

Synthesis, Properties, and Applications of Vanadium Pentoxide (V_2O_5) as Photocatalyst: A Review

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Abstract Water pollution has increased worldwide, sparking interest in photocatalysis, a viable water treatment approach. Vanadium pentoxide (V_2O_5) is a good photocatalyst for photocatalytic degradation due to its excellent crystallinity, high yield and recyclability, low cost, photo-corrosion resistance, small band gap (2.3 eV), improved electron mobility, and broad absorption range. Pure V_2O_5 's photocatalytic efficiency is limited by inefficient photonic and quantum processes, and its tiny structure enables photogenerated carriers to recombine, reducing efficiency. This prevents widespread use of V_2O_5 . This mini-review examines V_2O_5 as a potent visible-light photocatalyst, focusing on its structure, synthesis methods, and modifications that improve its efficiency. Hydrothermal, sol-gel, co-precipitation, solvothermal, and others are reviewed. The methods employed affect the photocatalyst's efficiency. Photogenerated electron-hole separation, charge transfer to catalyst surface or across two-phase catalyst interfaces, and reactive species interaction with hazardous contaminants are all affected. Photoredox uses have been explored for dyes, phenols, and pharmaceutical wastes. According to a review of the past decades, V_2O_5 has primarily been used for the degradation of dye pollutants, with fewer applications for pharmaceutical wastes and other pollutants. More research on V_2O_5 's capabilities and qualities on diverse target pollutants is needed. This mini-review discusses present obstacles in producing vanadium pentoxide-based systems and future research prospects. Despite its potential as a photocatalyst, V_2O_5 has not been thoroughly researched as an electron storage material. Numerous investigations have shown that V_2O_5 can store energy like lithium batteries. This finding will likely motivate researchers and newcomers to explore V_2O_5 's potential to synthesise nanomaterials with increased electron storage capacity, making it a good day-night photocatalyst. This review should improve future V_2O_5 research.

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Introduction

Among the many challenges that the world is facing in the present day, protecting the environment is quickly becoming the most pressing concern. The widespread consumption of fossil fuels results in the emission of greenhouse gases; these emissions are one of the primary contributors to the phenomenon of global warming. Alternative energy sources, particularly renewable energy strategies such as solar, wind, and others, are becoming increasingly popular topics of discussion to find solutions to this problem. The conversion of light energy like solar to chemical energy using photocatalysts has been one of the areas that has seen rapid development in the past decade. The fundamental drive for research in this subject has been the discovery of innovative photocatalysts

that are efficient and economical for photocatalytic water splitting. Photocatalysts can also be used to remove organic contaminants and harmful heavy metal ions from water that has already been contaminated [1][2]. The kinetic energy of the light stimulates the photocatalyst to produce electron-hole pairs, which play a crucial part in the mineralisation of contaminants. Developing effective storage technology is crucial for the widespread adoption of renewable energy sources, which have limited availability and cannot reliably feed the grid on demand. Electrochemical energy storage is emerging as a frontrunner in this field. Titanium dioxide (TiO_2) has become the dominant product in the photocatalysis industry because of its abundance, environmental safety, and stable photochemical state. However, since it can only be excited by ultraviolet (UV) light, it is inefficient and experiences rapid charge recombination. This is because UV light is the only electromagnetic wave that can excite it. On the other hand, the search for a photocatalyst that is efficient, affordable, environmentally friendly, and driven by visible light continues to be a formidable obstacle for researchers in photocatalysis area.

In recent years, there has been a lot of interest in a layered semiconductor that operates in visible light. This material has a band gap of 2.3 eV and is called vanadium pentoxide (V_2O_5). Since 2011, the 2D sheet material V_2O_5 , which has the potential to be used in visible light without undergoing any modifications, has been the subject of extensive research up until this point. Also, due to its non-toxicity, high oxidising power, long-term chemical and photostability, and low toxicity, vanadium pentoxide is the semiconductor of choice in many studies to produce excellent photocatalysts [3]–[6]. Accordingly, after looking at the results of other studies, it has become clear that various production techniques like co-precipitation method [7], the hydrothermal method [8], the sol-gel method [9] and others result in photocatalysts with varying characteristics. The best method should be one that is straightforward, inexpensive, has a low growth temperature, increases photocatalytic activity when exposed to visible light, and is efficient for the photodegradation of organic pollutants. To this day, many researchers have looked into the different photocatalytic abilities that V_2O_5 can have, and many potential applications in the field of environmental science have emerged as a result. This mini review examines the synthesis method of vanadium pentoxide and its properties' effects, as well as the application of vanadium pentoxide to the degradation of a wide variety of pollutants, such as dyes, phenols, and pharmaceutical waste, all of which will be thoroughly discussed elsewhere in this article.

Vanadium oxides are known as vanadium monoxide (VO), vanadium sesquioxide (V_2O_3), vanadium dioxide (VO_2), and vanadium pentoxide. They occur as single valence oxides in the oxidation states ranging from V^{2+} to V^{5+} . Out of all the different vanadium oxides, V_2O_5 is the one with the best stability and known to have natural n-type conductivity [10]. An oxyanion transition metal, vanadium pentoxide (V_2O_5) has a melting point of 936 K, a boiling temperature of 2020 K, a colour that is either pale or yellow, and a band gap energy of 2.3 eV [11]. The electron configuration of vanadium in its ground state is $3d^34s^2$. When transition elements undergo ionisation, the loss of their valence s electrons occurs before the loss of their valence d electrons. Five of the valence electrons of vanadium can be lost. There are four common oxidation states of vanadium: +5, +4, +3, and +2, and each state can be identified by the colour it displays. For instance, the oxidation state +5 is frequently shown in a yellow colour [12]. Pyramids of VO_5 are formed as a result of the formation of a network between oxygen and the V chain that is present in V_2O_5 . This network results in a distorted trigonal bipyramidal coordination polyhedron. A single V-O bond in the perpendicular position only makes a tenuous connection with the oxygen in the layer below it. This layered property allows numerous ions to enter the lamellar gap, which causes a shift in the crystalline structure and results in varied properties [13]. Crystalline V_2O_5 has a one-of-a-kind orthorhombic layered structure, and it possesses direct optical energy gap, good chemical property, thermal stability, and excellent specific energy as summarised in Figure 1. It exists in this state because it is crystalline.

