



OPEN Novel bilayer 2D V_2O_5 as a potential catalyst for fast photodegradation of organic dyes

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Two-dimensional (2D) materials have recently drawn interest in various applications due to their superior electronic properties, high specific surface area, and surface activity. However, studies on the catalytic properties of the 2D counterpart of V_2O_5 are scarce. In the present study, the catalytic properties of 2D V_2O_5 vis-à-vis bulk V_2O_5 for the degradation of methylene blue dye are discussed for the first time. The 2D V_2O_5 catalyst was synthesized using a modified chemical exfoliation technique. A massive increase in the electrochemically active surface area of 2D V_2O_5 by one order of magnitude greater than that of bulk V_2O_5 was observed in this study. Simultaneously, ~ 7 times increase in the optical absorption coefficient of 2D V_2O_5 significantly increases the number of photogenerated electrons involved in the catalytic performance. In addition, the surface activity of the 2D V_2O_5 catalyst is enhanced by generating surface oxygen vacancy defects. In the current study, we have achieved $\sim 99\%$ degradation of 16 ppm dye using the 2D V_2O_5 nanosheet catalysts under UV light exposure with a remarkable degradation rate constant of 2.31 min^{-1} , which is an increase of the order of 10^2 from previous studies using V_2O_5 nanostructures and nanocomposites as catalysts. Since the enhanced photocatalytic activity emerged from the surface and optical properties of the catalyst, the current study shows great promise for the future application of 2D V_2O_5 in photo- and electrocatalysis.

Two-dimensional (2D) materials exhibit exotic physical, electrical, and optical properties that vary from their bulk counterparts. By altering the number of layers, the properties of 2D materials can be tailored. This distinctiveness provides opportunities for controlling the surface, optical, magnetic, and electrical properties of 2D materials for a range of applications. 2D materials are excellent choices for applications involving surface redox reactions, such as catalysis and gas sensing, because of their very high specific surface area and density of surface active states^{1–8}. For instance, graphene exhibits a high specific surface area of $\sim 2600 \text{ m}^2/\text{g}$, whereas it is $\sim 8 \text{ m}^2/\text{g}$ for natural graphite⁹. In addition to the high surface-to-volume ratio⁹, the presence of edge defects in 2D structures, which are responsible for stabilizing the structure, enhances the catalytic properties. For example, graphene with zig-zag edges shows good catalytic activity¹⁰. Theoretically, edge defect states strongly increase the electronic density of states at the edges compared to the plane of 2D materials¹¹. In addition, the presence of dislocations, vacancy defects, impurities, and functional groups can significantly increase the density of surface active states and, consequently, the catalytic activity of the materials¹². The impressive mechanical stability, generally shown by 2D materials, offers high stability and durability as catalysts and catalyst supports. Additionally, materials such as graphene, which has high electrical conductivity, have been applied in electrocatalysis.

The effluent from the textile industry contains organic dye molecules that are potentially harmful to human health and the ecosystem. Textile dyes are non-biodegradable and generally highly stable under light, heat, and oxidizer exposure¹³. Generally, catalyst-mediated redox reactions are cost-effective methods for the degradation of textile dyes^{14–16}. Semiconducting metal oxides with bandgaps in the range of visible and UV light energies, such as V_2O_5 ¹⁷, SnO_2 ¹⁸, ZnO ¹⁹, ZrO_2 ²⁰, and TiO_2 ^{21,22}, are generally used as photocatalysts. As a transition metal, V possesses multiple oxidation states²³, and the vanadium oxide surface can undergo reversible redox reactions^{24,25}. This property makes V_2O_5 a promising catalyst. In addition, V_2O_5 nanostructures with various morphologies and heterostructures of V_2O_5/rGO , and $V_2O_5/\text{graphene}$ also show good catalytic performance^{26–28}. Under ambient conditions, V_2O_5 crystallizes in its orthorhombic polymorph α - V_2O_5 , a layered van der Waals crystal²⁹. The surface of the V_2O_5 catalyst consists of three differently coordinated oxygen atoms: vanadyl (O_I), bridge (O_{II}), and chain (O_{III}) oxygen (the number in the subscript indicative of the coordination number of the oxygen atom)²⁹. The bridging oxygen connects the double V–O chains in the crystal structure along the b -axis. The VO_4 sites on

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the *ab*-plane V_2O_5 surface are the active surface sites for catalysis³⁰. The supported vanadium oxide catalysts on oxide surfaces also tend to show improved catalytic performance by controlling the specific activity of VO_4 sites³⁰.

Using 2D V_2O_5 , one can significantly reduce the defect formation energy and increase the active surface area for the catalytic reaction, consequently improving the catalytic performance. However, the catalytic properties of the 2D counterpart of V_2O_5 have not been reported before. The present study thoroughly examined the catalytic property of 2D V_2O_5 for the degradation of organic dyes. The chemically exfoliated V_2O_5 nanosheets were used as catalysts in the current study. The photocatalytic performance of 2D V_2O_5 for the degradation of methylene blue (MB) dye was investigated and compared with that of bulk V_2O_5 .

