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Spin-Coated Nanostructured Tungsten Oxide (WO_3) Thin Films for Photocatalytic Degradation of Organic Dyes: A Comprehensive Review

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Abstract

The rapid release of colored waste water, which is typically contaminated with synthetic organic dyes from the textile, paper, leather, pharmaceutical, and printing industries, is a significant threat to the environment. These dyes can be toxic and persist in the environment. A viable solution to address these threats includes using semiconductor photocatalysis, as it is a method that is highly effective, safe to the environment and sustainable. Several photocatalytic materials have been studied; however, among them, tungsten oxide (WO_3) is one of the most attractive due to its relatively narrow band gap energy (1.23 eV), good chemical stability, visible light photoactivity, and low toxicity. Spin coated nano-structured WO_3 thin films are being widely investigated because they provide advantages such as low production costs, high uniformity of the thin films deposited onto substrates with controlled thickness and scalability to large area substrates. This article provides a thorough analysis of developments of spin-coated nanostructured WO_3 thin films based on photocatalytic degradation of organic dyes. The crystalline structures, optical properties, electronic characteristics, photocatalytic processes and other critical factors that affect the performance of WO_3 thin films were analyzed. Modifications to increase the photocatalytic efficiency included metal or non-metal doping, hetero-junction formation, defect engineering and plasmonic enhancements that facilitate charge separation and enhance photocatalytic activities under visible light illumination. Finally, comparative studies regarding the degradation efficiencies of representative organic dyes (such as methylene blue, rhodamine B, methyl orange, and Congo Red) were reviewed. Furthermore, the main challenges that need to be addressed in order to develop stable long-lasting photocatalysts at large scales, while suggesting potential areas for future investigation on multi-functional coatings and solar driven photocatalytic systems.

Keywords: Tungsten oxide (WO_3), Spin coating, Thin-film photocatalyst, Nanostructured materials, Photocatalysis, Organic dye degradation, Visible-light photocatalysis, Wastewater treatment, Semiconductor photocatalysts, Environmental remediation.

1. Introduction

Water pollution is today considered one of the biggest environmental problems all over the world due to fast development of industry and cities, and increasing number of people. Synthetic organic dyes from textile, paper, leather, pharmaceutical, cosmetic, food-processing and printing industries represent persistent pollutants among other contaminants. Due to their large aromatic molecular structure, good chemical resistance, bad biodegradability, and potential harmfulness for ecosystems and humans, they present a danger for both aquatic ecosystems and human life [1]. According to estimates, there are more than 100,000 commercially available dyes produced all around the world. Each year alone, more than 7×10^5 tones of dyes are produced. It is estimated that up to 90% of them end up in waste-water during the dye-making process and dyeing processes [2, 3]. In addition, even if present in small amounts, dyes may block sunlight penetrating through aquatic environment, diminish photosynthesis activity, increase the amount of chemical oxygen demand and biochemical oxygen demand, and also generate mutagenic, teratogenic and carcinogenic compounds in the same way producing a threat to ecosystem and human health. To eliminate dyes from wastewater several traditional removal technologies have been used, including adsorption, coagulation-flocculation, membrane filtration, ion exchange, biological treatments, ozonations and chemical oxidation. While each technology may be efficient for its own purposes under certain conditions, they all suffer from significant disadvantages. Those include inadequate mineralization; elevated operational expenses; creation of secondary sewage sludges; clogging of membranes; and inefficiency to degrade resistant organics [3–6]. For this reason, advanced oxidation processes have gained much interest as a new method to remove organic pollutants from wastewater sustainably because they allow the full mineralization of organic pollutants into harmless substances

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like CO_2, H_2O and inorganic ions when illuminated by light [8]. The basic principle behind photocatalysis is the ability of semiconductors to generate electrons-holes by illuminating the material using wavelengths smaller than the bandgap of the semiconductor. Once generated, the electron-hole pair migrates toward the surface of the semiconductor where it participates in redox reaction. The result of this process is the formation of ROS which include •OH radicals, $•O_2^-$ radicals, singlet oxygen, and H_2O_2. The ROS then effectively degrades complex organic pollutants [5, 9]. During last two decades considerable research efforts have been made to develop semiconductor-based photocatalytic materials. Some examples of those are TiO_2, ZnO, WO_3, SnO_2, Fe_2O_3, $BiVO_4$ and g-C_3N_4. Nevertheless, many of those materials show some drawbacks regarding the too large band gap energy, too little use of visible light, rapid decay of charge carriers and too short lifetime [10].

There are many types of semiconductors that react to light in the visible spectrum; among them, Tungsten Trioxide (WO_3), as a photocatalyst due to its relatively small energy band gap and excellent chemical-thermal stabilities under acidic and oxidizing conditions, as well as being naturally abundant, low toxic, and exhibiting beneficial photoelectrochemical properties [11]. Unlike titanium dioxide, which absorbs mostly UV light, only 5% of the total solar spectrum, WO_3 effectively uses visible light down to around 480 nm, thus especially useful for solar powered environmental remediation [12]. Furthermore, WO_3 shows high quality electrochromic, photochromic, gasochromic, and catalytic properties that provide potential use outside of photocatalysis to include smart windows, gas sensors, photoelectrochemical water splitting, lithium ion battery and electrochemical devices [13 – 14]. WO_3 is an n-type transition-metal oxide semiconductor that exists in multiple crystallographic forms including monoclinic, triclinic, orthorhombic, tetragonal, hexagonal, and cubic. Its crystal structure, degree of crystallinity, shape/morphology, O vacancy density, exposure of facets and surface chemistry all significantly affect how WO_3 absorbs light optically, transports charges and performs as a photocatalyst [5, 15].