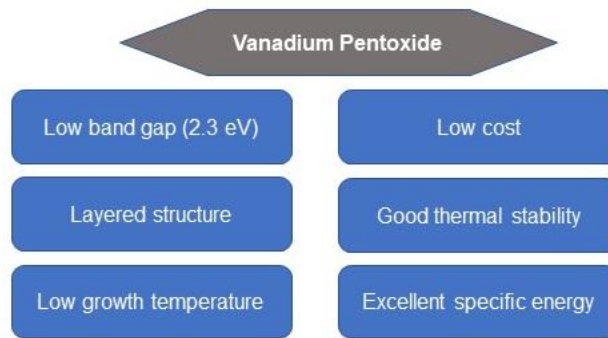


Figure 1. Basic properties of V_2O_5

Along with its layered structure and optical properties, vanadium pentoxide finds widespread use in the field of photocatalysis [8], [14]–[18]. Many studies proved the optical and structural properties of vanadium pentoxide affect its performance on degradation of pollutants. Preeyanga, Vinesh and Neppolian, (2022) [18] found a bandgap value of 2.2 eV, a sheet like structure with particles linked to each other in scanning electron microscopy (SEM) analysis has contributed to the great photodegradation performance of dye pollutants. Aslam *et al.* (2015) [19] also reported on one of the unique properties of vanadium pentoxide which contribute to effectiveness of V_2O_5 as photocatalysts is surface defects in V^{4+} could play a big role for the production of $O_2\cdot$ radicals. The schematic illustration of surface traps and electrons transfer to produce $O_2\cdot$ radicals under light are displayed in Figure 2. When a photon with an energy of 2.3 eV or more interacts with a V_2O_5 photocatalyst, an electron-hole pair is produced, which is the basic concept of photocatalysis. The electron then travels to the conduction band (CB), where it forms the superoxide radical by reacting with oxygen molecules, and the hydroxyl radical by reacting with H_2O_2 . In the meantime, water's H_2O molecule reacts with a hole in the valence band (VB), creating a hydroxyl radical that functions as a powerful oxidising agent to break down contaminants into less hazardous chemicals. Figure 3 shows the illustrated photocatalysis by V_2O_5 .

To calculate the band gap value, by using Equation (1) and Equation (2), one can determine the VB and CB potentials of V_2O_5 at the point where there are zero charges.

$$E_{VB} = X - E_c + 0.5 E_g \quad (1)$$

$$E_{CB} = E_{VB} - E_g \quad (2)$$

Where E_{VB} denotes the valence band edge potential, X denotes the electronegativity of V_2O_5 , which is approximately 6.1 eV, E_c denotes the energy of free electrons on hydrogen, which is approximately 4.5 eV, E_g denotes the band edge of materials, and E_{CB} denotes the conduction band edge potential. The V_2O_5 band-edge absorption ranges somewhere between 2.0 and 2.7 eV. As a result, E_{VB} is approximately 2.6–3.0 (eV vs. normal hydrogen electrode (NHE)), and E_{CB} is approximately 0.6–0.2 (eV vs. NHE) (eV vs. NHE). Holes can produce $HO\cdot$, whereas electrons at the bottom CB are unable to reduce oxygen molecules (O_2). To elucidate the electronic structure of V_2O_5 in its entirety, significantly more in-depth research is required. Since they offer potential benefits in a wide range of applications, V_2O_5 micro-nanostructures have attracted a lot of attention, and their production can take place in several ways. According to reports, vanadium nanoparticles can be made using a variety of chemical and physical processes, including the thermal evaporation method [16], the co-precipitation method [7], the sol-gel method [9], the solvothermal method [20], and the hydrothermal method [21].

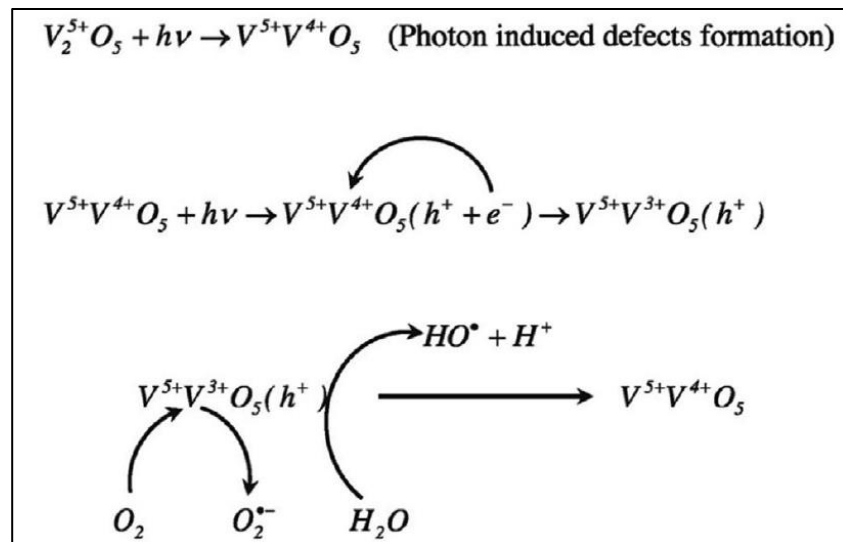


Figure 2. Schematic illustration of surface traps and electron transfer of V_2O_5 [19]