Methods

Synthesis and characterization of 2D V_2O_5 nanosheets

2D V_2O_5 nanosheets were synthesized by a modified chemical exfoliation method by altering the concentration of bulk V_2O_5 in formamide²⁹. Previous reports have shown that V_2O_5 intercalated with formamide molecules can provide a stable suspension of tiny flakes of V_2O_5 in formamide medium^{29,31}. For the synthesis, bulk V_2O_5 powder (Merck, 99.99%) was dispersed in formamide (Merck, 99%) for 24 h. To separate the exfoliated nanosheets, the dispersion of formamide-intercalated V_2O_5 was subjected to a 1 h ultrasonic treatment at room temperature. The resultant suspension was then coated on a quartz substrate by drop casting (for the photocatalysis study), followed by heating at 100 °C to completely remove the formamide molecules. Furthermore, the exfoliated nanosheets were annealed for three hours at 250 °C under a continuous flow of O_2 ²⁹. The substrate was replaced with SiO_2/Si and high pure gold for AFM and Raman spectroscopic studies, respectively.

A multimode scanning probe microscope (INTEGRA, NT-MDT, Russia) was used to record the atomic force microscopy (AFM) topography and estimate the thickness of the exfoliated nanosheets coated on the SiO_2/Si substrate. Intermittent contact mode was used for imaging. Atomic-resolution STEM images were collected using probe aberration-corrected Thermo Fisher Scientific Themis Z ultrahigh-resolution TEM at an acceleration voltage of 300 kV. Oxygen vacancy defects in the sample were identified using X-ray photoelectron spectroscopy (XPS) (SPECES Surface Nano Analysis GmbH, Germany). A monochromatic Al K_α X-ray source (1486.7 eV) was used for the XPS measurements. Ultraviolet–visible (UV–Vis) absorption spectroscopy (Avantes) was carried out in absorption mode to determine the band gap. UV–Vis absorption spectra of the bulk and 2D V_2O_5 nanosheets were collected using a cuvette with a width of 1 cm and the same light source. Raman spectroscopy (InVia, Renishaw, UK) was carried out utilizing a 532 nm Nd:YAG solid-state laser as the excitation source in the backscattering geometry, an 1800 g/mm grating, and a thermoelectrically cooled charged coupled device as the detector.

Estimation of specific surface area

The electrochemically active surface area (ECSA) of bulk and 2D V_2O_5 were calculated and compared. The ECSA was estimated from the non-Faradic capacitive current associated with double layer charging using the scan rate dependence of cycle voltammograms (CV)^{32,33}. The experimental setup consists of a three-electrode system with a Pt counter electrode and Ag/AgCl as the reference electrode. In the present study, for bulk V_2O_5 , a 5 mM dispersion of bulk V_2O_5 in propanol was taken. Around 630 μ L was dispersed on carbon paper with dimensions of 1.5 cm \times 1.5 cm. The volume of the sample dispersion was chosen to ensure a conformal coating on the carbon paper. For 2D V_2O_5 , 250 μ L of a 1 mM dispersion of exfoliated V_2O_5 nanosheets (45 μ g of sample) in formamide was coated on a similar substrate. The CV of the samples with 1 M H_2SO_4 electrolyte was recorded (using PGSTAT 302 N, Metrohm Autolab e.v.), and the peak current, I_c , was taken from the non-Faradic region.

Photocatalytic study

The degradation of MB ($C_{16}H_{18}ClN_3S$ (Merck India)) dye was examined to understand the photocatalytic properties of the bulk material and 2D V_2O_5 . The V_2O_5 catalyst mixed with the dye was subjected to UV-C (254 nm, 9 W, PL-S, PHILIPS, Poland). The intensity of the light source was measured using a Lutron UV light meter (Taiwan) at a distance of 3 cm from the light source, and the intensity was 2.21 mW/cm². An aqueous solution of dye and bulk V_2O_5 (concentration 0.18 mg/mL) was prepared in the dark and maintained at adsorption–desorption equilibrium. For 2D V_2O_5 , 5 mL of 2D V_2O_5 dispersion (around 0.9 mg) was deposited on a quartz substrate and dipped into dye solution³². To achieve adsorption–desorption equilibrium, the sample was kept in the dark. The amount of 2D V_2O_5 sample was selected so that, for 5 mL of stock solution, the catalyst amount maintained the same as that for the bulk V_2O_5 catalyst. Light source was then exposed upon the dye solution containing the catalyst for various durations. Five milliliters of the irradiated solution was then subjected to UV–Vis spectrometry. By monitoring the MB dye absorption peak at 664 nm, the degradation of MB dye was studied. For the quantitative study, the UV–Vis absorption spectra of the solutions were periodically recorded.

Results and discussion

Estimation of nanosheet thickness and atomic resolution STEM studies

AFM studies were carried out on the exfoliated V_2O_5 sample to determine the thickness. Figure 1a shows the AFM image of evenly distributed nanosheets on a Si/SiO_2 substrate. The exfoliated layers in the ensemble have lateral dimensions between 100 and 300 nm, as observed from the FESEM image (Fig. S1). The observed step height has a standard deviation of 0.1 nm. The theoretical thicknesses of the monolayer, bilayer and trilayer V_2O_5 nanosheets are ~0.43, 0.87 and 1.3 nm, respectively²⁹. The experimentally observed thicknesses of the individual layers of 2D V_2O_5 nanosheets are in the range of 1.0–1.5 nm, as shown in the height profile (Fig. 1a). The numerical distribution of the nanosheet thicknesses shown in Fig. 1b indicates that the quantity of bilayer thin nanosheets in the sample is substantially greater. To verify the atomic structure and chemical composition,

