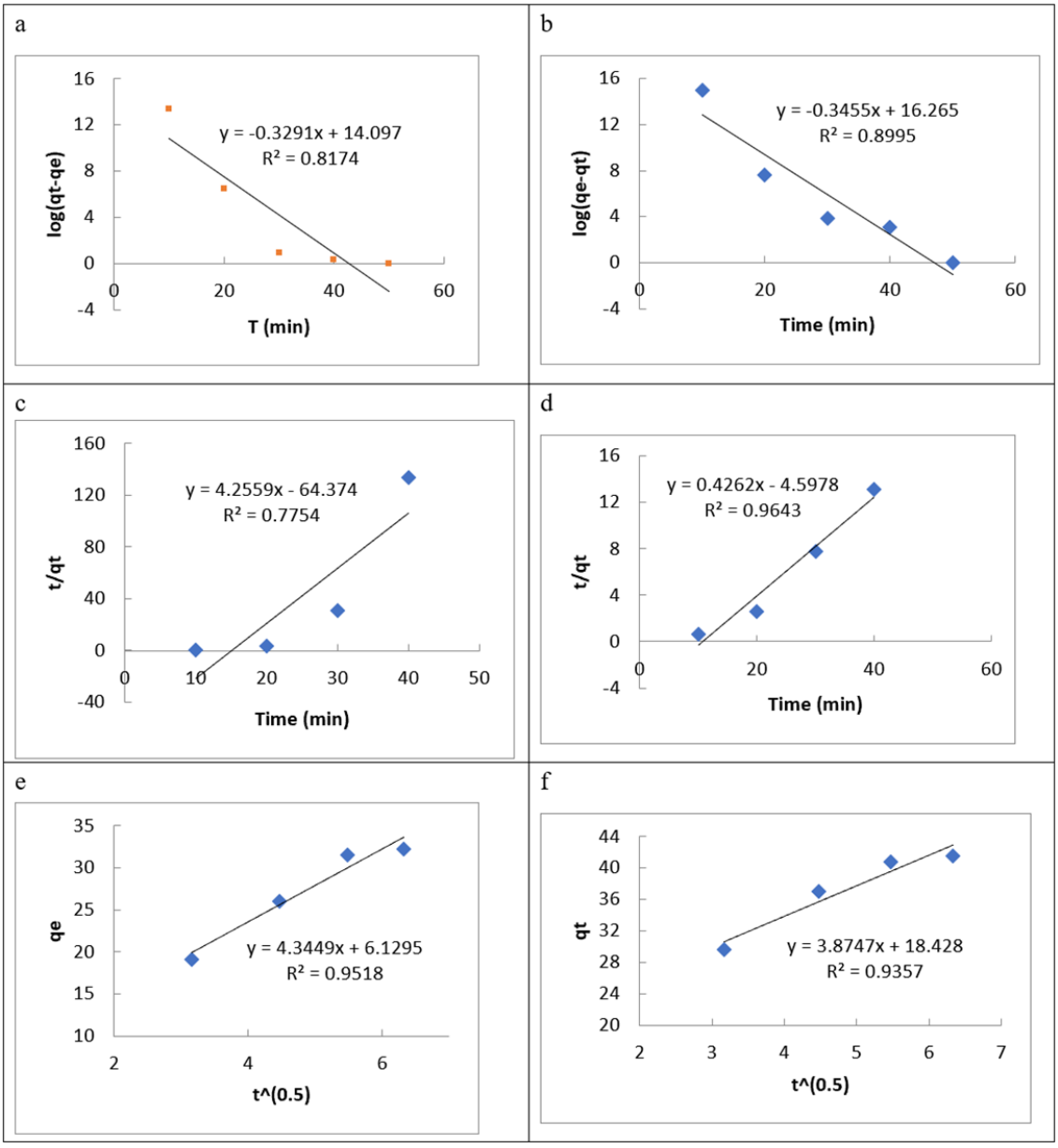

Figure 11. Pseudo-first-order plot (a, b), pseudo-second-order plot (c, d), intra-particle diffusion plot (e, d) for MO adsorption onto r-GO and a-GO-V, respectively.