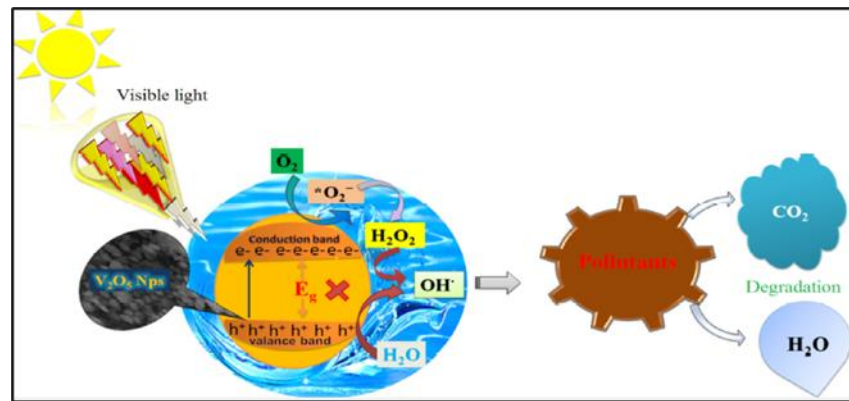


Figure 3. Schematic diagram of photocatalysis process by V_2O_5 [8]

Synthesis of Vanadium Pentoxide

A variety of methods have been used to successfully synthesise V_2O_5 based photocatalysts in various applications, including thermal condensation, solvothermal and sol-gel synthesis. Other common methods include hydrothermal approach and co-precipitation method. To construct an effective V_2O_5 photocatalyst, the optimal method must be used, which is determined by the photocatalyst's desired properties.

Hydrothermal Method

The term hydrothermal technique refers to a wet chemical process that makes use of an aqueous solution as the reaction system within a particular sealed container at a relatively high temperature and pressure reaction environment. According to a study by Sahraeian, Esmaeilzadeh and Mowla, (2021) [22], nanosphere particles of V_2O_5 were produced using the hydrothermal method at various temperatures. The study also revealed that a decrease in temperature causes more deposits to precipitate and that the majority of nanospheres had specific surface areas (BET) ranging from 126 to 207 m^2/g , based on the hydrothermal reaction temperatures. Utilising X-ray diffractometer (XRD), Raj *et al.*, (2015) [23] found that nanoparticles of V_2O_5 synthesised via the hydrothermal method have a crystalline morphology and a crystallite size of 61.6 nm. Rasheed *et al.*, (2021) [24] found porous V_2O_5 nanoparticles between 70.34 and 86.03 nm in size. They used approximately 0.1 g of ammonium metavanadate and 0.1 g of cetyltrimethyl ammonium bromide (CTAB) in a mixture of water-ethanol (100 mL) and added nitric acid until an orange-coloured precipitate formed, which was

then annealed at 250, 500, and 750 °C for two hours. The band gap increased to 2.63 eV when the sample was annealed at 250 °C but decreased to 2.48 eV when the sample was annealed at 500 °C. When annealed at 750 °C, the band gap grew to 2.56 eV. Vanadium nanoparticles underwent a phase transformation from amorphous to crystalline as the annealing temperature rose. Using 0.1 M ammonium metavanadate solution and 0.05 M sodium hydroxide (NaOH) solution, combined with carbon from tamarind fruit shells, and transferred to Teflon autoclave at 140 °C for three hours, Parashuram *et al.*, (2022) [6] were able to produce V₂O₅ nanoflakes. This was accomplished by heating the mixture in a Teflon autoclave. The SEM analysis demonstrated that the V₂O₅ nanoflakes had been successfully manufactured. This hydrothermal method was found to cause the anchoring of flaky V₂O₅ around N-doped carbon spheres, which can be confirmed by transmission electron microscopy (TEM) analysis. This was another finding of the research. It is anticipated that a successful catalytic performance will result from the correct attachment of V₂O₅ flakes over the carbon backbones.

Sol-Gel Method

Sol-gel nanoparticles are typically prepared by reacting precursors in a solvent and stirring them at low temperatures. This is the most prevalent nanomaterials-making process. After a given period, the nanomaterial is created by the hydrolysis and condensation of the gel intermediate, a natural consequence of colloidal particle aggregation. Sol-gel features minimal external energy consumption, economical precursors, good purity and uniformity in the end product, and decreased calcination temperature and time. These conditions generate photocatalysts with large surface area and crystallinity [8]. Mishra *et al.*, (2020) [9], for example, found that V₂O₅ nanoparticles (NPs) prepared by the sol-gel method and sonochemical methods were very stable and were found to be in single phase as shown by XRD and Raman spectroscopic studies and excellent nanoparticle dispersion in the reduced graphene oxide (rGO) sheets by SEM characterization. Acidic or alkaline catalysts are utilized to speed up this sluggish reaction and create stable particle sol. As time passes, the sol ages and the colloidal particles begin to clump together. During the research, nanoparticles of V₂O₅ were manufactured by dissolving citric acid in distilled water and then adding ammonium metavanadate to the resulting solution. This process was repeated several times. The V₂O₅ nanoparticles formed into a variety of different structures, including spherical, cylindrical, and rod-like structures. The band gap value obtained was 2.46 eV.

Isopropanol, vanadium (V)-triisopropoxide, and water were combined in a third experiment that was conducted by Shao *et al.*, (2014) [25]. This experiment synthesised V₂O₅ in accordance with the sol-gel method. In the experiment, the solution was first subjected to refluxing before it was heated to 70 °C and subjected to hydrolysis. As the heating temperature was raised, the XRD analysis showed that there was an increase in the sharpness of diffraction lines of V₂O₅ as well as an increase in crystallite size from several nm up to several tens of nm. This was one of the findings that emerged from the investigation. Sajid *et al.*, (2020) [8] have examined the similarities and differences between the hydrothermal method and the sol-gel method to prepare V₂O₅ nanoparticles. The hydrothermal (HT) method resulted in a high degree of crystallinity, whereas the disorder that results from the sol-gel (SG) method results in a lack of crystallinity. When compared to V₂O₅ nanoparticles made using the SG-method, those made using the HT-method have a significantly larger surface area as well as higher adsorption. The hydrothermal method makes it possible to prepare nanomaterials quickly and easily with a variety of morphologies.