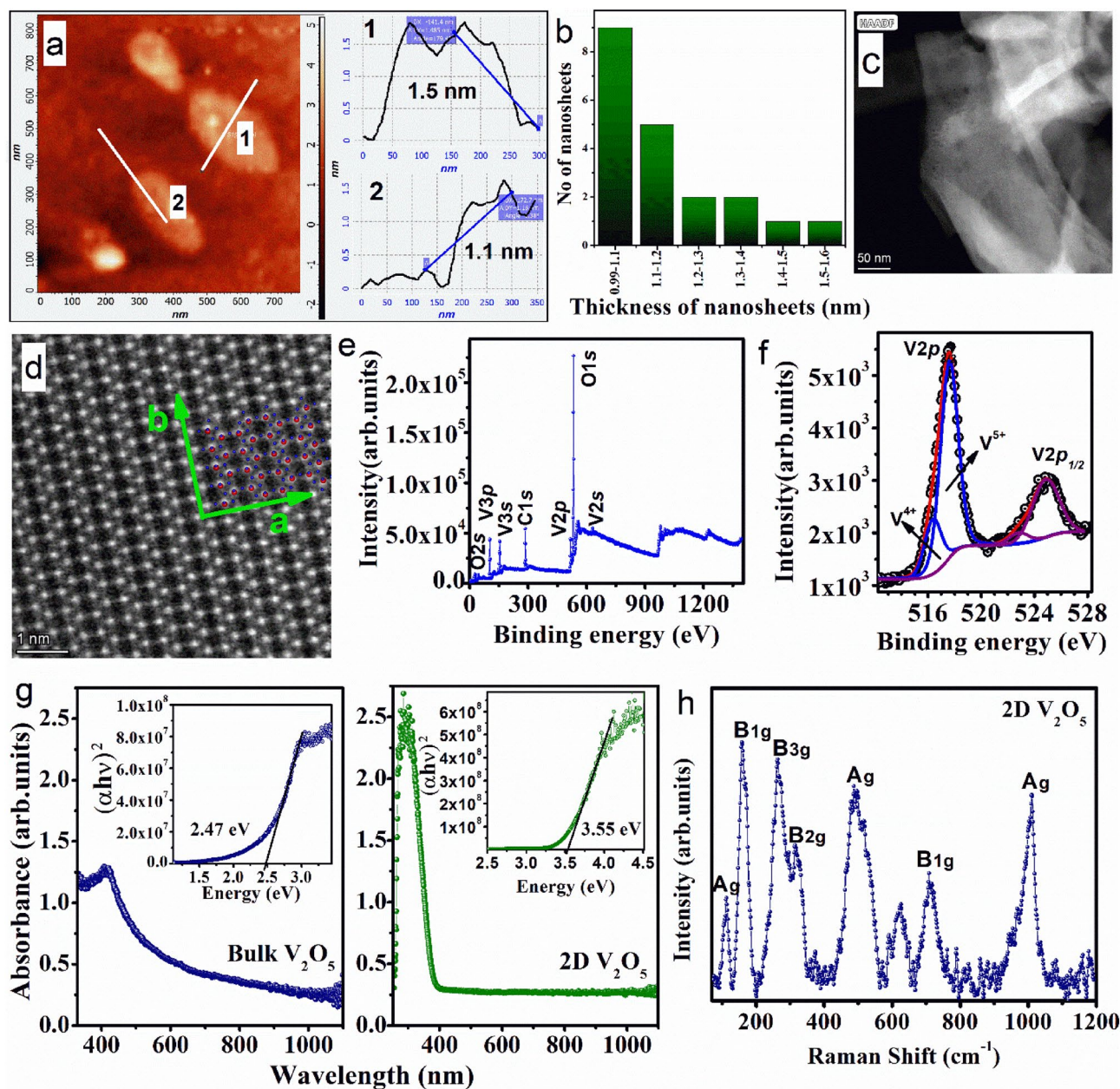


Figure 1. (a) AFM topography and height profile of exfoliated nanosheets. (b) Distribution of the thickness of 2D V_2O_5 nanosheets. (c) STEM image and (d) atomic resolution annular dark field (ADF)-STEM image of 2D V_2O_5 nanosheets. (e) XPS survey spectrum of 2D V_2O_5 and (f) the core-level spectrum corresponding to the binding energies of $V2p_{3/2}$ for the V^{5+} and V^{4+} states of V atoms in 2D V_2O_5 nanosheets. (g) UV–Vis absorption spectra of bulk and 2D V_2O_5 . The Tauc plot for understanding the optical band gap is given in the corresponding insets. (h) Raman spectrum of the 2D V_2O_5 nanosheets.

an atomic resolution scanning transmission electron microscopy (STEM) image of the exfoliated nanosheets was obtained. Figure 1c and d show dark field (DF) STEM image and atomic resolution annular dark field (ADF)-STEM image of 2D nanosheets. The nanosheets in the DF-STEM image shown in Fig. 1c are folded, which is commonly observed in unsupported 2D structures³⁴. The atomic resolution ADF image, displayed in Fig. 1d, is collected from the flat area of the individual nanosheets and demonstrates the arrangement of the VO_5 square pyramidal structure in α - V_2O_5 along the (001) plane. The 2D layer is generated by joining the 1D chain of VO_5 pyramids along the b -axis with chain oxygen (O_{II}) along the a -axis.

