

Vanadium pentoxide (V_2O_5) as a next-generation electrode: Classification, synthesis strategies, and electrochemical applications

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Abstract

The escalating demand for advanced electrochemical energy storage drives the search for high-performance electrode materials. Vanadium pentoxide (V_2O_5) has emerged as a premier candidate due to its abundance, rich redox chemistry, and distinctive layered structure that facilitates multivalent-ion intercalation. This review systematically examines recent advancements in V_2O_5 research, beginning with a structural classification of its nanomaterials (0D to 3D). We critically evaluate state-of-the-art synthesis strategies—such as hydrothermal and sol-gel methods—highlighting how precise morphological control governs electrochemical behavior. Furthermore, we explore the diverse applications of V_2O_5 across next-generation platforms, with particular emphasis on aqueous zinc-ion batteries, lithium/sodium-ion systems, and high-energy supercapacitors. Addressing inherent limitations like low intrinsic conductivity and structural degradation during cycling, we analyze the latest mitigation strategies, including defect engineering and conductive hybridization. Finally, this review outlines remaining bottlenecks and future perspectives, offering a strategic roadmap to accelerate the transition of V_2O_5 electrodes from laboratory research to commercial energy storage technologies.

Keywords: vanadium pentoxide, energy storage, nanostructures, zinc-ion batteries, supercapacitors.

Pentóxido de vanádio (V_2O_5) como eletrodo de próxima geração: Classificação, estratégias de síntese e aplicações eletroquímicas

Resumo

A crescente demanda por sistemas avançados de armazenamento eletroquímico de energia impulsiona a busca por materiais de eletrodo de alto desempenho. O pentóxido de vanádio (V_2O_5) tem se destacado como um candidato promissor devido à sua abundância, à sua rica química redox e à sua estrutura em camadas característica, que favorece a intercalação de íons multivalentes. Esta revisão examina sistematicamente os avanços recentes nas pesquisas sobre V_2O_5 , começando pela classificação estrutural de seus nanomateriais, de estruturas zero-dimensionais (0D) a tridimensionais (3D). Avaliamos criticamente as estratégias de síntese mais avançadas, como os métodos hidrotérmicos e sol-gel, destacando como o controle preciso da morfologia influencia o comportamento eletroquímico. Além disso, exploramos as diversas aplicações do V_2O_5 em plataformas de armazenamento de energia de próxima geração, com ênfase especial em baterias aquosas de íons zinco, sistemas de íons lítio e sódio e supercapacitores de alta densidade energética. Considerando as limitações intrínsecas do material, como a baixa condutividade elétrica e a degradação estrutural durante os ciclos de carga e descarga, analisamos as estratégias mais recentes para minimizar esses problemas, incluindo a engenharia de defeitos e a formação de híbridos com materiais condutores. Por fim, esta revisão apresenta os principais desafios ainda existentes e as perspectivas futuras, oferecendo um roteiro estratégico para acelerar a transição dos eletrodos à base de V_2O_5 da pesquisa laboratorial para as tecnologias comerciais de armazenamento de energia.

Palavras-chave: pentóxido de vanádio; armazenamento de energia; nanoestruturas; baterias de íons zinco; supercapacitores.

1. Introduction

The rapid acceleration of global industrialization, combined with the urgent need to mitigate climate change, has driven unprecedented demand for clean, renewable energy sources such as solar, wind, and hydroelectric power. However, the intermittent nature of these energy sources presents significant challenges for grid stability, necessitating the development of efficient, scalable, and reliable electrochemical energy storage systems (EESSs).

While lithium-ion batteries (LIBs) currently dominate the portable electronics and electric vehicle (EV) markets owing to their high energy density and long lifespan, concerns regarding lithium resource scarcity, escalating costs, and safety hazards associated with organic liquid electrolytes have highlighted the need for alternative and complementary storage technologies. Consequently, next-generation energy storage platforms—including aqueous zinc-ion batteries (AZIBs), sodium-ion batteries (SIBs), and high-power supercapacitors—have gained intense research interest (Ding et al., 2019).