Co-Precipitation Method

The production of a precipitate is a vital part of the co-precipitation technique. The technique entails the utilisation of a powerful base to accomplish the precipitation of iron oxide. The method involves heating of stable iron salt solutions with a known concentration is to be accompanied by the addition of a powerful base and the vigorous stirring of the solution. After allowing the solution to age for the precipitate to form, it is then decanted multiple times to remove any remaining residue. After obtaining the solid material, it is subjected to higher temperatures while being under vacuum conditions [26]. The synthesis of size-controlled nanoparticles is achieved using a modified version of the co-precipitation technique. This method calls for the mixing of cationic and anionic solutions, as well as the consistent monitoring of pH and temperature. The semiconducting material V₂O₅ is capable of forming into a variety of shapes using the co-precipitation technique, including nanoflakes, nanosheets, and nanospheres [7], [19].

Aside from that, co-precipitation is advantageous because it uses inexpensive precursor materials, is kind to the environment, and makes it simple to exert control over the end product. In a study that was conducted by Mukhtar *et al.*, (2021) [27] ternary ZnO/ V₂O₅/ WO₃ photocatalyst was synthesised by obtaining precipitates after the mixture was stirred for three hours and then annealed at a

temperature of 700 °C. The ZnO/ V₂O₅/ WO₃ nanocomposite used in the production of the photocatalyst exhibited a band gap value of 2.63 eV when measured. In the meantime, pure V₂O₅ had shown a band gap value of 2.2 eV, which indicates that the co-precipitation method successfully produced a photocatalyst based on V₂O₅ that is sensitive to a wider light spectrum. The scanning electron microscopy examination discovered that the produced photocatalyst had a globular and roughly hexagonal morphology and an average particle diameter of 5 µm, both of which are advantageous for photocatalytic activity. Oxalic acid, succinic acid, malic acid, and citric acid were the organic acids that were used as precursors in the co-precipitation methods that were investigated in a study that was conducted by Inomata *et al.*, (2021) [28].

As a result of the synthesis, it was discovered that the specific surface area of vanadium oxide catalysts increased to a maximum of 41 m²g⁻¹ when oxalic acid and succinic acid were used in the reaction. The thermogravimetric analysis (TGA) also confirmed that when these organic acids were used as a precursor, weight loss occurred at a higher temperature (400 °C). This indicates that the synthesis of vanadium oxide is best carried out at a lower temperature. In 2015, Aslam and colleagues [19] conducted research on the synthesis of a V₂O₅-ZnO photocatalyst using the co-precipitation method. In the experiment, ammonium metavanadate and zinc nitrate were mixed in 500 mL of deionized water while drop-by-drop additions of 0.5 mL of sodium hydroxide were made until a yellowish precipitate was obtained. The precipitate was then calcined at 450 °C in a muffle furnace for four hours. It was discovered that the size of photocatalyst ranged between 10.5 and 18 nm, and that it was high crystalline, as confirmed by XRD analysis. The parameters of their synthesis, such as temperature and pH, were really influence their size and morphology. As a result, it is essential to conduct research on the enhancement of V₂O₅ utilising the co-precipitation method.

Solvothermal Method

The solvothermal synthesis approach uses elevated pressures and temperatures to decompose precursor components in a solution to create the target product. The hydrothermal route and this one is quite comparable. Both processes are typically carried out in an autoclave made of stainless steel. The only distinction is that the precursor solution is typically one that does not contain water. Dimethylformamide and a variety of alcohols are examples of common types of solvents. At a temperature of 200 °C, Liu *et al.*, (2020) [29] successfully synthesised a TiO₂/ V₂O₅ composite by employing solvothermal synthesis and using isopropanol as their precursor. Based on the results of the SEM analysis, ultrathin nanosheets of V₂O₅ have been produced and uniformly covered on the surface of the TiO₂ nanobelts. The size range of these nanosheets is between 50 and 300 nm. In the meantime, a different study that was conducted by Li *et al.*, (2022) [30] used approximately 0.24 g of ammonium metavanadate that was dispersed in 40 mL of N, N-dimethylformamide (DMF) along with 0.2252 g of zinc acetate to produce V₂O₅/ZnV₂O₆ nanosheets. According to the results of an XRD study, the structure of V₂O₅ can be thought of as a series of layers that run perpendicular to the (001) direction, with only a weak interaction (primarily Van der Waals) occurring between the layers. Each layer is made up of periodic edge and corner sharing distorted VO₅ square pyramids. Additionally, this method produced V₂O₅ / ZnV₂O₆ with a calculated band gaps value of 1.87 eV, whereas the value for V₂O₅ by itself is 2.13 eV. Jansi Rani, Ravi and Yuvakkumar, (2020) [31] successfully synthesised good crystalline V₂O₅ nanostructures with an orthorhombic phase. This was verified by XRD analysis using the high intense peak of the (101) plane. The research looked at the effects of varying the treatment time over the course of 12, 25, and 36 hours during the solvothermal process. According to the findings, a treatment time of 12 hours produced agglomerated undefined nanostructures. A treatment time of 25 hours resulted in the formation of nano-cuboids as a morphological structure, and finally, a treatment time of 36 hours resulted in the production of thin nanosheets.

Thermal Evaporation Method

In thermal evaporation, a substance is evaporated by heating it until its vapour pressure is detectable. This causes surface atoms or molecules to be lost in a vacuum. Coatings, which are sometimes referred to as films, typically have a thickness that ranges from angstroms to microns and can be composed of either a single material or multiple materials arranged in a layered structure. Thiagarajan, Thaiyan, and Ganesan (2015) [32] produced V₂O₅ thin films of different thicknesses using electron beam-physical vapour deposition. During production, the substrate was shifted away from the aim. XRD investigation confirmed that a thicker coating enhances crystallinity and polycrystalline nature.