A few reviews have covered WO_3-based photocatalysts but most of those reviews addressed either all photocatalytic materials broadly speaking, powder catalysts or broadly-speaking environmental applications rather than reviewing spin-coated nanostructure WO_3 thin film photocatalysts specifically addressing their structural-property relations in dye-degradation. Moreover, this review aims to evaluate the role that process-related parameters play in determining the photodegradation performance of WO_3 thin films and discuss recent approaches to modify the photocatalytic properties of WO_3 thin films including doping and defect engineering in addition to creating hetero-junctions. The last part of this review outlines the existing major obstacles to developing stable-durable-scalable-solar driven photocatalysts for water treatment that could meet the needs of sustainable technologies [11, 16].

2. Fundamentals of Tungsten Oxide (WO_3) Photocatalysts

2.1. Crystal Structure and Phase Transition of WO_3

Tungsten Trioxide (WO_3) is an n- type semiconducting material known for having excellent chemical durability, strong light absorbing ability within the visible region, and possessing many useful physical/chemical characteristics. As such, WO_3 has been identified as a very promising photocatalytic material for use in environmental cleanup processes and photo-electrochemical systems [17]. The primary factors affecting how well WO_3 performs as a photocatalyst are the structure of the crystals present, the extent of crystallization, the shape/morphology of the crystals, and the amount of defects present. Crystallographically, WO_3 is comprised of corner sharing WO_6-octahedral units which form a distorted ReO_3 type perovskite framework. WO_3 can exist in a variety of polymorphic forms depending upon the reaction temperature and other synthesis parameters. There have been reports of six different polymorphic forms of WO_3; monoclinic, triclinic, orthorhombic, tetragonal, hexagonal and cubic. Although moderate levels of oxygen deficiency will typically enhance photocatalytic activity via improved light absorbency, extremely high vacancy densities may result in decreased activity from promoting recombination sites for charge carriers. Therefore, maintaining strict control over vacancy density is critical to balancing light harvesting and charge carrier transport [18].

Table 1: Crystal phases, structural characteristics, and photocatalytic significance of WO_3 polymorphs.

Crystal Phase	Crystal System	Stability	Characteristics	Photocatalytic Significance	Reference
Triclinic (δ-WO_3)	Triclinic	Low temperature	Distorted crystal lattice	Limited photocatalytic application	[2, 3]
Monoclinic (γ-WO_3)	Monoclinic	Stable at room temperature	Thermodynamically stable and highly crystalline	Excellent visible-light photocatalytic activity	[2, 3]
Orthorhombic (β-WO_3)	Orthorhombic	Intermediate temperature	Transitional crystal phase	Moderate photocatalytic performance	[3, 4]
Tetragonal (α-WO_3)	Tetragonal	High temperature	High crystal symmetry	Improved charge transport at elevated temperatures	[3, 17]
Cubic WO_3	Cubic	Very high temperature	Highly symmetrical crystal structure	Limited ambient stability	[2, 4]
Hexagonal WO_3	Hexagonal	Metastable	Tunnel-like open framework with large channels	High surface area and enhanced adsorption capability	[2, 17]

Table 1 lists the various polymorphic forms of WO_3 along with their structural attributes, thermal stability, and catalytic properties related to photocatalysis. Monoclinic WO_3 is the most thermally stable form of WO_3 at room temperature and has been extensively used in many different types of visible light photocatalytic applications. WO_3's phase (crystal) and morphological structures are greatly affected by both synthesis procedures and heat treatments. Sol-gel processing, spin coating, hydrothermal synthesis and sputtering have all proven useful in controlling the degree of crystallinity as well as nano-structure of a material [40].

2.2. Electronic Structure and Optical Properties of WO_3

The photocatalytic performance of WO_3 is primarily determined by its electronic structure. Since it acts like an n-type semiconductor with a band gap of approximately 2.4 – 2.8 e.v, WO_3 can absorb visible light at wavelengths up to approximately 480 nm [11, 17, 19] and thus be used more efficiently for solar energy harvesting. In the valence band of WO_3, orbitals predominantly composed of o 2p are present. The conduction band of WO_3 is predominantly comprised of W 5d orbitals. When irradiated using visible-light, electrons from the valence band are promoted into the conduction band. Upon promotion of these electrons, electron-hole pairs are formed which drive oxidation-reduction reactions involving photocatalysis [20]. Additionally, sub-stoichiometric states of WO_3 that include oxygen vacancies further modify this band structure by introducing defect levels below the minimum energy level within the conduction band. This facilitates lower-energy excitations. In comparison to traditional photocatalysts such as TiO_2, the narrower band-gap of WO_3 allows it to utilize visible light more effectively. Therefore, the use of WO_3 offers enhanced solar-energy harvesting capabilities and improved photocatalytic activity under natural sunlight. However, due to the relatively positive potential of the conduction-band of WO_3, the reduction capability of WO_3 is limited. Additionally, rapid recombination between the photo-generated electron hole-pairs decreases quantum efficiency. To overcome these limitations, several modification strategies including elemental doping, engineering of oxygen-vacancy concentration, construction of heterojunctions, and deposition of plasmonic metals have been developed to enhance charge carrier separation and extend the range of visible light absorption [11, 21].

