ORIGINAL SCIENTIFIC PAPER
DOI: 10.63395/STEDConf14022025928G295
Submitted: 21.08.2025.
Accepted: 25.10.2025.

THIN-FILM SUSTAINABLE TECHNOLOGIES: THE POTENTIAL OF VANADIUM OXIDES

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ABSTRACT

Vanadium oxides (VO_x) represent a diverse family of transition metal oxides with rich structural and electronic properties, making them promising candidates for a wide range of applications in sustainable technologies. Their ability to exhibit multiple oxidation states and reversible redox behavior enables their use in electrochemical systems such as supercapacitors, lithium-ion batteries, and electrochromic devices. Simultaneously, VO_x compounds possess tunable optical and semiconductor properties that make them attractive for photochemical applications, including photocatalytic degradation of pollutants and solar-driven water splitting. This mini review explores the multifunctional nature of VO_x materials, with a focus on their integration into thin films and nanostructures that enhance performance and enable scalable use. Emphasis is placed on recent advances in deposition techniques, structure–property relationships, and the dual electrochemical and photochemical potential of VO_x-based systems. By showcasing their adaptability and relevance to clean energy and environmental technologies, this review positions vanadium oxides as key materials for future innovation in green and smart devices.

Keywords: vanadium, oxides, electrochemistry photochemistry.

INTRODUCTION

The growing global demand for clean energy, environmental remediation, and sustainable technologies is driving the development of advanced functional materials. As the world transitions toward low-carbon and circular economies, the design and deployment of materials that are both high-performing and environmentally benign have become critical. In this context, multifunctional thin films of metal oxides have attracted increasing interest due to their wide range of applications, including microelectronic devices, catalysis, biocompatible materials, and solar energy systems (Pacchioni, 2012). Among various candidates, vanadium oxides have emerged as a promising class of multifunctional materials due to their unique physicochemical properties, including a wide range of accessible oxidation states, structural diversity, and strong redox activity. As a result, there has been accelerated research and development of VO_x compounds for a variety of applications, including batteries, energy-saving smart windows, sensors, catalysts, and optoelectronic devices. Tailoring the electronic properties of vanadium oxides has become a key focus in the design of high-performance materials. This is because the electronic, catalytic, and photocatalytic properties of VO_x are highly structure-dependent, and their crystal structure also plays a critical role in determining the material's stability and suitability for specific applications (Hu et al., 2023).

Given their multifunctionality, tunable structure, and compatibility with low-temperature processing, vanadium oxides and their thin-film forms are gaining increasing attention for integration into a wide range of technologies. VO_x thin films, in particular, offer advantages such as controllable thickness, high surface-to-volume ratio, and the ability to be deposited on flexible or microstructured substrates (Dong et al., 2021). These properties make them especially attractive for miniaturized energy storage devices, transparent electronics, electrochromic smart windows, sensors, and photocatalytic coatings. Moreover, various synthesis methods — including reactive sputtering, sol–gel deposition, atomic layer deposition, and thermal evaporation — allow for precise control over stoichiometry, crystallinity, and morphology, which are critical for optimizing performance in target applications.

In the following sections, this paper presents a concise overview of recent literature on vanadium oxide materials for key applications in electrochemical energy storage, electrocatalysis, and photocatalysis, with a special emphasis on thin-film systems where such studies are available. The aim is to highlight the latest trends, underlying mechanisms, and technological relevance of VO_x-based materials while identifying opportunities and challenges for their future development in sustainable technologies.