The use of the thermal evaporation method results in films that are compact and dense, and it has been observed that the surface is highly homogenous and does not contain any pinholes, cracks, or voids. This shows that the films have a good microstructure. The band gap analysis is also in good

agreement with a theory that obtains a band gap value of 2.36 eV for higher thickness films. In a different study done by Koduru *et al.*, (2016) [33], the thermal evaporation method was used to set up conditions like growth temperature at 450 °C, all plasma parameters, plasma voltage (2500 volts), separation between electrodes (70 mm), and gas flow rate (where the plasma was used) were kept constant throughout the film in the entire process. The deposition, as well as the duration of the deposition itself, was limited to a maximum of 30 minutes. The findings of the SEM revealed the effect that the deposition process had on the surface morphology of the films by exhibiting smooth surfaces and showing structures consisting of nanoflakes and nanobelts. Amorphous and crystalline V_2O_5 films were produced because the thermal evaporation process was carried out in an oxygen-rich environment, as demonstrated by the findings of the XRD analysis. The numerous synthesis techniques that can be used to modify the characteristics of V_2O_5 as a photocatalyst are outlined in Table 1. Because the band gaps of various crystalline structures of V_2O_5 are distinct from one another, this is another factor that must be considered in the process of manufacturing highly effective photocatalysts. As a direct consequence of this, the level of photocatalytic activity was variable. Figure 4 shows some of the structures of V_2O_5 that have been produced in previous studies.

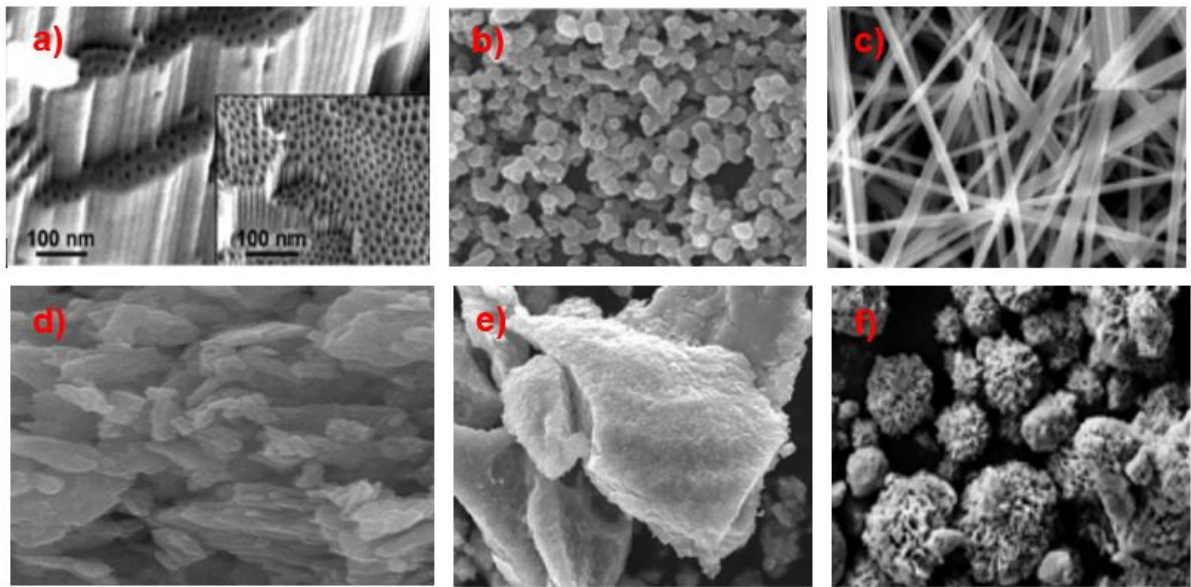


Figure 4. Some V_2O_5 micro-nanostructures: a) nanotubes [34] b) nanospheres [35] c) nanowires [36] d) nanoflakes [37] e) nanosheets [31] f) microflowers-like [38]

Table 1. Various synthesis methods of V_2O_5 as photocatalyst

Synthesis method	Description process	Starting materials	Morphology	Particle sizes	Band gap	References
Hydrothermal method	<ul style="list-style-type: none"> adopts an aqueous solution in a sealed container at high temperature and pressure; simple, easy to manage; no calcination needed. 	<ul style="list-style-type: none"> NH_4VO_3, distilled water, ethanol, nitric acid 	<ul style="list-style-type: none"> produced high crystallinity of photocatalyst have a large surface area 	70.34 - 86.03 nm	2.63 eV	[24]
Sol-gel method	<ul style="list-style-type: none"> Colloidal hydroxide or hydrated oxide precipitation are often formed from metal alcohol salts or inorganic metal salts hydrolysed fast in excess water. 	<ul style="list-style-type: none"> NH_4VO_3, distilled water, citric acid 	<ul style="list-style-type: none"> various structures of the particles like cylindrical, spherical, and rod-like structures 	400 to 800 nm	2.46 eV	[9]
Co-precipitation method	<ul style="list-style-type: none"> involves the formation of a precipitate. involves the precipitation of iron oxide using a strong base precipitation involves inexpensive precursor materials, environmental friendliness, ease of control over the final product 	<ul style="list-style-type: none"> vanadium nitrate hexahydrate $V(NO_3)_2 \cdot 6H_2O$, distilled water, NaOH 	<ul style="list-style-type: none"> globular and roughly hexagonal morphology High crystallinity 	5 μm	2.2 eV	[27]
Solvothermal method	<ul style="list-style-type: none"> adopts the nonaqueous solution at quite high temperature and pressure in a sealed container. 	<ul style="list-style-type: none"> ammonium metavanadate dispersed, N-dimethyl formamide (DMF) 	<ul style="list-style-type: none"> good crystalline V_2O_5 nanostructures with an orthorhombic phase 	50–300 nm	2.13 eV	[30]
Thermal evaporation method	<ul style="list-style-type: none"> heating a substance until the vapour pressure is significant and atoms or molecules are lost in a vacuum. 	<ul style="list-style-type: none"> Vanadium oxide V_2O_5 powder 	<ul style="list-style-type: none"> smooth surfaces and exhibiting nanoflakes and nanobelts structures. amorphous and crystalline V_2O_5 films 	31-45 nm	2.36 eV	[32]

Photodegradation Application of V₂O₅ Photocatalysts

In applications involving the cleaning of the environment and the conversion of energy, semiconductor photocatalysis is a field that is rapidly expanding. Due to their poor utilisation of visible light, semiconductors, in general, have not been able to be used in applications that require efficient energy conversion until recently. The finding of photocatalysts based on V₂O₅ stands out as an excellent choice in this regard because it offers a moderate band gap (2.3 eV) and a high sensitivity to visible light. In the following section, the application of photodegradation to the removal of organic pollutants such as dyes, pharmaceutical waste, and phenolic compounds is discussed.