2.3. Photocatalytic Mechanism of WO_3

Photocatalysis in tungsten trioxide (WO_3) results from the potential of absorbing visible light and creating an electron hole pair that participates in redox reactions. Due to a relatively small bandgap, WO_3 has the capability of utilizing the majority of the visible light spectrum; therefore, it may be utilized as a promising photocatalyst for environmental remediation [13, 22]. When exposed to photons having an energy greater than or equal to the band gap energy of WO_3, electrons are transferred from the valence band to the conduction band and positive holes remain in the valence band. As a result, the photo-generated electrons and holes travel to the surface of the photocatalyst. At the surface, these photo-generated species interact with adsorbed oxygen and water molecules. Holes within the valence band oxidize water molecules or hydroxide ions to create highly oxidative hydroxyl radical species while electrons within the conduction band reduce dissolved oxygen to form superoxide radical species. Both types of reactive oxygen species are capable of reacting with large molecular weight organic dyes; first breaking down these complex molecules into smaller intermediate products, then eventually mineralizing these products into carbon dioxide, water, and other inorganic ions [23]. As shown in fig 1, when a WO_3 material is exposed to visible light it causes electrons to be transferred from the valence band to the conduction band of the material creating "electron-hole" pairs that allow for the generation of reactive oxygen species. The reactive oxygen species then react with the organic dyes and oxidatively degrade them by converting the dyes into CO_2, H_2O, and inorganic ions. Therefore, WO_3 is an attractive choice as a photocatalyst for the degradation of organic dyes and treatment of wastewater due to its ability to operate under visible light, its chemical stability and its ability to produce reactive oxygen species [24].

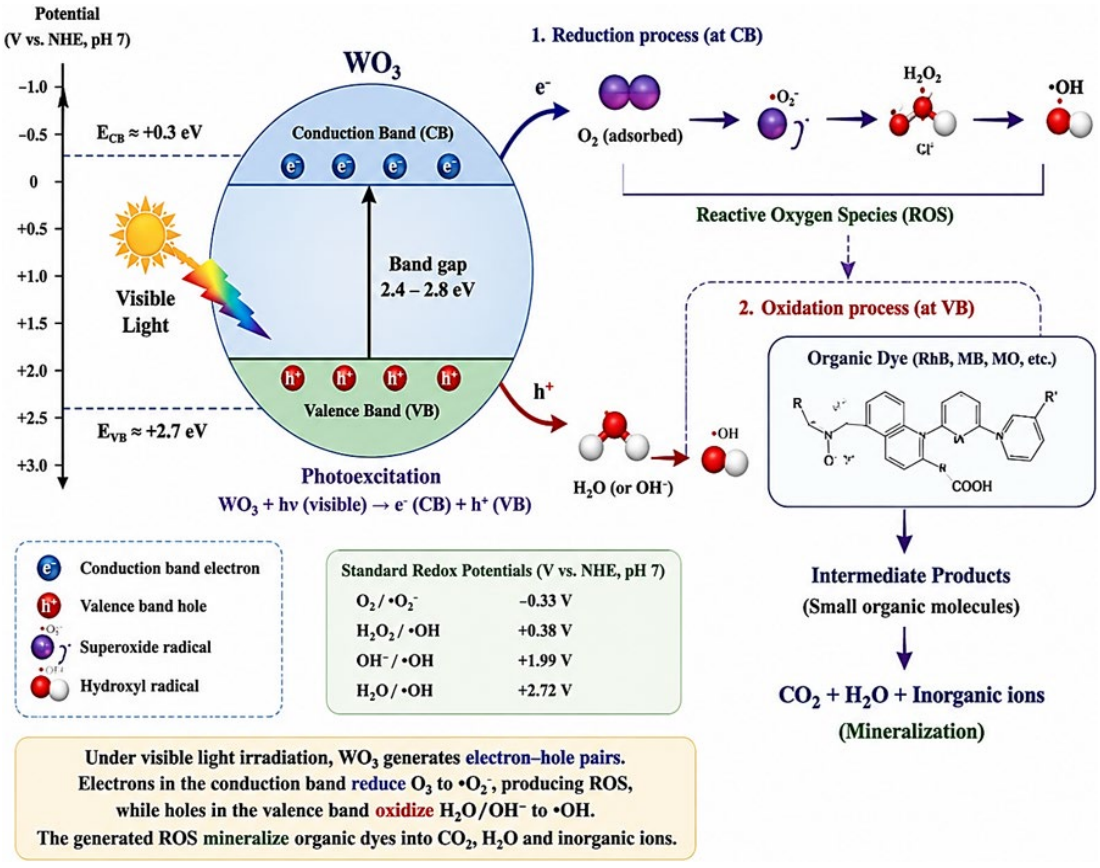

Fig 1: Energy band structure and visible-light photocatalytic mechanism of WO_3 showing electron–hole pair generation, reactive oxygen species (ROS) formation, and degradation of organic dyes under visible-light irradiation.

2.4. Advantages and Limitations of WO_3 Photocatalysts

Tungsten trioxide (WO_3) has been viewed as one of the most prominent candidates among visible-light responsive semiconductor photocatalysts due to the advantageous properties of this compound. The band gap of WO_3 is relatively narrower than other common photocatalysts like ZnO and TiO_2. This means that WO_3 will absorb much of the sun's light in the visible spectrum. In turn, the amount of sunlight absorbed allows for a much better use of solar radiation. Additionally, WO_3 has demonstrated high chemical stability and thermal stability. It possesses good resistance to corrosion from photoinduced reactions in acidic environments. Because WO_3 is non-toxic and mechanically stable, it has great potential for continuous use over many years in environmental remediation. As well, fabricating thin-film forms of WO_3 facilitates easy separation of the film after completion of the reaction. Thus, problems inherent in recovering catalyst particles from powdered photocatalysts are eliminated [25]. Nanoengineering of WO_3, defect manipulation, doped elements into WO_3, and hetero-photocatalyst formation may all contribute to improvements in the photocatalytic performance of WO_3. For example, thin films of nanostructured WO_3 have increased surface area per unit volume, more active sites for reaction and reduced path lengths for charge carriers to diffuse before being captured. These factors enhance the rate at which organic pollutants degrade. Also, manipulating the oxygen vacancies within WO_3 or combining WO_3 with another semiconductor material that provides charge separation can reduce electron-hole pair recombination and increase activity toward photocatalysis under visible light illumination [18].