STRUCTURAL AND ELECTRONIC PROPERTIES OF VO_x COMPOUNDS

VO_x exhibit a wide range of crystal structures and oxidation states, owing to the ability of vanadium to exist in multiple valence forms—primarily V^{3+}, V^{4+}, and V^{5+}. This allows for the formation of various stoichiometries such as V_2O_3, VO_2, V_2O_5, and V_6O_{13}, each with distinct structural, electronic, and optical properties that directly impact their electrochemical and photocatalytic performance (Alasmari et al., 2025). Mixed-valence VO_x compounds often arise from the introduction of oxygen vacancies. When vacancy concentrations exceed a critical level, they align along crystallographic planes to form shear structures, leading to reorganization of the V–O framework. This process results in structurally related phases, including the Magnéli series (V_nO_{2n-1}) and Wadsley phases ($V_{2n}O_{5n-2}$) (Beke, 2011). From a chemical perspective, vanadium oxide stands out as an excellent catalyst due to its rich and diverse chemistry, which stems from two key factors: the ability of vanadium to adopt oxidation states from +2 to +5, and the variability in oxygen coordination geometries. This structural complexity leads to the presence of differently coordinated oxygen species, which are critical in tuning surface-related physical and chemical properties. Moreover, V_2O_5 has layered crystal structure that enables facile intercalation of ions, making it highly promising for energy storage applications, especially in systems requiring high ionic capacity and reversible redox activity (McNulty et al., 2014). Due to the strong coupling between optical and electrical properties, VO_x materials are particularly attractive in thin-film form for integration into microelectronic devices. Notably, V_2O_5 has also been investigated for use in variable-transmittance electrochromic windows, enabling dynamic control of solar light transmission (Yang et al., 2023). Studies by Wu et al. (Wu et al., 2013) have shown that the electronic properties of VO_x compounds, such as charge carrier concentration, conductivity, and metal-insulator transition (MIT) behavior, are strongly influenced by their microstructure and electron-electron correlations. Controlling these features at the atomic scale has enabled the development of VO_x-based devices for energy storage, conversion, and utilization including lithium-ion batteries, supercapacitors and thermoelectric generators. In particular, VO_2 is well known for having a sharp and reversible MIT, accompanied by significant changes in optical transparency, electrical resistivity, and magnetic susceptibility. These properties open pathways for optoelectronic, thermal, and magnetic applications (Li et al., 2023).

Overall, the remarkable structural diversity and tunable electronic characteristics of vanadium oxides make them a unique class of materials with multifunctional potential. The interplay between oxidation state, crystal structure, and microstructural features governs their electrochemical, optical, and catalytic performance, enabling application-specific optimization. In particular, the reversible redox behavior, high ionic mobility, and metal–insulator transition properties underscore their suitability for a broad spectrum of energy-related technologies. Building on this fundamental understanding, the following sections will explore how these intrinsic properties are harnessed in practical applications, with an emphasis on VO_x-based thin films and nanostructures designed for electrochemical energy storage and photocatalytic systems.

VO_x FOR ELECTROCHEMICAL ENERGY STORAGE

VO_x have gained increasing attention for electrochemical energy storage due to their rich redox chemistry, structural versatility, and ability to reversibly host a variety of ions. Energy storage devices are generally categorized as batteries or supercapacitors, based on their charge storage mechanisms. While batteries offer high energy density, supercapacitors provide much higher power density but lower energy storage capacity. Traditionally, supercapacitor electrodes are composed of porous carbon materials; however, the incorporation of transition metal oxides has introduced pseudocapacitive behavior - charge storage via fast, reversible redox reactions. VO_x materials exhibit such pseudocapacitive characteristics, either through surface redox reactions or intercalation-driven processes, leading to significantly enhanced energy density. In thin-film form, VO_x also offers advantages in terms of tunable morphology, integration into microscale systems, and improved electrochemical performance. The following section reviews recent advances in the application of specific VO_x compounds in supercapacitors and batteries, highlighting their structure–function relationships and electrochemical behavior.