Dyes

The application of pollutant photodegradation by photocatalysts based on V₂O₅ has seen extensive use for the photodegradation of a wide variety of dye pollutants, including methylene blue, methyl violet, rhodamine B, crystal violet, and a great number of others. The production of azo dyes continues today even though these dyes are known to cause cancer and are also known to be toxic. This is due to the fact that azo dyes are very inexpensive [7]. Therefore, it is of the utmost importance to investigate different ways that the damaging effects of these pollutants on the environment can be mitigated. In this regard, several research organizations have looked into the possibility of utilising photocatalysts that are based on V₂O₅ for the photodegradation of the pollutants in question. Sekar *et al.*, (2021) [5] employed ultrasonication to generate graphitic carbon (GC) / V₂O₅ nanocomposites. They investigated the photocatalytic activity of these nanocomposites by exposing samples to visible light. Due to the encapsulation of defective V₂O₅ by conductive GC, GC / V₂O₅ nanocomposites improved photocatalytic dye-degradation efficiency by 98.4% in 105 minutes. GC may encapsulate flawed V₂O₅ surfaces, increasing photocatalytic crystal violet (CV) degradation activity. This may boost photocarrier transport and photocatalytic reaction at the mixture's interface and medium.

The researchers Badreldin *et al.*, (2021) [14] used a controllable and environmentally benign physicochemical reduction method to produce a novel black V₂O₅ material called b- V₂O₅. This material was used to degrade methylene blue (MB) dyes. After reaching adsorption equilibrium (capacity = 75 mg/L MB) without light illumination, it was determined that the optimized b- V₂O₅ photocatalyst was able to actively achieve 92% MB photodegradation in one hour when exposed to visible light with an intensity of 0.7 kW/m². The effective performance of photodegradation is thought to be due to the reduction of NaBH₄ that occurs during synthesis. It is believed that the relatively low level of intercalated Na⁺ in b- V₂O₅, which was produced because of the reduction of NaBH₄, makes it easier for neighbouring photogenerated electrons to transfer along the bridge-Na sites. Both help to inhibit the rate at which electrons and holes recombine, which in turn improves the visible light photodegradation kinetics. Vanadium pentoxide (V₂O₅) nanorods/graphene oxide (GO) nanocomposite was synthesised and characterised by Beaula Ruby Kamalam *et al.*, (2021) [15] for the purpose of degrading Victoria blue (VB) dye, and they reported that the dye underwent almost complete degradation (97.95 %) within just 90 minutes when it was exposed to direct sunlight illumination. During the photocatalysis process of VB dyes, a reduction in the recombination of electron-hole pairs increases the carrier concentration at the respective levels. This contributes to the best performance. It is believed that GO can act as an electron quencher and slows down the rate at which charge carriers can recombine in V₂O₅ nanorods. In this way, GO serves as a sink for photogenerated electrons, which speeds up the process of charge carrier separation in V₂O₅. During the process of photodegradation, these electron-hole pairs result in the production of hydroxyl radicals (OH·), superoxide radicals (O₂⁻), and a great deal of other oxygenated reacting species.

While this was going on, Jenifer, Sastri and Sriram, (2021) [39] used V₂O₅ nanoparticles that were synthesised using facile soft chemical method to degrade methyl violet (MV) dye and methylene blue (MB) dyes. It was found that there were 92% of MV dyes and 82% of MB dyes respectively. The mobility of the charge-free carriers in V₂O₅ is one of the factors that contributes to the material's performance as a photocatalyst. The high mobility of the charge carriers causes a reduction in the recombination rate, which leads to an increase in the redox reaction rates and an improvement in the photocatalytic activity of the dyes that are pollutants. Jayaraj *et al.* (2018) [11] found that degradation of Rhodamine 6G (Rh-6G) dye is initiated by the attack of •OH radicals on the Rh-6G dye, and an ester group formed and was converted to carboxylic acid and continued to produce by-product as shown in Figure 5. The by-products obtained were then subjected to additional oxidation, which resulted in the formation of benzoic acid (m/z = 122), glutaric acid (m/z = 132), 3-hydroxybenzoic acid (m/z = 138), 3,4-dihydroxybenzoic acid (m/z = 155), and phthalic acid (m/z = 166).