2.5. Comparison of WO_3 with Other Semiconductor Photocatalysts

Semiconductor photocatalysts including TiO_2, ZnO, $BiVO_4$, Fe_2O_3, and graphitic carbon nitride (g-C_3N_4) have been studied extensively for the degradation of organic contaminants. WO_3 has garnered significant attention due to its ability to absorb visible light through its narrow band gap enabling it to utilize more of the sun's energy compared to TiO_2 and ZnO. Both TiO_2 and ZnO are limited in their ability to use sunlight for photocatalysis due to large band gaps limiting them primarily to ultraviolet radiation. Additionally, WO_3 demonstrates excellent chemical durability and low toxicity along with stable operation under acidic conditions making it a viable candidate for water purification [17]. While TiO_2 continues to serve as a benchmark photocatalyst due to its high stability and high oxidative power, the material suffers from a wide band gap which limits its ability to utilize visible light. Although ZnO displays similar levels of photocatalytic activity when compared to TiO_2, ZnO suffers from photo-corrosion which greatly diminishes its long-term stability. $BiVO_4$ and Fe_2O_3 display good visible light absorption capabilities, yet suffer from poor carrier transport and high rates of e-h pair recombination resulting in less than optimal application for most practical uses. Similar to $BiVO_4$ and Fe_2O_3, g-C_3N_4 is also a metal-free semiconductor with acceptable visible light sensitivity, but typically exhibits lower specific surface areas and less efficient photocatalysis compared to single phase semiconductors [26].

3. Section 3: Fabrication of Nanostructured WO_3 Thin Films

3.1. Spin-Coating Technique

Spin Coating has been one of the most common means of preparing uniform, quality Tungsten Trioxide (WO_3) thin films due to its relatively simple nature, and because the method allows for control over both film thickness and surface morphology. The technique lends itself well to the preparation of nano-structured photocatalytic films on surfaces such as; glass, quartz, silicon and fluorine doped tin oxide and is therefore very useful in applications involving photo-electrochemical reactions and environmental remediation [27]. The general procedure for spin coating involves placing a solution containing tungsten salt or alkoxide precursors onto a clean substrate that is then subjected to high-speed rotation. During this time centrifugal force distributes the solution evenly over the substrate. As the solution continues to dry through solvent evaporation during the continued rotation of the substrate, a thin layer of precursor material will have formed on the substrate. Following drying, the deposited film is heated in an oven to remove excess solvents from the precursor, to break down organic components within the precursor, and to promote crystallization of the WO_3. The final properties of the thin film are dependent upon numerous processing parameters such as precursor concentration, solution viscosity, speed of rotation, time of rotation, number of coats applied and heating conditions used for drying and thermal decomposition [12]. Figure 2 presents the fabrication sequence for WO_3 thin films, including precursor preparation, substrate cleaning, spin coating, drying, and annealing.

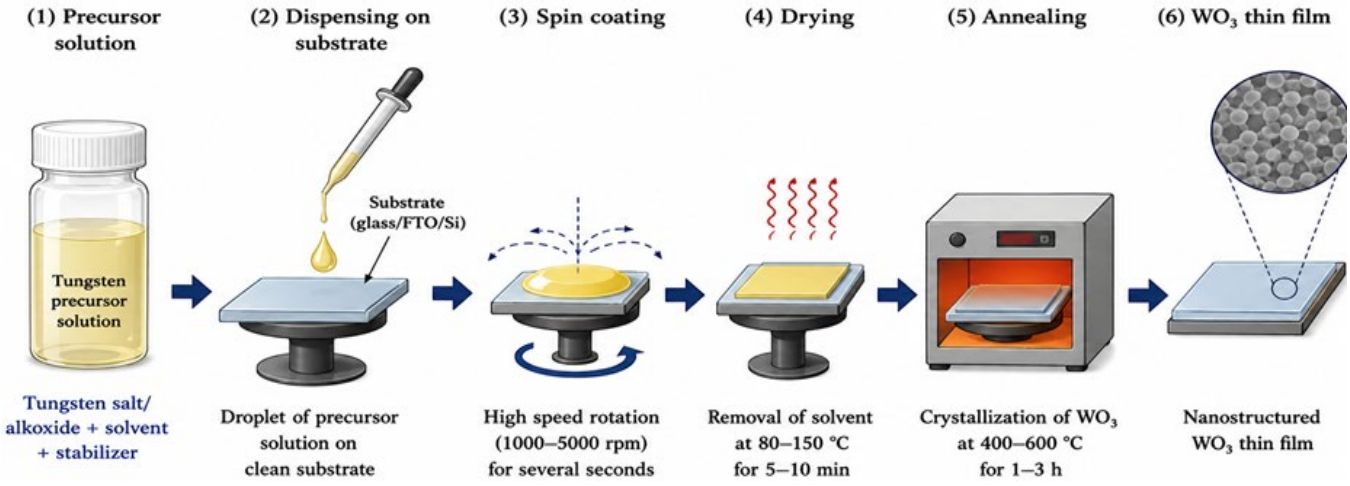

Fig 2: Schematic illustration of the spin-coating process for the fabrication of nanostructured WO_3 thin-film photocatalysts.

3.2. Effect of Spin-Coating Parameters on WO_3 Thin-Film Properties

When you create WO_3 thin films via spin-coating, your structural, optical, and photocatalytic characteristics will be affected by how you process them. Parameters such as the amount of precursors (e.g. tungsten oxide) per liter of water you use in your coating solution (the concentration), the rate at which you spin the coated substrate (spin speed), the number of times you coat the substrate (coating cycle(s)), and the temperature at which you heat it after coating (annealing temperature) all impact your final film thickness, crystal structure, topography, and the ability of the film to effectively degrade organic dyes when exposed to light. In terms of coating parameters, one of the most important factors in determining film thickness and uniformity is the spin speed. As a general rule, increasing your spin speed will produce thinner and more even films due to increased centrifugal forces and faster solvent evaporation rates. Conversely, using slower spin speeds will tend to produce thicker coatings that could have surface irregularities or cracks. Solution viscosity is impacted by precursor concentration. Generally, higher precursor concentrations lead to thicker films with better light absorption. However, excessive film thickness can impede carrier movement and cause an increase in electron-hole recombination, thus decreasing photocatalytic activity [28]. The spin-coating process strongly influences the thickness, morphology, crystallinity, and photocatalytic performance of WO_3 thin films. As illustrated in Fig 3**,** spin speed, precursor concentration, coating cycles, and annealing temperature determine the final film characteristics. Proper optimization of these parameters produces uniform, well-adhered and highly crystalline WO_3 films with improved visible-light photocatalytic activity.