In Equation (5), k_2 refers to the second-order adsorption rate constant (g/mg · min). The slopes and intercepts of the straight-line plots of *t/qt* versus *t* were used to obtain the values of (Mashhour *et al*., 2024) and k_2. The sorption of MO onto both reduced graphene oxide (r-GO) and vanadia-modified reduced graphene oxide (r-GO-V) was described by the pseudo-second order model. The pseudo-second order model represents a better fit of the experimental data of MO adsorption since the determination coefficients R^2 for r-GO-V were higher than those for the pseudo-first order model for r-GO-V. However, the R^2 of the pseudo-second order model for r-GO-V is higher than that for r-GO. (R^2 = 0.9643 and 0.7754) (**Figures 12 (c and d**)). The diffusion model was used to determine the mechanism of diffusion in the system, using the parameters obtained from the third kinetic intraparticle diffusion model established by Weber-Morris. The initial intra-particle diffusion rate can be expressed as Equation (6) (Aldabagh *et al*., 2024).

$$qt = K_d\, t\, 1/2 + C \qquad (6)$$

According to the intra-particle diffusion model, the diffusion constant K_d (mg/g·min$^{1/2}$) and the intercept C are critical parameters describing the adsorption mechanism. In this framework, the amount of adsorbate the sorbent *qt* takes up is expected to vary linearly with the square root of contact time $t^{1/2}$. The results of this kinetic model are illustrated in **Figures 12 (e) and 12(f)**. The K_d values were determined from the slopes of the plots of *qt* versus $t^{1/2}$. The linear plots did not intersect the origin, with correlation coefficients R^2 of 0.9518 for r-GO and 0.9357 for r-GO-V, indicating that intra-particle diffusion is not the sole rate-limiting step.

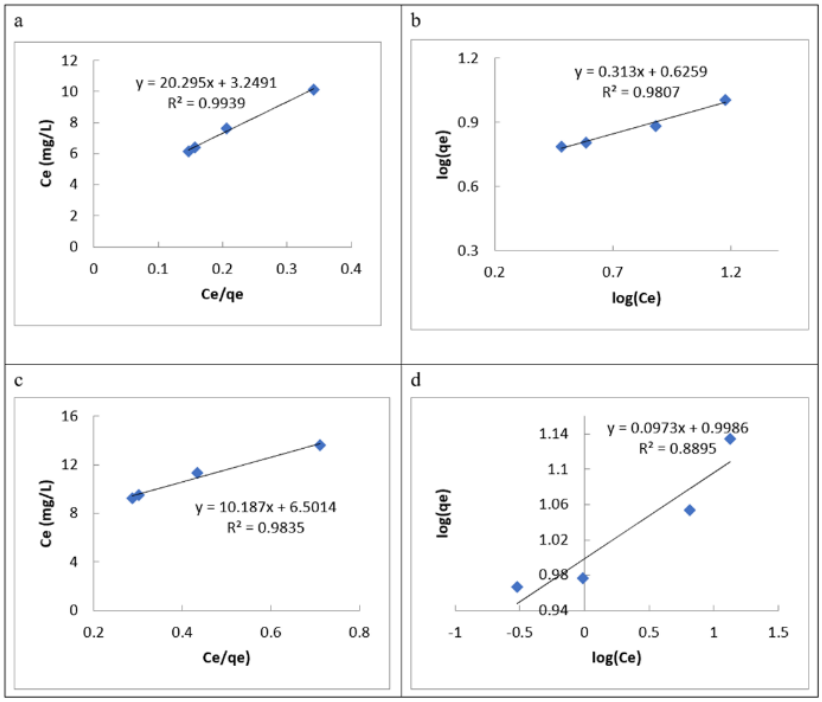

Figure 12. Isotherm models for MO adsorption on r-GO and r-GO-V (**a and b**); Langmuir and Freundlich isotherm models for MO adsorption on r-GO (c and d); Langmuir and Freundlich isotherm models for MO adsorption on r-GO-V.