The core of these advancing technologies is the search for electrode materials capable of delivering high specific capacity, rapid charge-discharge rates, structural durability, and cost-effectiveness. Among the wide spectrum of transition metal oxides (TMOs), vanadium pentoxide (V_2O_5) has emerged as a particularly compelling candidate. Possessing a multi-electron redox mechanism enabled by the flexible oxidation states of vanadium (V^{5+} , V^{4+} , and V^{3+}), V_2O_5 offers exceptionally high theoretical specific capacities (e.g., $\sim 294 \text{ mAh g}^{-1}$ for two-electron insertion processes).

Structurally, pristine V_2O_5 exhibits a layered crystal architecture consisting of corner- and edge-sharing VO_5 square pyramids held together by weak van der Waals interactions along the c-axis. This unique open-framework structure features wide interlayer spacings that facilitate the rapid intercalation and deintercalation of various mono- and multivalent cations (Li^+ , Na^+ , Zn^{2+} , Mg^{2+} , etc.) without suffering severe phase transformations (Niu et al., 2023).

Despite these intrinsic advantages, the practical application of pristine V_2O_5 in high-performance devices is constrained by several fundamental limitations. First, its inherently low electronic conductivity ($\sim 10^{-5}$ to $10^{-3} \text{ S cm}^{-1}$) and modest ionic diffusion coefficient severely hinder high-rate capabilities. Second, repeated insertion and extraction of guest ions—especially larger or multivalent cations—frequently induce lattice strain, structural collapse, and active material dissolution in aqueous media, leading to rapid capacity decay over extended cycling (Sasikumar et al., 2026).

To overcome these hurdles, extensive research efforts have focused on nanostructural architecture engineering, controlled synthetic design, and material modification strategies. Synthesizing V_2O_5 across various dimensions—ranging from zero-dimensional (0D) nanoparticles and one-dimensional (1D) nanowires/nanotubes to two-dimensional (2D) nanosheets and three-dimensional (3D) porous hierarchical networks—has proven highly effective in shortening diffusion pathways, exposing abundant active sites, and buffering volume fluctuations during cycling. Furthermore, defect engineering (such as oxygen vacancy introduction) and hybridization with highly conductive scaffolds (e.g., graphene, carbon nanotubes, or conducting polymers) have dramatically improved the electronic conductivity and structural integrity of V_2O_5 -based composites (Sasikumar et al., 2026).

Although numerous studies have demonstrated performance improvements in specific V_2O_5 -based electrode systems, an integrated assessment linking nanostructural design, synthesis methodologies, physicochemical properties, and application-specific electrochemical mechanisms remains necessary. This review provides a comprehensive overview of recent advances in V_2O_5 -based electrodes for electrochemical energy storage. First, V_2O_5 nanostructures are classified according to dimensionality, and the principal synthesis strategies are discussed in relation to their influence on morphology, crystallinity, and electrochemical performance.

Subsequently, the application of these materials in next-generation energy storage systems is critically examined, with particular emphasis on aqueous zinc-ion batteries, lithium- and sodium-ion batteries, and supercapacitors. Finally, optimization strategies, including defect engineering, interlayer modification, and hybridization with conductive materials, are evaluated alongside the remaining challenges associated with electronic conductivity, structural stability, cycling durability, and scalability. This review aims to establish structure–property–performance relationships and identify promising research directions for the development of efficient, durable, and commercially viable V_2O_5 -based electrodes.

2. Classification of V₂O₅ Nanostructures

The electrochemical performance of V₂O₅ electrodes—specifically capacity, rate capability, and cycling stability—is strongly influenced by morphology, crystallite size, and surface area. Unlike bulk V₂O₅, which suffers from slow ion diffusion kinetics and structural degradation during cycling, nanostructured V₂O₅ offers distinct advantages. Reducing the material to the nanoscale effectively shortens the solid-state diffusion distance for guest ions and electrons, increases the contact area at the electrode-electrolyte interface, and better accommodates the mechanical strain induced by repeated insertion and extraction of ions. Based on their spatial dimensionality, V₂O₅ nanomaterials are systematically classified into zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) architectures (Akhtar et al., 2026).