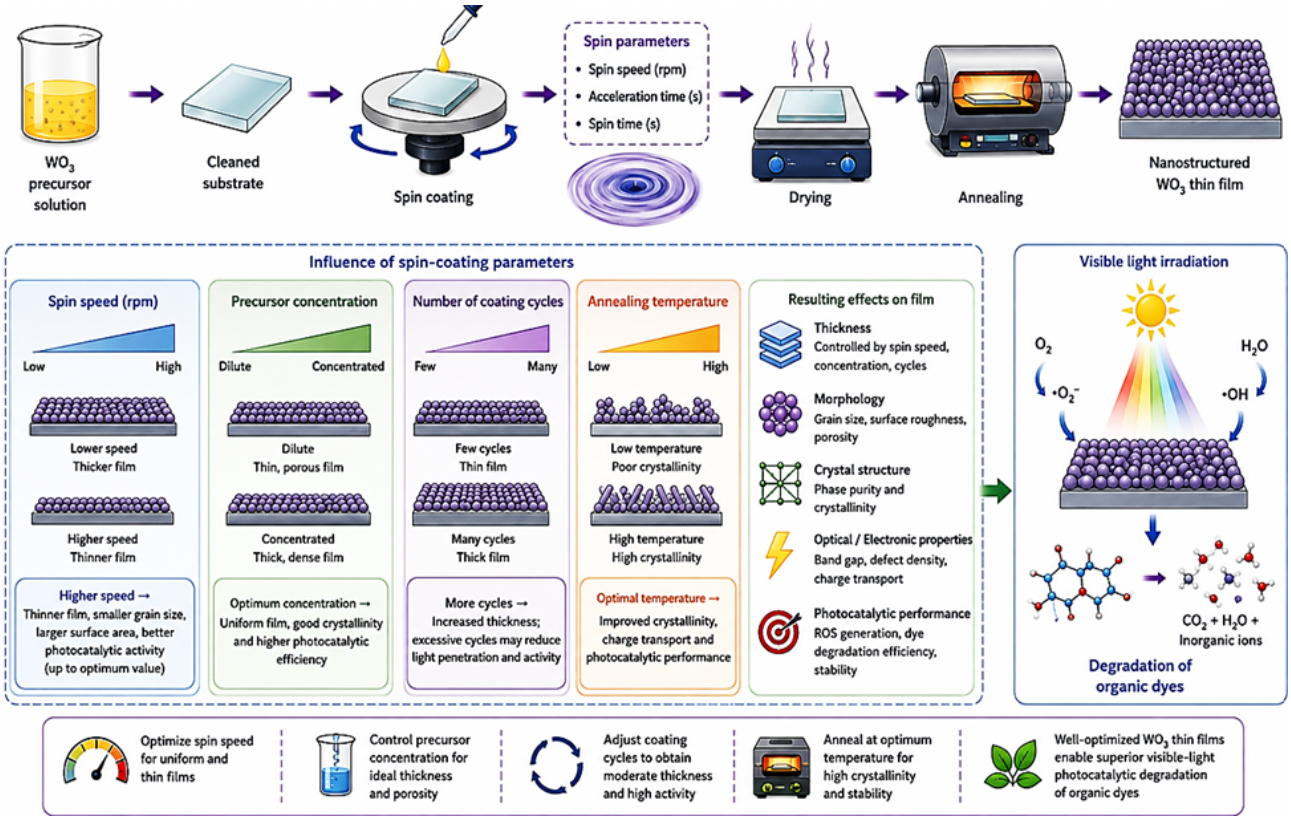

Fig 3: Schematic illustration of the spin-coating process and the influence of key processing parameters on the thickness, morphology, and photocatalytic performance of nanostructured WO_3 thin films.

3.3. Characterization of Spin-Coated WO_3 Thin Films

Comprehensive characterization of spin-coated WO_3 thin films is essential for developing an understanding of how process conditions effect structural features and photo-catalytic performance. A variety of techniques are used to provide information on crystalline structure, morphology, chemical composition, optical properties and surface characteristics of these films. Atomic force microscopy provides fundamental insight into the surface roughness and topography at the nanoscale level. In addition to this it may be possible to identify physical defects that could impact charge transfer. X-ray diffraction is widely employed to determine the crystalline phase, estimate particle size and determine the degree of crystallinity. When heat-treated at appropriate temperatures, spin-coated WO_3 films generally exhibit monoclinic crystalline phase which is favorable for photo-catalysis using visual light. Scanning electron microscopy and atomic force microscopy provide information on surface morphology, particle distribution, grain size, film thickness and surface roughness. Transmission electron microscopy provides details on the nanostructure and lattice fringes of WO_3 particles. Furthermore, the FTIR analysis shows the presence of W-O and W-O-W bond vibrational modes and the Raman analysis will provide additional structural lattice vibration data to support further determination of the overall structure-property relationship in the spin coated WO3 thin film samples. The combination of both the aforementioned analytical methods will allow us to achieve a full understanding of the relationships among structure, properties and efficiency for photocatalytic materials as applied to environmental remediation [29].