The deviation from the origin suggests the influence of boundary layer effects, as reflected by the intercept values. Specifically, the *C* and K_d values were 6.1295 and 18.4280 for r-GO, and 4.3449 and 3.8747 for r-GO-V, respectively. A higher C value indicates a more pronounced

boundary layer resistance, highlighting the significance of surface sorption in controlling the adsorption rate. A summary of these parameters is provided in **Table 4**.

Table 4. Comparison of Kinetic Model Equations for the Sorption of MO onto r-GO and r-GO-V.

Pseudo-First Order			Pseudo-Second Order			Intra-Particle Diffusion		
k_1 (min^{-1})	qe cal (mg/g)	R^2	k_2 (g/mg min)	qe cal (mg/g)	R^2	Kd (mg/g $min^{1/2}$)	C	R^2
0.7579	1.14913	0.8174	0.0395	0.2349	0.7754	4.3449	6.1295	0.9518
0.7957	1.2113	0.8995	0.0395	2.3463	0.9643	3.8747	18.428	0.9357

3.7. Adsorption isotherm of MO removal using r-GO and r-GO-V.

The applicability of the Langmuir and the Freundlich isotherms for MO was evaluated by plotting *Ce/qe* versus *Ce* (as described in Equation (7)) and *log(qe)* versus *log (Ce)* (as outlined in Equation (8)), respectively (Fathi *et al*., 2024).

$$\frac{Ce}{qe} = \frac{1}{KLqmax} + \frac{Ce}{qmax\ b} \tag{7}$$

where *Ce* is the concentration of the pollutant in the solution at equilibrium (mg/L) (Mashhour *et al*., 2024), which is the mass of MO that is adsorbed by the sorbent at equilibrium (mg/g). Also, *qmax* is the maximum tested amount of pollutant that can be adsorbed per unit weight of the sorbent (mg/g), and *b* is the Langmuir adsorption equilibrium constant (L/mg), which is a measure of adsorbent-pollutant affinity.

$$log\ qt = log\ KF + \frac{1}{n}\ log\ Ce \tag{8}$$

where *KF* and *1/n* are the Freundlich adsorption constant for *1/n* (in mg/g) and the Freundlich adsorption constant for understanding adsorption intensity (in mg/L). Both r-GO and r-GO-V fitted well with the Langmuir equation in the isotherm data (**Figures 12 (a) and (b)**), and R^2 values were 0.9939 and 0.9835, respectively. This suggests that the adsorption of MO was a monolayer surface reaction, and the monolayer adsorption model (Langmuir) describes it well. The value of the Freundlich parameter *n* denotes the adsorption intensity, which is 3.1949 and 10.2775 for r-GO and r-GO-V, respectively. Relaxation time was not found to obey a simple exponential law, and it did not indicate a difference in overall adsorption reported here is higher ($n > 1$) than physical adsorption. The adsorption isotherm of MO on r-GO-V conforms to Langmuir and presents monolayer adsorption property (Iqbal *et al*., 2017; Mahdy & al-Naseri, 2024).

Sometimes, the Flory-Huggins isotherm model (Jehad *et al*., 2024; Chu *et al*., 2023) is used to obtain the degree of surface coverage characteristics of the adsorbate on the adsorbent. It can also represent the feasibility and spontaneity of the adsorption process. *KF* and *KL* were the equilibrium constants of the Freundlich and Langmuir isotherms, respectively. The latter constants are used for spontaneous elaboration of the process using the Gibbs free energy connected with Equation (9).

$$\Delta G^o = -RTln(K) \tag{9}$$

The parameters of *R*, *T*, and *K* in the thermodynamic equation represent the universal gas constant (8.314 J/mol·K), absolute temperature, and the equilibrium constant *KL* for Langmuir or KF for the Freundlich isotherms, respectively. Based on this relationship, the calculated Gibbs free energy changes ($\Delta G°$) for the Langmuir isotherm were -1.1127 and -4.5389 kJ/mol

for r-GO and r-GO-V, respectively. In contrast, the corresponding values for the Freundlich isotherm were −0.5551 and -1.7856 kJ/mol.