2.1 Zero-dimensional (0D) nanostructures

Zero-dimensional V₂O₅ structures primarily encompass nanoparticles, quantum dots, and nanospheres, characterized by nanoscale dimensions across all three spatial coordinates. The primary electrochemical advantage of 0D V₂O₅ lies in its exceptionally high surface-to-volume ratio, which provides abundant active sites for faradaic reactions and ensures intimate contact with the electrolyte. Furthermore, the ultrascale dimensions of 0D particles significantly minimize the solid-state diffusion paths for charge carriers (Li⁺, Zn²⁺, etc.), enhancing the reaction kinetics necessary for high-rate performance.

However, isolated 0D V₂O₅ nanoparticles frequently suffer from severe agglomeration driven by high surface energy. This aggregation negates the benefits of high surface area, leading to poor electrical contact between particles and current collectors. Consequently, 0D V₂O₅ is rarely used as a standalone electrode in advanced storage systems; instead, it is typically anchored onto or embedded within conductive matrices, such as reduced graphene oxide (rGO) or mesoporous carbon, to preserve its high surface area while mitigating agglomeration and low intrinsic conductivity (Hussain et al., 2026).

2.2 One-dimensional (1D) nanostructures

One-dimensional V₂O₅ architectures—including nanowires, nanobelts, nanorods, and nanotubes—have attracted intense research interest due to their highly anisotropic morphology. In 1D structures, two dimensions are restricted to the nanoscale, while the third dimension is extended, typically along a specific crystallographic axis (direction in V₂O₅). This morphology offers several critical benefits for energy storage. The elongated structure provides directed, uninterrupted pathways for rapid electron transport along the longitudinal axis, while the nanoscale radial dimension ensures short ion diffusion distances.

Furthermore, the high aspect ratio of 1D nanomaterials allows them to readily form interconnected networks or freestanding membranes, which can function as binder-free electrodes. Nanotubes, in particular, offer both inner and outer surfaces for electrolyte contact and act as hollow buffering spaces that effectively absorb the volumetric expansion associated with multivalent-ion (e.g., Zn²⁺) intercalation, thereby enhancing cycling stability (Kashif et al., 2026a).

2.3 Two-dimensional (2D) nanostructures

Given that pristine V₂O₅ is intrinsically a layered material with weak van der Waals forces acting along the *c*-axis, it is ideally suited for processing into two-dimensional (2D) nanostructures, such as nanosheets and nanoflakes. 2D V₂O₅ structures boast an ultra-thin thickness (often on the order of a few atomic layers) combined with large lateral dimensions. The planar morphology of 2D V₂O₅ exposes a maximal fraction of active surface atoms to the electrolyte, significantly boosting the pseudocapacitive charge storage contribution and resulting in exceptional specific capacities.

The wide, unhindered 2D planes allow for rapid and uniform ion migration. Furthermore, exfoliated V₂O₅ nanosheets frequently exhibit expanded interlayer spacings and increased structural flexibility compared to bulk phases, lowering the energy barrier for the insertion of large guest ions. Like 1D structures, 2D nanosheets can be easily hybridized with conductive 2D materials, such as graphene, to form mechanically robust, face-to-face stacked heterostructures with superior charge transfer characteristics (Kashif et al., 2026b).

2.4 Three-dimensional (3D) hierarchical architectures

Three-dimensional (3D) V_2O_5 architectures represent an advanced structural design in which lower-dimensional building blocks (0D nanoparticles, 1D nanowires, or 2D nanosheets) self-assemble or are templated into complex, macroporous frameworks. Examples include micro-flowers, urchin-like microspheres, and aerogels. These 3D hierarchical structures synergistically combine the kinetic advantages of nanoscale building blocks with the thermodynamic stability of microscale assemblies.

The macroscopic framework prevents the restacking of 2D nanosheets and the severe aggregation typical of 0D/1D structures, ensuring long-term structural integrity. Crucially, the abundant multi-scale porosity—comprising micro-, meso-, and macropores—facilitates deep and rapid electrolyte penetration into the interior of the electrode, ensuring complete utilization of the active material even at high current densities. Additionally, the porous internal voids act as structural buffers, effectively accommodating volume changes during prolonged charge/discharge cycling and suppressing active material pulverization (Khan et al., 2026a).

3. Synthesis Strategies for V_2O_5 Nanomaterials

The morphology and electrochemical properties of V_2O_5 nanomaterials are intrinsically linked to the synthesis method used. Advanced synthesis routes enable precise control of crystallite size, porosity, defect concentration, and crystallographic orientation. Among the various techniques developed, hydrothermal/solvothermal processing, sol-gel methods, and electrospinning have emerged as the most prominent pathways for fabricating high-performance V_2O_5 electrodes for energy storage applications.