3.4. Nanostructure Engineering of WO_3 Thin Films

Nanostructure engineering is a method used to optimize the

photocatalytic performance of WO_3 thin films as well as to increase light absorption, increase the specific surface area, and separate charges generated during light exposure. As a result of varying synthesis routes and processing conditions, WO_3 has been formed into a wide range of nanostructures (nanoparticles; nanorods; nanowires; nanosheets; nanotubes; nanoflower; porous thin films) which allow for increased site availability for photocatalytic reaction processes and shorter distances for charge carrier diffusion resulting in reduced electron-hole recombination [30]. Due to their one-dimensional structure, both nanorod and nanowire configurations provide efficient electron transport while nanosheet configurations provide larger surface areas than other configurations exposing more reactive surfaces toward pollutants for adsorption. In addition, porous WO_3 thin film configurations are capable of improving photocatalytic activity through improved reactant molecule diffusion and improved light harvesting via multiple internal reflections. Hierarchically structured nanoconfigurations that include two or more types of nanostructures have demonstrated the ability to improve photocatalytic activities by creating interconnective paths for charge transport and increasing visible light use.

4. Photocatalytic Degradation of Organic Dyes Using Spin-Coated WO_3 Thin Films

The growing number of dye-laden effluent discharges originating from textile and leather processing, as well as from paper manufacturing, pharmaceuticals and print production processes are necessitating the development of new treatment solutions that can efficiently remove harmful pollutants while being both economically viable and environmentally safe. Thin-film WO_3 spin coated on glass or other surfaces represent one of the most advanced forms of visible-light responsive photocatalysts presently available. In comparison to particulate photocatalysts, thin-films are also significantly easier to recover and reuse. Upon exposure to visible light (which represents approximately 45% of all sunlight) electrons will be produced within the WO_3 material through a process known as photo-excitation. These electrons then form an electron-hole pair; once formed, they will rapidly react with dissolved O_2 and H_2O to produce very reactive free radical species known as superoxides and hydroxyl radicals. These highly reactive species can break down large complex dye molecules into numerous intermediate products, which are typically eventually oxidized into CO_2, H_2O and inorganic salts [31].

Table 2: Representative studies on WO_3 thin-film photocatalysts for the degradation of organic dyes.

WO_3 Photocatalyst	Target Dye	Light Source	Key Finding	Reference
Spin-coated WO_3 thin film	Rhodamine B (RhB)	Visible light	Efficient degradation due to high crystallinity and uniform film morphology	[19]
Nanostructured WO_3 thin film	Methylene Blue (MB)	Simulated solar light	Enhanced photocatalytic activity through increased surface area	[32]
WO_3 thin film	Methyl Orange (MO)	Visible light	Improved degradation efficiency with optimized film thickness	[19]
Oxygen vacancy-rich WO_3	Congo Red (CR)	Visible light	Oxygen vacancies promoted charge separation and ROS generation	[33, 34]
WO_3 heterojunction thin film	Crystal Violet (CV)	Visible light	Heterojunction formation significantly suppressed electron–hole recombination	[35, 36]
Doped WO_3 thin film	Malachite Green (MG)	Solar light	Metal doping enhanced visible-light absorption and photocatalytic stability	[37, 38]

Table 2 is a selection of literature to illustrate how WO_3 thin film photocatalysts are used to degrade a wide variety of organic dyes. Overall results indicate that nanostructured design (the size and shape of the nanoparticles), defects within those nanoparticles, and creating heterojunctions all contribute to increased photocatalysis at wavelengths corresponding to "visible light". Recent research has even optimized WO_3 thin film photocatalysis by using dopants as well as forming heterojunctions and modifying defects. These methods improve the ability of charges to separate from one another, prevent electron-hole pairs from recombining, and increase production of ROS.

4.1. Factors Affecting Photocatalytic Degradation Efficiency

Photocatalytic degradation efficiency of WO_3 thin film (prepared using the spin coating technique) is largely influenced by numerous process parameters and properties of materials which are responsible for absorption of light, separating charges of carriers and generating reactive oxygen species. Film thickness is one of the key variables since the excessive thinness of the film may result in limited availability of catalytically active sites while over-thickness may prevent light from penetrating into the film and thus increase recombination rate of electrons and holes. Therefore, there exists an optimal thickness of the film which allows maximum activity of photodegradation. In addition to the film thickness solution pH affects the photocatalytic activity by changing surface charge density of WO_3 and degree of ionization of dye molecule which in turn influences its adsorption and further degradation. Nature and intensity of light used for activation also significantly affect photocatalytic activity. As WO_3 is visible-light responsive semiconductor, light sources emitting visible light (or simulating solar irradiance) are generally better suited to activate WO_3 than UV radiation alone. Additionally, crystallinity, oxygen vacancy concentration, and structural characteristics of nanostructure of WO_3 thin films substantially determine separation of charge carriers and reactive oxygen species production. Therefore, nanostructured WO_3 thin films having optimized defect structures allow to achieve greater visible light absorption and enhanced kinetic constants of degradation. Optimization of above-mentioned reaction parameters is crucial to achieve maximum photocatalytic activity of spin coated WO_3 thin films, and consequently enable their practical application in water treatment technologies [39].