X-ray photoelectron spectroscopy studies

Figure 1e displays the XPS survey spectrum of 2D V_2O_5 . The V_2O_5 phase of the exfoliated nanosheets was further validated by the observation of peaks at 517.4 ($V2p_{3/2}$), 524.8 ($V2p_{1/2}$), and 530.1 (O 1s) in the XPS survey spectrum³⁵. The deconvoluted peaks in the core-level spectrum observed at 517.4 and 516.3 eV corresponded

to the binding energies of $V2p_{3/2}$ for the V^{5+} and V^{4+} states, respectively (Fig. 1f). The peaks at 524.8 and 523.1 eV correspond to the binding energies of $V2p_{1/2}$ for the V^{5+} and V^{4+} states, respectively³⁶. The presence of the peaks corresponding to V^{4+} indicates the presence of oxygen vacancy sites in the samples²⁹. The percentage of oxygen vacancy defects in 2D V_2O_5 was $\sim 17\%$, as determined by the area under the curve. The presence of these oxygen vacancy sites can potentially increase the surface activity and, consequently, the catalytic property of the sample.

UV–Vis absorption studies for estimating the optical band gap

Bulk V_2O_5 is a semiconductor with a bandgap of ~ 2.4 eV and a Fermi energy between the O 2p valence band and V 3d conduction band³⁷. Within this gap, however, two localized split-off bands exist approximately 0.6 eV below the main V 3d band due to crystal field splitting³⁷. The xy-derived levels of the conduction band are predicted to be at the lowest energies because they are not affected by vanadyl oxygen interactions. However, only two of the four xy-derived levels interact with the bridging oxygen and move up into the conduction band. Hence, the strong, indirect V–V interactions across the bridging oxygen are found to be the cause of the existence of split-off bands³⁷. Figure 1g shows the UV–Vis absorption spectra and Tauc plots for estimating the band gap for bulk and 2D V_2O_5 . A significant increase in the absorbance value from 0.22 to 1.58 was seen between bulk and bilayer V_2O_5 (Fig. 1g). Additionally, there is a substantial increase in the optical absorbance for 2D and bulk V_2O_5 with the same concentration of sample and intensity of incident light. This observation is possibly due to the pronounced excitonic effects in bilayer 2D V_2O_5 , which is also observed in other 2D materials arising out of the reduced dielectric screening effect^{38,39}. This increase in the optical absorbance of 2D V_2O_5 indicates an exceptionally high number of photogenerated free charges, which can actively participate in the photocatalytic process. In addition, an absorption edge blueshift from bulk to bilayer 2D V_2O_5 was observed, indicating electronic decoupling with decreasing layer thickness in the 2D nanosheets of V_2O_5 ²⁹. The optical bandgap and E_g of bulk and 2D V_2O_5 are experimentally calculated from Tauc's Plot to be 2.47 and 3.55 eV, respectively (Fig. 1g). These results are in agreement with our earlier report on the synthesis of 2D nanosheets of V_2O_5 ²⁹.

Raman spectroscopic analysis of bilayer 2D V_2O_5

The Raman spectrum of the 2D V_2O_5 is given in Fig. 1h. The sample exhibited nine vibrational modes corresponding to 2D V_2O_5 . The low-frequency vibrational modes A_{1g} and B_{1g} at 111 and 158 cm^{-1} , respectively, are due to chain translation along the crystallographic *c*- and *a*-axes. V–O_{II}–V bending vibration causes the B_{3g} mode at 262 cm^{-1} . The deflection of V–O_{III} and V–O_{III'} along the *c* direction is responsible for the vibrational mode B_{2g} at 324 cm^{-1} . The A_{1g} peak at 489 cm^{-1} arises from the bending vibration of V–O_{II}–V in the *c* direction. The vibration of V–O_{III'} and V–O_{III} along the *a*-axis is the origin of the vibrational mode B_{1g} at 713 cm^{-1} . The highest frequency A_{1g} mode at 1010 cm^{-1} corresponds to the stretching vibration of V–O_I along the *c*-axis²⁹. The peak at 620 cm^{-1} in the Raman spectrum is expected to arise due to surface oxygen vacancies and consequent surface reduction²⁹.

Electrochemical surface area of bulk and 2D V_2O_5

The specific surface area of the 2D V_2O_5 nanosheets was compared with that of bulk V_2O_5 by calculating the ECSA. The ECSA of a sample is essentially estimated from the electrochemical double-layer capacitance. The measurement can be performed either from the non-Faradic capacitive current associated with double-layer charging from the scan rate dependence of CV or from the frequency-dependent impedance of the system using electrochemical impedance spectroscopy^{32,39}. In the present study, the first method was adopted for the measurement of the ECSA. The faradic process will be absent in the potential window of, typically, 0.1 V around the open circuit voltage. The CV curves of the samples were recorded using 1 M H_2SO_4 as the electrolyte. From the non-Faradic part, the peak current, I_c , is obtained. Thus, the ECSA may be determined using,

$$ECSA = \frac{C_{dl}}{C_s} \quad (1)$$

where C_s is the specific capacitance of an atomically smooth planar surface of the material per unit area under identical electrolyte conditions. For the 1 M H_2SO_4 electrolyte, the C_s were found to be 0.035 mF/cm^2 ^{32,39,40}. Figure 2a and b show CV diagrams of bulk and 2D V_2O_5 , respectively. The values of the double layer capacitance (C_{dl}) are 1.29 mF for bulk, as shown in Fig. 2c, and 3.32 mF for 2D V_2O_5 , as shown in Fig. 2d. The corresponding ECSAs per 1 g of bulk and 2D V_2O_5 were determined to be 6.5 and 211 m^2/g , respectively (Fig. 2e). According to the literature, bulk V_2O_5 has a shallow specific surface area $< 10 \text{ m}^2/\text{g}$ ^{31,32}. Thus, the observed specific surface area of bulk V_2O_5 is in agreement with the literature. This study revealed that, in comparison with the bulk equivalent, 2D nanosheets of V_2O_5 exhibited an increase in specific surface area of approximately 32 times.