3.1 Hydrothermal and solvothermal synthesis

Hydrothermal synthesis is a highly versatile, solution-based method typically conducted in a sealed autoclave, utilizing aqueous or organic solvents at elevated temperatures and vapor pressures. This method is favored for its ability to produce highly crystalline V_2O_5 powders and complex nanostructures without the need for high-temperature post-calcination, which can frequently cause particle agglomeration. Ammonium metavanadate (NH_4VO_3) is widely used as a primary vanadium precursor.

By carefully controlling thermodynamic parameters—such as reaction temperature (typically 160–200 °C), duration, and solvent pH—the precursor undergoes hydrolysis and dehydration reactions to form crystalline V_2O_5 . The high-pressure environment of the autoclave heavily dictates the anisotropic growth of V_2O_5 crystals. By altering the specific solvents, surfactants, or structure-directing agents (e.g., organic acids like oxalic acid), researchers can selectively yield 1D nanowires, 2D nanosheets, or complex 3D architectures like nanoflowers and nano-urchins. Hydrothermally synthesized V_2O_5 often exhibits an orthorhombic α - V_2O_5 phase characterized by a robust layered structure of edge- and corner-sharing $[VO_5]$ double chains. The resultant nanostructures provide an abundant electroactive surface area and shortened solid-state diffusion pathways, drastically improving reversible capacity and structural stability during multivalent-ion intercalation (Gul et al., 2025).

3.2 Sol-gel processing

The sol-gel technique is distinguished by its molecular-level mixing, low processing temperatures, and exceptional ability to create intimately mixed homogeneous composites. It involves the conversion of a liquid solution (sol) into a solid, biphasic network (gel). The sol-gel process for V_2O_5 relies on the hydrolysis and condensation of precursor materials. Under acidic conditions (e.g., pH 2), hydrated V^{5+} centers undergo ololation to form chain polymers, followed by oxolation—a condensation reaction that cross-links these chains into an extended lamellar structure.

Drying the resulting gel under ambient conditions yields a dense V_2O_5 xerogel, whereas supercritical drying preserves the porous framework, forming a highly porous aerogel. V_2O_5 xerogels frequently exhibit expanded interlayer spacings (approximately 1.17 nm), which significantly lowers the energy barrier for the insertion of large solvated guest ions without disrupting the crystal lattice (a topotactic process). A primary advantage of the sol-gel route is the ease of integrating conductive additives (Zahoor et al., 2026).

For instance, single-walled carbon nanotubes (SWCNTs) can be dispersed directly into the sol before complete gelation. This allows V_2O_5 structures to nucleate and grow directly onto the SWCNT surface, yielding a highly

conductive 3D interpenetrating network that effectively mitigates the low intrinsic conductivity of pure V_2O_5 .

3.3 Electrospinning techniques

Electrospinning is a scalable and highly effective technique specifically designed for the fabrication of continuous, ultra-long 1D nanofibers and interconnected non-woven mats. In this process, a viscous precursor solution—typically comprising a salt dissolved in a solvent alongside a carrier polymer (such as polyvinylpyrrolidone or polyacrylonitrile)—is extruded through a spinneret under a high-voltage electrostatic field. The electric field overcomes the surface tension of the droplet, drawing it into a continuous nanoscale fiber. The as-spun composite fibers undergo subsequent thermal annealing to burn off the carrier polymer template and promote the crystallization of the V_2O_5 inorganic phase.

Precise control of the calcination heating rate is critical; rapid off-gassing of the polymer can induce beneficial mesoporosity within the resulting V_2O_5 fibers. The primary electrochemical advantage of electrospun V_2O_5 is the ability to directly utilize the resulting non-woven nanofiber mats as freestanding, binder-free electrodes. By eliminating electrochemically inactive polymeric binders and conductive carbon black additives, the overall mass of the electrode is reduced, maximizing the specific energy density of the final storage device. Furthermore, the 1D fibrous architecture provides uninterrupted longitudinal electron transport, which is crucial for high-power applications (Shah et al., 2024).