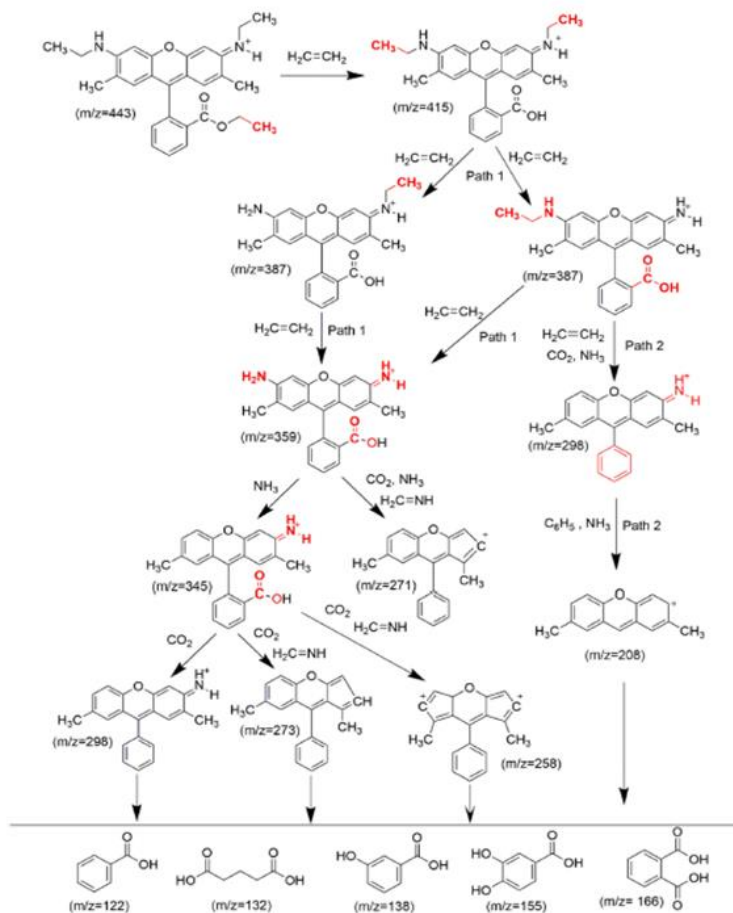


Figure 5. The proposed degradation pathway of Rh-6G dye by V_2O_5 [11]

Pharmaceutical Wastes

Pharmaceutical wastes are manufactured or naturally occurring substances present in prescription pharmaceuticals, over-the-counter drugs, and veterinary treatments with clinical significance. The rising usage of pharmaceutical items is affecting traditional wastewater treatment facilities due to poor or non-existent pharmaceutical species removal. These chemicals produce and consume pharmaceutical-laden wastewaters that must be treated before being discharged into the environment. Even at low quantities, pharmaceutical chemicals offer a toxicological danger, raising concerns about their expanding environmental presence. Pharmaceutical products (PPs) can be persistent, stubborn, and have biological actions that can cause endocrine disruption [40]. Photocatalysis is used in treatment trains to mineralise medicines.

Photocatalysis with V_2O_5 -based photocatalysts has seen extensive use for the photodegradation of a wide variety of pharmaceutical wastes, including diclofenac, tetracycline, doxycycline, and oxytetracycline, as well as amoxicillin, ciprofloxacin, erythromycin, and a great number of other pharmaceutical wastes. Vanadium pentoxide (V_2O_5) was synthesised for the purpose of this research by Oliveros *et al.* (2021) [41], and it was integrated into boron-doped graphitic-carbon nitride (BCN) to degrade diclofenac (DCF). They found that the DCF almost reached its target degradation level of 100% in less than 105 minutes. Boron doping on g- C_3N_4 (BCN) enhances charge carrier separation and allows heterojunction formation for effective photogeneration of oxidants, leading to nearly 100% DCF degradation. During this time, Huang *et al.* (2021) [42] conducted research to investigate the photodegradation of tetracycline (TC) by a photocatalyst composed of V_2O_5 and NH_2 -MIL-101(Fe). It was reported that the photocatalyst had been responsible for the degradation of approximately 88.35% of the TC. The heterojunction structure between V_2O_5 and NH_2 -MIL-101(Fe) suppresses photo-generated electron-hole recombination and separates interaction photo-generated electron-holes quickly. This is the primary factor that contributed to the results that were obtained. Liu *et al.* (2020) [29]

used polymer-clothed TiO₂/V₂O₅ nanobelts in their investigation of the photodegradation of TC antibiotics. Their results showed that an almost complete degradation of TC has been reported, which can be primarily attributed to the construction of a heterojunction, which promotes the interfacial separation of photogenerated charge.

Le *et al.* (2021) [16] developed a V₂O₅ nanodot-decorated laminar C₃N₄ (VO/CNNS) material to degrade amoxicillin (AMX) under solar light. Calcination method was used to prepare the VO/CNNS photocatalyst. This technique formed an S-scheme heterojunction, which helped the photocatalyst degrade AMX residues in artificial sunlight. The S-scheme heterojunction structure of the VO/CNNS nanocomposite increased the separation and transfer of photogenerated charge carriers for reactive oxygen species (ROS) production and photocatalytic degradation. During the photodegradation of AMX, the most important reactive species are free radicals, such as O₂[•] and h⁺ radicals. As shown in Figure 6, AMX has been fully degraded into H₂O and CO₂.

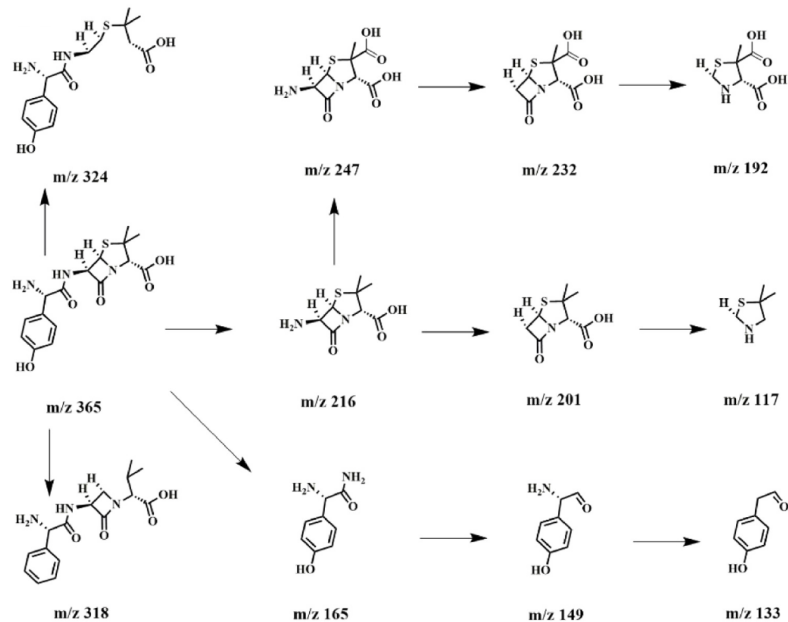


Figure 6. Proposed degradation pathway of amoxicillin by V₂O₅-based photocatalyst [16]