Degradation of MB dye under UV irradiation

The photodegradation of MB dye was studied using bulk and 2D V_2O_5 as catalysts. The UV–Vis absorption spectra of aqueous dye solutions collected at various UV light exposure times containing the bulk and 2D V_2O_5 catalysts are displayed in Fig. 3a and b. The benzene ring and heteropoly aromatic bond of the MB dye molecule are broken upon exposure to UV light in the presence of the catalyst, which is apparent from the decrease in the strength of the absorption peak at 662 and 608 nm ^{32,41}. As a result, upon exposure to UV light in the presence of the catalyst, the dye molecules undergo degradation. The amount of catalyst was kept the same for all bulk and 2D V_2O_5 samples for the same amount of dye solution. The photodegradation of MB dye under UV light exposure without any catalysts was also tested and is shown in Fig. S2 (Supplementary information). The degradation of MB dye using 2D and bulk V_2O_5 catalysts was also studied under exposure to visible light, and

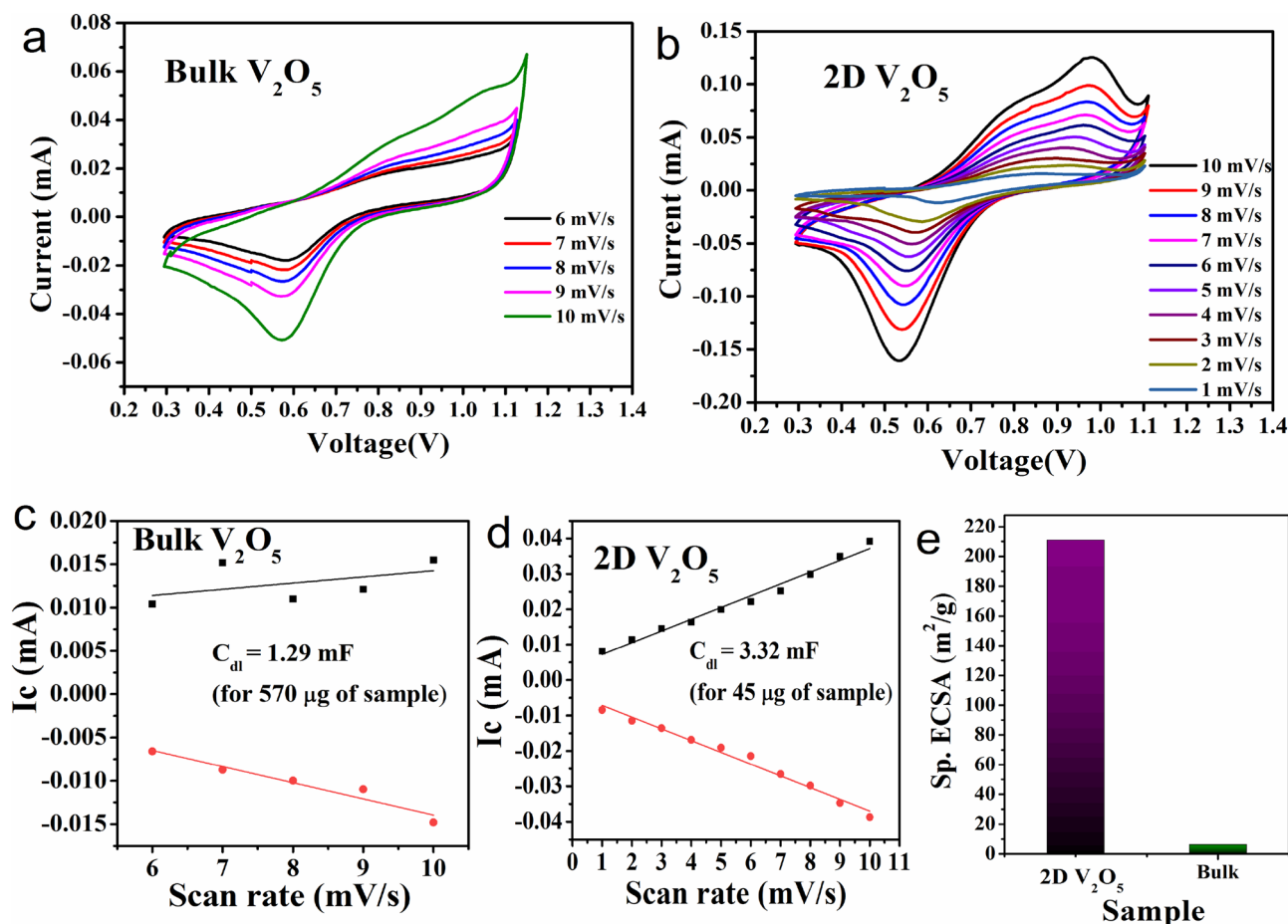


Figure 2. CV diagram of (a) bulk V_2O_5 and (b) 2D V_2O_5 . Peak current versus scan rate in the non-Faradic region for (c) bulk V_2O_5 and (d) 2D V_2O_5 . (e) ECSA for 1 g of bulk and 2D V_2O_5 .

the results are shown in the supplementary information (Fig. S3). Only ~5% of the dye underwent degradation with a UV light exposure of 160 min. As shown in Fig. 3a and b, the bulk V_2O_5 catalyst caused only minimal degradation of 7.7% after 35 min of UV exposure of the dye (16 ppm), whereas 2D V_2O_5 catalyst resulted in the degradation of ~99% in just 3 min.