4. Electrochemical Mechanisms and Applications in Aqueous Zinc-Ion Batteries (AZIBs)

Aqueous zinc-ion batteries (AZIBs) are highly promising for large-scale energy storage due to their intrinsic safety, low cost, and the environmental friendliness of both the aqueous electrolytes and metallic zinc anodes. Within this system, vanadium pentoxide (V_2O_5) stands out as a premier cathode material, offering high theoretical capacities driven by versatile structural architectures and multielectron redox processes, such as transitions between V^{5+} , V^{4+} , and V^{3+} . However, the practical deployment of V_2O_5 in AZIBs hinges on understanding and managing its complex charge storage mechanisms.

4.1 Charge storage and intercalation mechanisms

The fundamental energy storage mechanisms of V_2O_5 in AZIBs remain a subject of active investigation, with several interconnected pathways defining its electrochemical behavior. The conventional model involves the direct insertion and extraction of zinc ions within the host lattice. A primary challenge in this mechanism is the high charge density of divalent Zn^{2+} , which induces strong electrostatic interactions with the V–O lattice, leading to sluggish solid-state diffusion kinetics and significant structural strain.

Recent operando analyses indicate that charge storage frequently occurs via a cooperative dual-ion mechanism. Highly mobile protons (H^+) rapidly intercalate into the V_2O_5 lattice alongside or before Zn^{2+} , a process often accompanied by the reversible precipitation and dissolution of basic zinc salts, such as $Zn_4SO_4(OH)_6 \cdot nH_2O$, on the electrode surface in response to local pH fluctuations. Utilizing hydrated vanadium oxide ($V_2O_5 \cdot nH_2O$) significantly mitigates kinetic limitations. The pre-existing interlayer water molecules expand the gallery spacing up to ~ 11 Å and act as an electrostatic shield, solvating the incoming Zn^{2+} ions. This shielding drastically reduces the diffusion energy barrier and enhances the structural flexibility of the layers during multivalent ion insertion (Amir et al., 2025).

4.2 Degradation mechanisms

Despite achieving high initial specific capacities, bare V_2O_5 cathodes frequently experience rapid performance degradation over long-term cycling. The repeated insertion of highly polarizing Zn^{2+} ions provokes severe structural distortion within the V–O coordination polyhedra. Furthermore, water molecules in the electrolyte continuously attack exposed vanadium sites, leading to active material dissolution and the irreversible formation of electrochemically "dead vanadium" byproducts like $Zn_3(OH)_2V_2O_7 \cdot 2H_2O$.

4.3 Structural optimization strategies

To stabilize the lattice and accelerate reaction kinetics, researchers have developed advanced structural modification strategies. Introducing organic molecules like saccharin or inorganic cations like K^+ or Al^{3+} into the

interlayer space effectively pins the layers, suppressing structural collapse. This further modulates the coordination environment of vanadium to support rapid, durable ion transport. The deliberate introduction of oxygen vacancies alters the local electronic structure of the cathode. This defect-mediated approach not only improves intrinsic electronic conductivity but has also been shown to activate specific proton-dominated transport pathways, maximizing the synergistic $\text{H}^+/\text{Zn}^{2+}$ co-storage effect for superior rate capabilities (Khan et al., 2025b).

5. Modification Strategies: Defect Engineering and Conductive Hybridization

While nanostructuring effectively shortens ion diffusion pathways, it does not fully resolve the intrinsic limitations of pristine V_2O_5 , namely its inherently low electrical conductivity (10^{-7} to 10^{-6} S cm^{-1}) and the sluggish diffusion kinetics of large or multivalent guest ions. Furthermore, the repeated volumetric expansion during deep cycling inevitably leads to structural degradation. To build commercially viable energy storage devices—from lithium-ion batteries to asymmetric supercapacitors—researchers have primarily relied on two synergistic modification strategies: defect engineering and conductive hybridization.

5.1 Defect engineering via oxygen vacancies

Defect engineering—specifically the deliberate introduction of oxygen vacancies (Ov)—has emerged as a powerful technique to intrinsically alter the electronic structure and electrochemical activity of V_2O_5 materials. Oxygen vacancies can be induced through various methods, including thermal treatment in reducing atmospheres (e.g., hydrogen gas), plasma treatment, or during the oxidative polymerization of conducting polymers.