As listed in **Table 5**, these values indicate that the adsorption process is thermodynamically favorable and spontaneous, particularly under the studied conditions. Compared to the Freundlich model, the more negative $\Delta G°$ values associated with the Langmuir model suggest a stronger interaction between MO molecules and the adsorbents. Furthermore, the significantly more negative $\Delta G°$ value for r-GO-V relative to r-GO in the Langmuir isotherm implies that MO adsorption onto r-GO-V is more spontaneous and energetically favorable.

To understand the efficiency of the adsorbent synthesized to remove methyl orange, comparisons must be made between the findings presented here and other research conducted with different adsorbents. The highest adsorption capacity achieved was 44.63 mg/g applying r-GO-V, which is relatively practical. To compare this result with similar adsorbents, namely silica gel (Nuraeni *et al*., 2023), LD I, MCM-48 mesoporous silica LD 0.049 mg/g (Fathi *et al*., 2024) (equilibrium fitted to Langmuir isotherm as well). One of the most common adsorbents used is activated carbon, owing to its adsorption capacity, with the CAR900 material and CA being about 15.72 and 16.90 mg/g, respectively (Taquieteu *et al*., 2023). In addition, biochar and metal oxide nanoparticles have been investigated for methyl orange adsorption, and their capacities have also changed within 37.31 and 20.53 mg/g according to their surface character and the way of synthesis (Do *et al*., 2023; Chaukura *et al*., 2017).

Table 5. Correlation coefficients and constant parameters were calculated for various adsorption models for MO adsorption on r-GO and r-GO-V.

Langmuir				Freundlich			
qmax **(min^{-1})**	**K_L (L/mg)**	**R^2**	**$\Delta G_L°$ (kJ/mol)**	**K_F (mg/g)**	***n***	**R^2**	**$\Delta G_F°$ (KJ/mol)**
0.0982	1.5669	0.9835	-1.1127	1.2511	10.2775	0.8895	-0.5551
0.0493	6.2463	0.9939	-4.5389	2.0559	3.1949	0.9807	-1.7856

3.8. Bibliometric and SDG Relevance

A bibliometric analysis was conducted using the Scopus database with the query *TITLE-ABS-KEY ("water" AND "remediation")* covering the period 1928–2025. As shown in **Figure 13**, global publication activity in this domain has grown exponentially, reaching 7,599 documents in 2025, compared to only 2,027 publications in 2017, out of a total of 60,014 indexed studies. This upward trend reflects the accelerating scientific and policy focus on sustainable water management, environmental protection, and the development of advanced remediation technologies. Bibliometrics has been well-used in many areas as reported elsewhere (Nandiyanto *et al*., 2025; Solehuddin *et al*., 2025; Mubarokah *et al*., 2024; Maryanti *et al*., 2022).

The bibliometric trend strongly aligns with SDGs, which call for innovative, cost-effective, and scalable solutions to ensure access to clean water and to mitigate pollution at its source. Research on nanostructured materials, particularly carbon- and metal-oxide–based composites, has dominated the field since 2020, emphasizing their role in adsorption, catalysis, and water purification applications.

Positioned within this global framework, the present study contributes to the emerging paradigm of sustainable nanotechnology-driven water remediation. By integrating bibliometric insights with experimental validation, the research confirms both its scientific

novelty and global relevance, providing evidence that the development of rGO-V_2O_5 nanocomposites directly supports the progress of SDG 6 and strengthens the knowledge foundation for future smart and resilient urban water systems. Finally, this study also adds new information regarding the adsorption process, which is in line with other works Nandiyanto *et al*., 2020; Nandiyanto *et al*., 2025; Nandiyanto *et al*., 2022; Nandiyanto *et al*., 2023d, Nandiyanto *et al*., 2023e).