Estimation of the rate constant and efficiency of dye degradation

Generally, the degradation obeys pseudo-first-order kinetics^{32,41,42}, and according to the observations, the degradation reaction fits well with the equation $\ln \frac{C_0}{C_t} = kt$, where C_0 is the absorption at $t = 0$, and C_t is the absorption after the time interval t of the irradiation (Fig. 3c). Based on Fig. 3c, the rate constants for dye degradation using the bulk and exfoliated V_2O_5 catalysts were calculated. The 2D and bulk V_2O_5 catalysts exhibit distinct rate constants for the degradation of MB dye: 2.311 min^{-1} and 0.0023 min^{-1} , respectively.

The percentage (%) of photocatalytic dye degradation efficiency was calculated using Eq. (2)⁴³.

$$D(\%) = \frac{C_0 - C_t}{C_0} \times 100 \quad (2)$$

Figure 3d depicts the effect of light exposure duration on degradation efficiency. As discussed in the previous sections, the specific surface areas (ECSA) of the bulk and 2D V_2O_5 are 6.5 and 211 m^2/g , respectively. As a result of this increase in the specific surface area, the photocatalytic performance of the 2D nanosheets substantially improved compared with that of the bulk V_2O_5 catalyst. In addition, surface oxygen vacancies can act as active sites for redox reactions and enhance surface activity. A comparison of the reported literature with the present study (Table 1) also indicates the superior catalytic performance of 2D V_2O_5 nanosheets.

Effect of scavenging agents on dye degradation

The MB dye contains active sites for oxidative attack. To understand the active oxidative species involved in the catalytic process, the effects of scavenging reagents in quenching superoxide (O_2^-) and hydroxyl (OH^\cdot) radicals during the catalytic process were studied. *p*-Benzoquinone and isopropanol were used as the scavenging reagents for superoxide (O_2^-) and hydroxyl (OH^\cdot) radicals, respectively. *p*-benzoquinone and isopropanol were added at concentrations of 10 mM and 20 mM, respectively. The catalytic degradation of the MB dye molecule was studied