Karthikeyan et al. (Karthikeyan et al., 2025) demonstrated that 2D VO_x nanosheets, synthesized hydrothermally, show promising supercapacitor performance with high specific capacitance, excellent cycling stability, and a high-power density in an asymmetric configuration - highlighting their potential for advanced energy storage applications. However, VO_x materials often face challenges that limit their ability to reach theoretical capacities or display full multifunctional behavior, such as voltage-dependent color changes. These limitations are primarily due to their inherently low electrical conductivity and structural instability during charge–discharge cycling, which can lead to structural collapse. To overcome these issues and fully exploit their potential, recent strategies have focused on heteroatom doping and combining VO_x with more conductive materials to enhance overall conductivity. For example, nitrogen-doped V_2O_5 on CoS (Zhou et al. 2025) and sulfur-doped V_xO_γ on carbon supports (Song et al., 2025) have shown significant improvements in both energy and power densities. Moreover, the combination of VO_x pseudocapacitive properties with its electrochromic behavior has led to the development of multifunctional electrochromic supercapacitors. Yang et al. (Yang et al., 2024) developed copper vanadium oxide yolk–shell microspheres where adding Cu as rigid component weaken structural collapses and to improve conductivity. Such electrode material displays three color transitions at potential 1.2 V, 0 V and -0.8 V.

In thin-film form, V_2O_5 has been deposited using RF magnetron sputtering and investigated for its potential application as a supercapacitor electrode and as a cathode material for Li-ion batteries. Studies have shown that key deposition parameters (oxygen partial pressure, sputtering power, substrate temperature, and deposition time) influence the microstructure, crystallinity, and oxidation state of the resulting films. These microstructural characteristics, in turn, affect the electrochemical behavior of the films, including their capacitance, cycling stability, and Li^+ intercalation capacity (Dhananjaya et al., 2020).

In terms of battery applications, VO_x materials have been widely explored as cathodes for Li-ion batteries; however, recent research has increasingly focused on their use in zinc-ion batteries (ZIBs). In particular, thin films of V_6O_{13} have been deposited via DC magnetron sputtering, demonstrating promising performance (Zhao et al., 2025). The unique layered structure of V_6O_{13} facilitates efficient electrolyte penetration, while the V–O interlayers promote reversible Zn^{2+} ion insertion and extraction. Furthermore, these thin-film electrodes exhibit excellent structural stability during cycling, a critical factor in extending the operational lifespan of energy storage devices. Also vanadium oxide nanostructures showed potential in using as cathode for K-ion batteries (Xie et al., 2025), Na-ion batteries (Sayeed et al., 2025), ammonium-ion batteries (Zhang et al., 2025), and Li-S batteries (Hou et al., 2025).

To conclude, recent progress in engineering the VO_x materials highlights their significant potential for advanced electrochemical energy storage. These developments reflect a growing ability to tailor their performance through controlled synthesis and device integration. Looking ahead, further research into enhancing conductivity, stability, and multifunctionality will be key to unlocking the full capabilities of VO_x in next-generation energy storage systems.

VO_x FOR ELECTROCATALYSIS AND PHOTOELECTROCATALYSIS

Recent research has expanded the application of VO_x into electrocatalysis and photoelectrocatalysis, where they demonstrate activity in energy conversion reactions. Their catalytic behavior is strongly influenced by their oxidation state, defect chemistry, and interaction with light or external potentials. In photoelectrocatalysis, VO_x materials are particularly attractive due to their ability to absorb visible light and facilitate charge transfer at the interface. This section presents recent advances in VO_x-based catalysts, with an emphasis on structural tuning, combinations with other materials, and performance metrics in both electrochemical and light-assisted catalytic processes.

To demonstrate that the oxidation state and crystal structure of vanadium in VO_x play a significant role in electrocatalytic activity, Choi (Choi, 2022) compared differently synthesized VO_x materials for the oxygen evolution reaction (OER) and found that monoclinic VO_2 exhibits the highest catalytic activity. Another promising application of VO_x materials in electrocatalyst design is their use as a support for nanoparticles. Recent studies showed that single-atom Co dispersed onto highly crystalline V_2O_5 exhibits high OER activity and excellent durability (Youn et al., 2022), which is crucial for potential real-world applications. Additionally, combining oxygen-deficient VO_x materials with carbon to form supports for Ir nanoparticles has shown high activity for the hydrogen evolution reaction (Zhan et al., 2024).