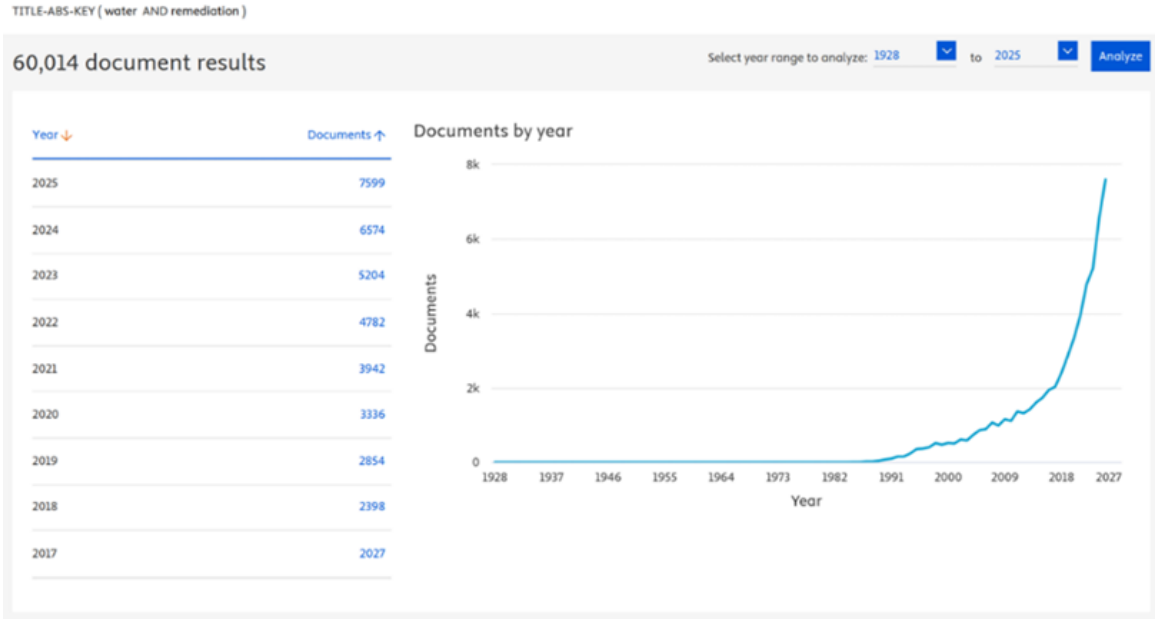

Figure 13. Annual publication trends on water remediation research based on Scopus data (1928-2025), showing exponential growth in global scientific output related to sustainable water management and nanotechnology applications. Data was taken and updated in November 2025.

4. CONCLUSION

This study highlights the successful preparation and characterization of a nanocomposite combining reduced graphene oxide and vanadium pentoxide (rGO-V_2O_5), which demonstrated high efficiency in the adsorption of methyl orange dye from aqueous solutions. The results demonstrated high adsorption efficiency and speed, and confirmed the application of the Langmuir single-layer adsorption model. The results clearly indicating that the adsorption was governed by chemical reactions and that the material surface was homogeneous. The synergistic interaction between V_2O_5 and rGO enhanced electron transport, increased surface activity, and a greater number of active sites, resulting in a stable and reusable nanomaterial that can be recycled multiple times. These findings demonstrate the important role that hybrid nanocomposites can play in developing sustainable water treatment solutions, in line with SDGs (especially SDG 6), in providing clean water and sanitation. The scientific contribution of this work lies in combining the potent oxidizing properties of vanadium pentoxide with the distinctive structural and surface properties of graphene, resulting in a multifunctional material capable of supporting smart urban water systems with high environmental efficiency. The novel theoretical innovations in this research are based on the synergistic effects between the strong oxidizing behavior of vanadium oxide and the structure and surface behavior of graphene.Furthermore, bibliometric analysis demonstrates that this research aligns with the growing global interest in using graphene-metal oxide combinations to develop sustainable wastewater treatment technologies.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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