4.2. Recent Advances in WO3 Thin-Film Photocatalyst for Organic Dye Degradation

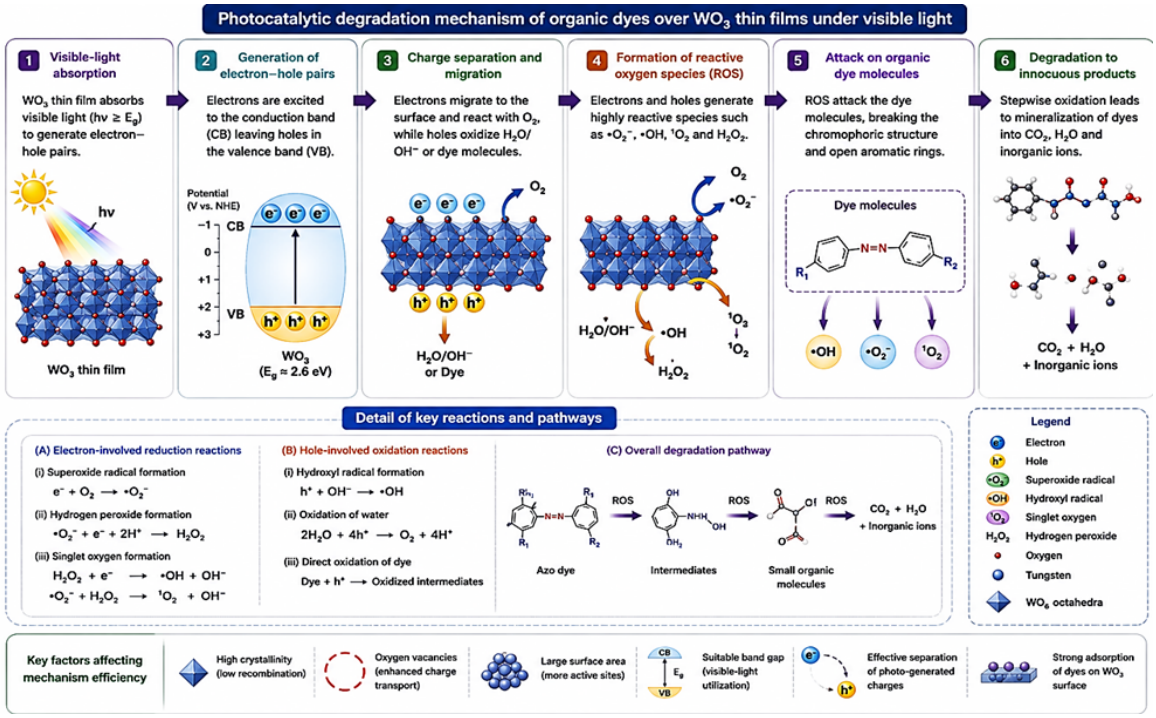

Fig 5: Photocatalytic degradation mechanism of organic dyes over WO_3 thin films under visible-light irradiation, showing charge generation, reactive oxygen species formation, and stepwise degradation of dye molecules.

Recent findings suggest that photo-catalytically active nano-structured thin film WO^3 (titanium dioxide) are stable and can be reused many times without significant loss of catalytic ability. Because these thin films are attached or "immobilized" on a surface, there is no need to remove and/or recycle loose particulate catalysts following treatment, which makes them more suited for use as continuous flow systems for water treatment than other types of powdered catalysts. Alongside this, developments in chemical precursors and optimized coating procedures have made it possible to produce films of titanium dioxide having excellent uniformity, crack free surfaces, higher crystalline structure, good adhesion to the substrate and improved catalytic properties. Nevertheless, despite advancements, several additional challenges remain to increase the quantum efficiency, improve the long-term durability of the material's structure and develop methods to fabricate the materials at a larger scale. Therefore, future research will focus on developing multi-functional hetero-junctions, precisely engineered defects and solar driven photo-catalysis using titanium dioxide thin film photo-catalysts to enable their use in environmental remediation [20]. Table 3 represents an important comparison of key approaches used for enhancing photocatalysis of WO_3 thin film.

Table 3: Critical comparison of modification strategies for WO_3 thin-film photocatalysts.

Modification Strategy	Advantages	Major Limitations	Research Gap/Future Need	References
Pristine WO_3	Good visible-light absorption, high chemical stability, reusable thin films	Rapid electron–hole recombination and low quantum efficiency	Improve charge separation without sacrificing stability	[40]
Metal-ion Doping (Ag, Fe, Cu, Mo, etc.)	Enhances visible-light absorption and charge transport	Dopant concentration must be optimized; excess dopants become recombination centers	Develop stable, low-cost dopants with long-term durability	[41]
Non-metal Doping (N, C, S, B)	Narrows band gap and improves solar-light utilization	Limited thermal stability and possible lattice distortion	Control dopant distribution and defect formation	[42]
Oxygen Vacancy Engineering	Increases active sites and promotes charge separation	Excess vacancies may decrease structural stability	Optimize vacancy concentration for maximum activity	[43]
Heterojunction Formation (WO_3/TiO_2, $WO_3/g\text{-}C_3N_4$, $WO_3/BiVO_4$)	Efficient charge separation and broader light absorption	Complex synthesis and interfacial instability	Design robust Z-scheme and S-scheme heterojunctions	[44]
Plasmonic Metal Decoration (Ag, Au)	Localized surface plasmon resonance enhances visible-light harvesting	High material cost and possible nanoparticle agglomeration	Develop low-cost plasmonic alternatives	[45]

5. Conclusion

The use of spin coated nano-structured thin film of WO_3 has been widely studied as an efficient material for the photodegradation of organic dyes through its high light absorbency, low toxicity and good chemical stability. The spin coating method is one of the most commonly used

methods for producing uniform thin films of WO_3 due to it being relatively inexpensive, easy to scale up, and allows for controlling the film's thickness, structure and crystalline phase. The structural, optical and photocatalytic characteristics of WO_3 thin films are strongly dependent upon process conditions such as precursor concentration, spin speed, number of coatings and heat treatment temperature. The modification of nano structures, oxygen vacancies and dopant elements in addition to forming hetero-junctions are some recent approaches that improve photocatalytic performance of WO_3 thin films by enhancing the ability to absorb visible light and reduce the rate of electron-hole pair recombination. Using spin coated thin films, the photocatalytic activity of WO_3 can be utilized efficiently for the removal of a broad variety of organic dyes (methylene blue, rhodamine B, methyl orange, congo red) which demonstrate the applicability of WO_3 thin films for wastewater treatments. Additionally, immobilizing the thin films facilitates reusing them without needing additional steps to separate the catalyst from treated solution and enables scaling-up to integrate into continuous flow water treatment systems.