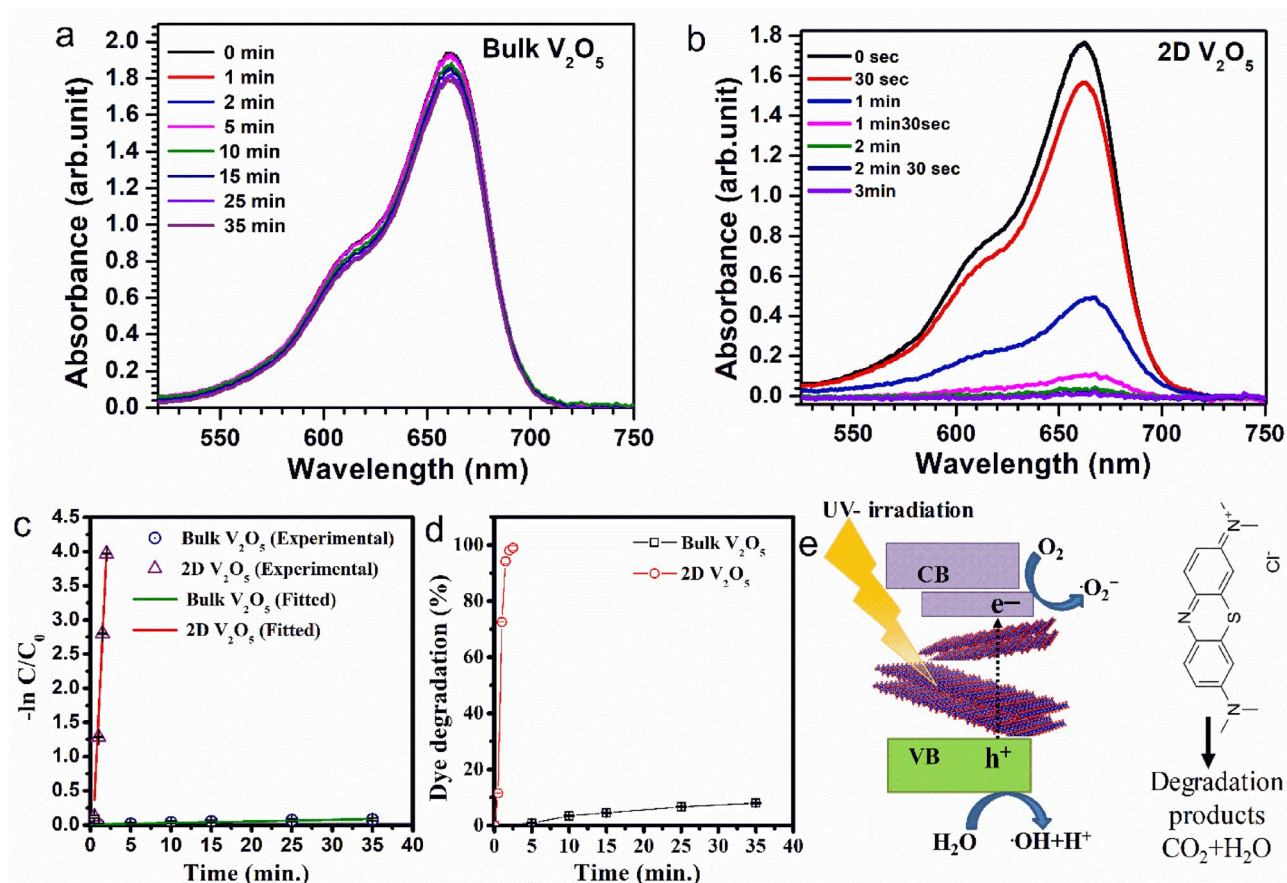


Figure 3. UV–Vis absorption spectra of MB dye solutions for different durations with (a) bulk V_2O_5 and (b) 2D V_2O_5 as catalysts. (c) The curve of $\ln(C_0/C_t)$ vs. light exposure time (d) Dye degradation efficiency using the bulk and 2D V_2O_5 samples as catalysts versus the duration of light exposure. (e) Schematic of dye degradation mechanism of 2D V_2O_5 .

Photocatalyst	Rate constant min^{-1}	Degradation time (min)	Efficiency (%)	Reference
V_2O_5 np	0.00742	20	31	44
rGO- V_2O_5	0.0184	20	71	44
rGO- V_2O_5	0.0078	255	85	45
V_2O_5 -nanorods	0.00135	300	24	46
V_2O_5 thin film	–	210	75	47
V_2O_5 np	0.025	–	92	48
Graphene- V_2O_5	0.0367	90	98	27
Nd^{3+} doped V_2O_5	–	120	80	49
Ho-doped V_2O_5	–	160	93	50
Yb-doped V_2O_5	–	160	95	50
$Na_2Ti_3O_7/V_2O_5/g-C_3N_4$	0.103	–	–	51
$Na_2Ti_3O_7/V_2O_5$	0.0865	–	–	52
V_2O_5/rGO	0.048	100	98	53
2D V_2O_5	2.311	3	~ 99	Present study

Table 1. Comparison of the present study on the photocatalytic degradation of MB dye using a 2D V_2O_5 catalyst with the reported literature on related materials as catalysts.

using the same method as described in the previous sections. Figure S3a and b show the UV–Vis absorption spectra of MB dye molecules in the presence of the 2D V_2O_5 catalyst and the scavengers *p*-benzoquinone and isopropanol, respectively. Figure 4a and b show the rate constants obtained in the presence of *p*-benzoquinone and isopropanol, respectively. The rate constant of the catalytic degradation of MB dye decreased to 0.01 min^{-1} in the presence of *p*-benzoquinone, while it decreased to 2.31 min^{-1} without any scavengers. In the presence

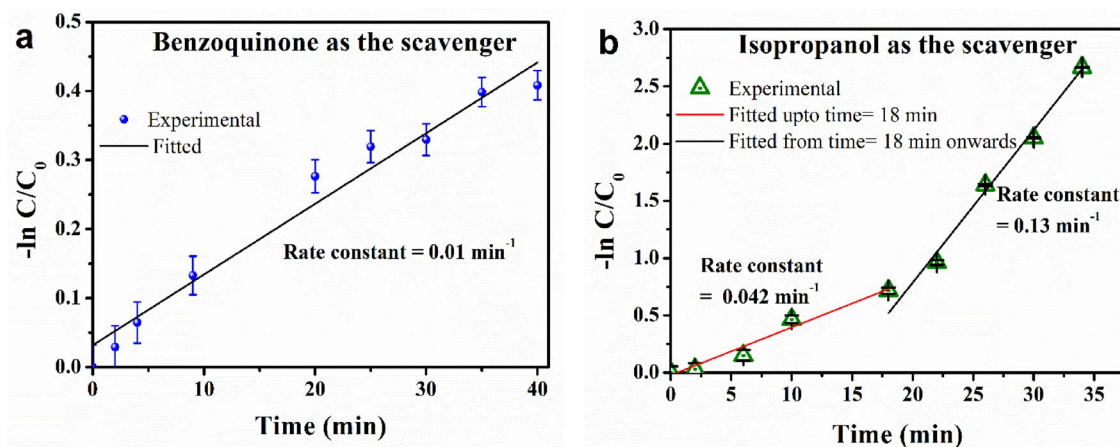


Figure 4. The curve of $\ln(C_0/C_t)$ vs. UV exposure time using 2D V_2O_5 as the catalyst in the presence of scavengers, (a) benzoquinone, and (b) isopropanol.

of isopropanol, the rate constant decreased to 0.04 min^{-1} during the first 18 min of UV light illumination, followed by a rate constant of 0.13 min^{-1} . This change in the rate constant is due to the decrease in the isopropanol concentration due to evaporation. In the presence of both scavenging reagents, a significant reduction in the rate constant is observed. The change in rate constant indisputably proves that the $\cdot O_2^-$ and $\cdot OH$ radicals are involved in the photocatalytic reaction.