The electrochemical benefits of oxygen-deficient materials are multifaceted. The removal of oxygen atoms from the crystal lattice leaves behind unbound electrons, effectively creating intermediate, lower-valence states, most notably V^{4+} . This mixed-valence system ($\text{V}^{5+}/\text{V}^{4+}$) facilitates electron hopping within the lattice, significantly narrowing the bandgap and enhancing the intrinsic electrical conductivity of the material. Oxygen vacancies induce localized lattice distortions that slightly expand the interlayer spacing.

Density functional theory (DFT) calculations have demonstrated that these widened pathways effectively lower the migration energy barrier for guest ions like Zn^{2+} and Li^+ . The presence of surface oxygen vacancies significantly increases the surface energy of V_2O_5 . These high-energy defect sites can serve as nucleation centers that facilitate phase transitions during the intercalation and deintercalation processes, thereby providing additional adsorption sites for charge carriers and boosting specific capacity (Kashif et al., 2024).

5.2 Conductive hybridization

An equally critical and highly compatible strategy is hybridizing with highly conductive matrices. Because pristine materials often aggregate during prolonged cycling, anchoring them to a robust scaffold addresses both conductivity and mechanical stability. Integrating V_2O_5 with carbonaceous materials—such as carbon nanotubes (CNTs), reduced graphene oxide (rGO), and nitrogen-doped carbon (NC)—provides an interconnected 3D electron transport network. This conductive matrix minimizes the interfacial charge transfer resistance and physically buffers the severe volume expansion that is undergone during ion insertion. For example, the use of rGO has been shown to stabilize the structure and prevent active material dissolution in aqueous electrolytes, extending the cycle life over thousands of cycles. Coating with conducting polymers, such as polypyrrole (PPy) or polyaniline (PANI), serves a dual purpose.

The polymer layer not only bridges the electrical gaps between adjacent oxide particles but also acts as a flexible, protective "skin" that prevents the direct dissolution of vanadium ions into the electrolyte. The most advanced high-performance electrodes utilize in-situ synthetic routes that combine both strategies simultaneously. For instance, during the high-temperature carbonization of a polymer precursor to form a nitrogen-doped carbon shell around the core V_2O_5 , the reducing environment inherently strips oxygen from the oxide lattice. This results in an oxygen-vacancy-rich V_2O_5 core encapsulated by a highly conductive carbon shell—simultaneously maximizing electronic/ionic transport and ensuring long-term structural integrity (Zhou et al., 2025).

6. Applications in Advanced Energy Storage Systems

The versatile layered structure and rich redox chemistry of V_2O_5 make it highly adaptable across various electrochemical energy storage platforms beyond aqueous zinc systems. Its ability to intercalate alkali-metal ions

and facilitate rapid surface redox reactions positions it as a critical material for both high-energy batteries and high-power supercapacitors.

6.1 Lithium-ion and sodium-ion batteries (LIBs and SIBs)

V₂O₅ has been extensively investigated as a cathode material for alkali-metal ion batteries due to its high theoretical capacity and thermodynamic stability. In LIBs, V₂O₅ offers a theoretical capacity of up to 394 mAh g⁻¹ (assuming two Li⁺ insertions per formula unit). Its layered crystal lattice provides optimal interstitial sites for Li⁺ accommodation. However, profound phase transitions (from the α phase to the δ phase, and eventually to the irreversible ω phase) during deep discharge cycles limit its long-term reversibility.

For SIBs, the significantly larger ionic radius of Na⁺ (1.02 Å compared to 0.76 Å for Li⁺) requires host materials with expansive interlayer spacing. The inherent weak van der Waals interactions between V₂O₅ layers allow for structural breathing, accommodating the sluggish kinetics and large volume expansion associated with Na⁺ insertion. Employing 2D nanosheets or 3D aerogels effectively mitigates the diffusion limitations of both Li⁺ and Na⁺. Hybridizing V₂O₅ with carbon matrices further buffers the volumetric strain, preventing the pulverization of the electrode during prolonged alkali-ion cycling (Wang et al., 2018; Yao et al., 2018; Yue; Liang, 2017).