Phenolic Compounds

Phenols are among the most resilient potential pollutants in wastewater, and the toxicity of phenol derivatives is determined by the number of atoms in the compound as well as their location in relation to the hydroxyl group. The phenol derivatives, particularly those that have been substituted at the 2-position of the aromatic ring, are further stabilised by the formation of hydrogen bonds within the molecule [43]. The phenolic compound is toxic to all living things, including plants, animals, and even microorganisms, in addition to being carcinogenic and mutagenic. In the past many years, vanadium pentoxide has been used as a base semiconductor in the photocatalysis process for the remediation of many kinds of phenolic compounds, such as bisphenol A (BPA), nitrophenols, 2,4-dichlorophenols (2,4-DCP), and others. This process has been successful in removing a variety of these compounds from the environment. Parashuram *et al.* (2022) [6] investigated the possibility that nitrogen-doped carbon spheres made from Tamarindus indica shells and decorated with vanadium pentoxide photocatalyst could break down BPA. The photocatalyst that was developed was successful in achieving photodegradation of BPA at a rate of 95% in a period of 80 minutes. The band gap of V₂O₅ nanoflakes is believed to have shrunk after being decorated with N-doped carbon matrix. The presence of nitrogen is thought to be responsible for the increased activity, and the high surface area of carbon spheres (CS) conduction is thought to have contributed to the increased mobility of electrons. As a result, this makes it an efficient photocatalyst for the degradation of BPA. The possible photodegradation pathway of BPA using V₂O₅ based photocatalyst is shown in Figure 7. It found that the degradation of BPA produced the 4,4'-(1-hydroxyethane-1,1-diyl) diphenol after being attacked by hydroxyl radicals. Then the photodegradation is continued to C–C bond cleavage reaction and followed by atomic ring opening to produce formic acid and acetic acid and lastly mineralised to carbon dioxide and water.

In the meantime, a study conducted by Zheng and Zhang, (2021) [17] found that photodegradation of chlorophenols could be achieved using V_2O_5 that was incorporated with $Ni_3V_2O_8$. Based on the results of the photocatalysis study, it was determined that approximately 90% of the 2,4-DCP had been successfully photodegraded. Due to proximity of the interface between V_2O_5 and $Ni_3V_2O_8$, the photogenerated charge separation is carried out more successfully. In the meantime, the distinctive hollow structure could make effective use of multiple light reflections within the cavity for the purpose of light harvesting. Because of these characteristics, the $V_2O_5 / Ni_3V_2O_8$ hollow sphere n-n heterojunction possesses enhanced photocatalytic activity for the degradation of 2,4-DCP when it is exposed to visible light. Aslam *et al.* (2015) [19] published a study that compared the photodegradation performance of various phenolic compounds, such as 2-nitrophenols (2-NP), 4-nitrophenols (4-NP), and 2,4-dinitrophenols (2,4-DNP), by employing V_2O_5 -ZnO composites as the photocatalyst. It was discovered that the mineralisation of 2-NP was significantly quicker than that of 4-NP and 2,4-DNP, with complete photodegradation occurring in only 180 minutes. According to the findings that were obtained concerning the deterioration of NP substrates, the activity of the composites decreases with increasing V_2O_5 contents. This is because consideration needs to be given to the positions of the band edges of the two semiconductors. When ZnO absorbs photons, one of the processes that takes place is the trapping of photogenerated electrons by V_2O_5 surface states. This process is favoured because it can improve efficiency by reducing the amount of charge carriers that recombine after being generated.

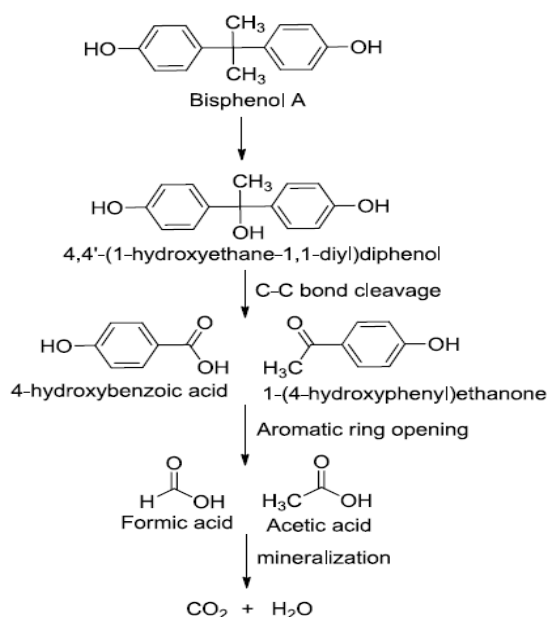


Figure 7. Propose photodegradation pathway of BPA using V_2O_5 based photocatalyst [6].

Conclusions

V_2O_5 has a long history of being used in a variety of applications, based on the methods by which it is obtained and the properties of its final structure. This mini review has provided a concise summary of the various methods for obtaining vanadium pentoxide, with an emphasis on the various structures. Due to V_2O_5 's adaptability and stability, numerous studies have been conducted on the structural changes that occur depending on the property of interest. Then, after using a variety of methods for obtaining information, it was possible to locate several pollutants that had been subjected to photodegradation. In addition, the conditions and methods that are used can have a significant impact on the structural, optical, and electrical properties of the V_2O_5 films that are produced. The fact that V_2O_5 has a low cost and is simple to obtain, in addition to the wide range of synthesis options it provides, reveals that the material has a lot of potential in a variety of application fields, whether those fields are technological or innovative. In addition, the use of V_2O_5 has shown a promising response in every application, and in the not-too-distant future, the technology used to design new devices will include the V_2O_5 as one of the components.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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