Mechanism of photocatalytic degradation of MB dye

Figure 3e shows a schematic illustration of a possible pathway for the photocatalytic degradation of MB dye. When 2D V_2O_5 nanosheets are exposed to UV light, electrons are excited to the conduction band (CB), leaving holes in the valence band (VB). $\cdot OH$ radicals are generated when these holes interact with OH^- on the catalyst surface. These electrons lead to the production of $O_2^{\cdot -}$ superoxide anion radicals. The effect of scavengers on dye degradation has demonstrated that the oxidizing species in the photocatalysis reaction are $\cdot OH$ and $O_2^{\cdot -}$ radicals that are thereby produced. According to the results, the use of 2D V_2O_5 nanosheets effectively improved the separation of electrons and holes, which substantially enhanced the photocatalytic activity. The anticipated decrease in the screening effect of charges and the presence of excitonic levels in 2D materials could also be responsible for this enhanced separation of electrons and holes⁵⁴ in 2D V_2O_5 .

Recyclability of the catalyst

The recyclability of the 2D V_2O_5 catalyst was determined by reusing a 2D V_2O_5 sample coated on a quartz substrate. After each cycle, the sample on the substrate was collected, washed with deionized water (Millipore), and dried at 80°C . Figure 5a shows the degradation efficiency of the catalyst under UV light illumination, and Fig. 5b shows the degradation efficiency of the 2D V_2O_5 catalyst under UV light illumination for 3.5 min over three cycles. The decrease in efficiency can be due to the loss of catalyst from the substrate during the recycling process.

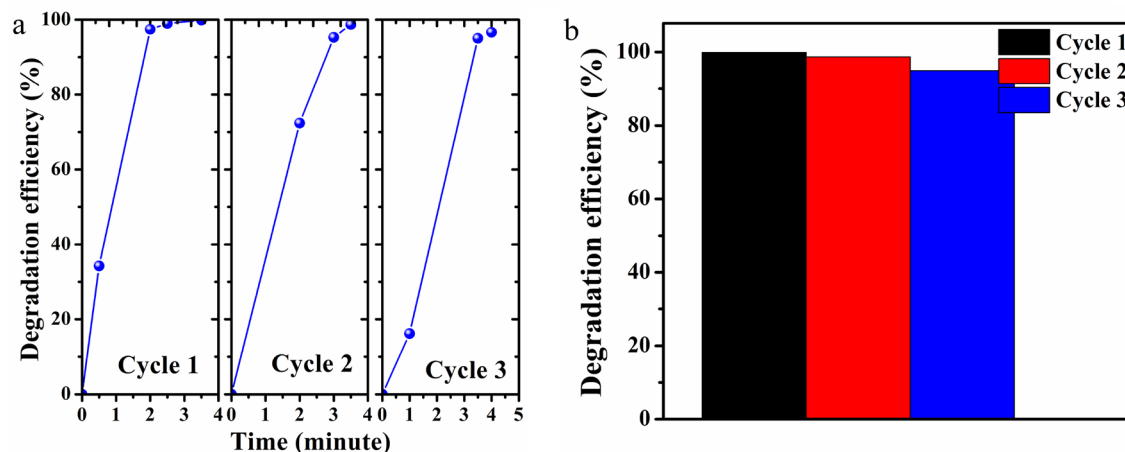


Figure 5. (a) MB dye degradation efficiency for three cycles of reuse of 2D V_2O_5 nanosheets. (b) Bar diagram showing the dye degradation efficiency after 3.5 min of UV light exposure for three cycles.

Conclusions

2D V_2O_5 nanosheets with a bilayer thickness were synthesized using a chemical exfoliation technique, which showed a ~ 30 -fold increase in the specific surface area from that of the bulk. The catalytic activity of 2D V_2O_5 was studied in detail and compared with that of bulk V_2O_5 . A considerable improvement in the degradation rate constant was observed for 2D V_2O_5 from bulk V_2O_5 catalysts. The rate constants for the bulk and 2D V_2O_5 catalysts were 0.0023 and 2.311 min^{-1} , respectively. The sizable improvement in the catalytic activity is attributed to three properties:

- A massive increase in the specific surface area of 2D nanosheets from bulk V_2O_5 was observed as a result of the formation of nanosheets with thicknesses down to the bilayer.
- The presence of oxygen vacancies acts as an active site for redox reactions, improving the surface activity.
- An increase in the optical absorption coefficient on the order of ~ 7 times substantiates a significant increase in the number of photoexcited electrons. The efficient separation of photogenerated carriers facilitates the generation of free radicals responsible for the oxidative decomposition of organic dye molecules.

The results obtained from the present study undeniably prove that the novel 2D V_2O_5 nanosheet is a promising photocatalyst. In addition, the 2D V_2O_5 catalyst is stable and abundant on earth, the catalyst is recyclable, and the synthesis method of the catalyst is cost effective. Additionally, the current study opens up new possibilities for using 2D V_2O_5 as electro- and photocatalyst because of its improved surface and optical properties. The increase in optical absorption leads to the possibility of efficiently generating hot electrons, creating novel possibilities for light energy conversion to electrical and chemical energy.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Author contributions

The central idea was conceived by R.P.R. and A.K.P. Sample synthesis, characterization, and data analysis were carried out by R.P.R. The manuscript was written by R.P.R., and all the authors discussed the results and the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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