Due to their relatively narrow bandgap, VO_x materials can efficiently absorb visible light, making them suitable for photoelectrocatalytic applications where electron excitation from the valence to the conduction band is essential. Ko et al. (Ko et al., 2022) developed a facile method to deposit oxygen-deficient VO_x nanosheets and demonstrated that a higher content of oxygen vacancies improved charge transport and interfacial charge transfer, enhancing the photoelectrocatalytic oxidation of water and methanol. However, a major limitation of VO_x photoanodes is their high electron–hole recombination rate, which reduces photocatalytic efficiency. One effective strategy to overcome this involves combining VO_x with other materials, such as noble metal nanoparticles. For instance, Ag nanoparticles have been shown to enhance photocatalytic performance by suppressing charge-carrier recombination at the metal/semiconductor interface (Waheed et al., 2025).

Overall, VO_x materials show great promise as electrocatalysts and photoelectrocatalysts, with their performance tunable through structural engineering, defect control, and strategic integration with other materials.

VO_x FOR PHOTOCATALYSIS AND ENVIRONMENTAL APPLICATIONS

VO_x materials have gained significant interest in photocatalysis and environmental remediation due to their tunable bandgap, ability to generate reactive oxygen species under illumination, and structural versatility that supports surface modification. In environmental applications, VO_x-based photocatalysts have been widely studied for the degradation of organic pollutants, particularly dyes, under visible-light irradiation. Recent strategies to improve VO_x performance have focused on overcoming its limitations by enhancing charge separation and increasing stability, often through doping and composite formation to stabilize surface-active sites. This section discusses recent advances in VO_x-based nanostructures and composite materials for dye degradation, with an emphasis on the role of structural modifications in improving photocatalytic performance.

To demonstrate the potential of VO_x nanoparticles as photocatalysts for Methylene Blue (MB) dye degradation, Nhan et al. (Nhan et al., 2024) employed a hydrothermal synthesis followed by annealing, showing that the annealing temperature strongly influences the morphology, crystal structure, optical properties, and consequently, the photocatalytic activity of VO_x. An improvement in the photocatalytic activity of V_2O_5 has been observed through Zr doping, which enhances the rate constant of the Rhodamine B (RdB) dye degradation reaction (Haribaaskar & Yoganand, 2024).

Another approach to enhance the photocatalytic efficiency of VO_x materials involves forming composites with complementary materials that impart desirable properties. For example, a type-II heterojunction between MoS_2 and V_2O_5 was synthesized to facilitate the photodegradation of MB. This heterostructure material demonstrated significantly higher MB removal efficiency under UV light compared to individual MoS_2 or V_2O_5 photocatalysts, highlighting its promise for wastewater treatment applications (Nadeem et al., 2025). Combining VO_x with graphitic carbon nitride (g-

C_3N_4) has proven highly effective not only for Rhodamine B (RhB) dye degradation but also for enhancing photocatalytic hydrogen (H_2) production. The favorable band alignment between V_2O_5 and g-C_3N_4 promotes the formation of a heterojunction, which facilitates efficient charge separation and suppresses electron–hole recombination, ultimately resulting in enhanced photocatalytic activity (Zhao et al., 2020).

CONCLUSIONS

In this work, we have presented recent advances in the use of VO_x as a versatile class of materials positioned at the intersection of electrochemistry, photochemistry, and materials science. Their rich structural diversity, wide range of oxidation states, and tunable electronic and optical properties have enabled integration into various sustainable technologies, including energy storage devices, electrocatalysts, and photocatalysts. In thin-film and nanostructured forms, VO_x compounds offer unique advantages such as enhanced surface area, improved charge transport, and compatibility with flexible and miniaturized devices.

This review has highlighted recent progress in the synthesis, structural control, and functional optimization of VO_x materials, with particular emphasis on their dual electrochemical and photochemical potential. Despite notable advancements, challenges remain, such as limited electrical conductivity, structural instability during cycling, and charge recombination in photocatalysis. Overcoming these issues through strategic material design includes doping, heterostructuring, and defect engineering will be essential to unlocking the full potential of VO_x in future applications.

Continued interdisciplinary research into the structure–property–performance relationships of vanadium oxides will not only deepen fundamental understanding but also accelerate their implementation in next-generation clean energy and environmental technologies.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

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