6.2 Supercapacitors

Beyond batteries, V₂O₅ is a highly effective pseudocapacitive electrode material, storing charge via rapid and reversible Faradaic surface redox reactions rather than deep bulk intercalation. The multiple oxidation states of vanadium enable exceptional pseudocapacitance. When configured in thin 2D nanosheets or highly porous 1D nanowire arrays, the material exposes a vast number of electrochemically active surface sites, leading to extremely high specific capacitance and high power density.

Because V₂O₅ operates optimally in specific potential windows, it is most effectively deployed in asymmetric supercapacitors. Pairing a V₂O₅ positive electrode with a carbon-based negative electrode significantly widens the overall cell voltage, bridging the energy density gap between traditional capacitors and batteries. While aqueous electrolytes (like neutral LiCl or Na₂SO₄) offer high ionic conductivity and safety, they can cause V₂O₅ dissolution. Utilizing non-aqueous or water-in-salt electrolytes significantly widens the operating potential window and dramatically enhances the long-term cycling longevity of the supercapacitor (Li et al., 2022; Temam et al., 2023; Tian et al., 2021).

7. Future Perspectives

Despite significant advancements, the transition of V₂O₅ from laboratory-scale research to commercial viability requires addressing several persistent challenges. Future research trajectories must prioritize the following critical areas: The precise charge storage and structural degradation mechanisms of V₂O₅, particularly in complex aqueous systems like AZIBs, remain partially obscured. Expanding the use of operando X-ray diffraction (XRD), *in situ* Raman spectroscopy, and advanced transmission electron microscopy (TEM) is essential to monitor real-time phase transitions, the exact role of structural water, and the precipitation of irreversible byproducts during deep cycling.

While intricate nanostructures and composite formulations exhibit superior electrochemical performance, their current synthesis routes (e.g., supercritical drying, complex electrospinning) are often highly energy-intensive and difficult to scale. Future efforts must prioritize the development of facile, low-temperature, and environmentally benign synthesis methods that yield uniform, high-performance V₂O₅ architectures at an industrial scale. The continuous dissolution of vanadium ions in aqueous electrolytes severely truncates device lifespan.

Future research must concurrently optimize electrolyte formulations—such as the adoption of highly concentrated "water-in-salt" electrolytes, the addition of specific sacrificial salts, or the development of solid-state polymer electrolytes—to widen the electrochemical stability window and passivate the electrode-electrolyte interface against dissolution. The overwhelming majority of V₂O₅ performance data is currently derived from idealized, half-cell coin configurations with massive electrolyte excesses and thin-film electrodes. To accurately assess commercial viability, the field must rapidly transition toward full-cell evaluations, specifically employing pouch cell architectures, thick electrodes with high mass loading, and lean electrolyte conditions to determine true volumetric and gravimetric energy densities.

8. Conclusions

Vanadium pentoxide (V_2O_5) demonstrates exceptional potential as a high-performance electrode material across a broad spectrum of next-generation electrochemical energy storage systems. Its distinct layered crystal architecture, natural abundance, and the rich multi-electron redox chemistry of vanadium provide intrinsic advantages for high-capacity energy storage. As established throughout this review, the strategic manipulation of V_2O_5 through nanostructural engineering—spanning 0D to 3D dimensions—effectively mitigates its primary kinetic limitations by drastically shortening ion diffusion pathways and maximizing electroactive surface area. Furthermore, advanced modification strategies, specifically defect engineering via oxygen vacancies and hybridization with conductive carbon matrices, have proven critical in overcoming the material's inherently low electrical conductivity and structural vulnerability during prolonged cycling.

9. Authors' Contributions

Muhammad Ahrar: conceptualization, investigation, writing – original draft, writing – review & editing, validation, and project administration.

10. Conflicts of Interest

No conflicts of interest.

11. Ethics Approval

Not applicable.

12. Artificial Intelligence Statement: Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that generative artificial intelligence (AI) was used exclusively to create the graphical abstract and to correct grammatical errors and improve the English language of the manuscript. After completion of these AI-assisted tasks, all content was carefully reviewed and verified by the authors, who assume full responsibility for the accuracy, originality, and integrity of the final manuscript. AI tools are not authors and do not qualify for authorship or bear responsibility for the content of the manuscript. The use of AI in the graphical abstract, including the name of the tool, has been disclosed directly in the graphical abstract image.

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