Although significant advancements have been made in utilizing WO_3 based materials for photocatalysis; there are still significant issues associated with recombining charges carriers during operation, stability over time and practicality for large scale implementations. Therefore, future work should be focused on developing multi-functional heterostructures composed of WO_3 and other materials; defect engineered thin films; and photo catalytic systems driven by sunlight with improved efficiencies and stabilities. Furthermore, investigating experimental data using simulations models combined with reactor scale experiments would expedite the transition from laboratory to practical application of WO_3 photocatalyst.

Credit authorship contribution statement

Prafulla S. Patil: Writing–Original draft, review & editing, Conceptualisation, Formal analysis and Data curation.

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Abbreviations

(Fe_2O_3) iron(III) oxide, ($BiVO_4$) bismuth vanadate, (g-C_3N_4) graphitic carbon nitride, (ROS) reactive oxygen species, (•OH) hydroxyl radical, (•O_2^-) superoxide radical, (UV) ultraviolet, (Vis) visible, (NIR) near-infrared, (XRD) X-ray diffraction, (SEM) scanning electron microscopy, (TEM) transmission electron microscopy, (AFM) atomic force microscopy, (FTIR) Fourier-transform infrared spectroscopy, (UV–Vis) ultraviolet–visible spectroscopy, (PL) photoluminescence, (BET) Brunauer–Emmett–Teller, (PEC) photoelectrochemical, (AOPs) advanced oxidation processes, (COD) chemical oxygen demand, (BOD) biochemical oxygen demand, (MB) methylene blue, (RhB) rhodamine B, (CR) Congo red, (CV) crystal violet, (LSPR) localized surface plasmon resonance, (PVD) physical vapor deposition, (PLD) pulsed laser deposition, (CVD) chemical vapor deposition,

References

1. Gayathri K, Saranraj P, Nayak AK, *et al*. Microbial Innovations for Sustainable Wastewater Management: A Comprehensive Review of Azo Dye Bioremediation. *Sustainability*. 2026;18:3041. doi:10.3390/su18063041
2. Bhowmik S, Uddin MdS, Sarker T, *et al*. A review on WO3-based photocatalysts: Functionalization, properties and applications for the removal of organic pollutants from wastewater. *Inorganic Chemistry Communications*. 2025;182:115577. doi:10.1016/j.inoche.2025.115577
3. Razali NAM, Salleh WNW, Aziz F, *et al*. Review on tungsten trioxide as a photocatalysts for degradation of recalcitrant pollutants. *Journal of Cleaner Production*. 2021;309:127438. doi:10.1016/j.jclepro.2021.127438
4. Dutta V, Sharma SC, Raizada P, *et al*. An overview on WO3 based photocatalyst for environmental remediation. *Journal of environmental chemical engineering*. 2021;9:105018. doi:10.1016/j.jece.2020.105018
5. Geldasa FT, Kebede MA, Shura MW, Hone FG. Experimental and computational study of metal oxide nanoparticles for the photocatalytic degradation of organic pollutants: a review. *RSC Advances*. 2023;13:18404-18442. doi:10.1039/d3ra01505j
6. Al-Wasidi AS, Abdelrahman EA, Rehman K ur, *et al*. Efficient removal of crystal violet and acid red 88 dyes from aqueous environments using easily synthesized copper ferrite nanoparticles. *Scientific Reports*. 2024;14:29599. doi:10.1038/s41598-024-80681-y
7. Elfiky AAEA, Mubarak MF, Keshawy M, *et al*. Novel nanofiltration membrane modified by metal oxide nanocomposite for dyes removal from wastewater. *Environment Development and Sustainability*. 2023;26:19935-19957. doi:10.1007/s10668-023-03444-1
8. Goodarzi N, Ashrafi-Peyman Z, Khani E, Moshfegh AZ. Recent Progress on Semiconductor Heterogeneous Photocatalysts in Clean Energy Production and Environmental Remediation. *Catalysts*. 2023;13:1102. doi:10.3390/catal13071102
9. Karousis N, Tasis D. Porous covalent organic frameworks in photocatalytic ROS-mediated processes. *Energy Advances*. 2024;3:712-740. doi:10.1039/d4ya00082j
10. Nabeel M, Hussain D, Ahmad N, *et al*. Recent advancements in the fabrication and photocatalytic applications of graphitic carbon nitride-tungsten oxide nanocomposites. *Nanoscale Advances*. 2023;5:5214-5255. doi:10.1039/d3na00159h
11. He L, Yu C, Lu K, *et al*. Recent advances in synthesis, performance, and application of oxygen vacancy-enriched WO3−x photocatalysts. *Tungsten*. 2025;8:8-36. doi:10.1007/s42864-025-00349-6
12. Hilliard S, Baldinozzi G, Friedrich D, *et al*. Mesoporous thin film WO3 photoanode for photoelectrochemical water splitting: a sol–gel dip coating approach. *Sustainable Energy & Fuels*. 2017;1:145-153. doi:10.1039/c6se00001k
13. Niklasson GA, Granqvist CG. Electrochromics for smart windows: thin films of tungsten oxide and nickel oxide, and devices based on these. *Journal of Materials Chemistry*. 2006;17:127-156. doi:10.1039/b612174h
14. Ahmadi M, Younesi R, Guinel MJ -F. Synthesis of tungsten oxide nanoparticles using a hydrothermal method at ambient pressure. *arXiv (Cornell University)*. 2014;29:1424-1430. doi:10.1557/jmr.2014.155
15. Uddin N, Zhang H, Du Y, *et al*. Structural-Phase Catalytic Redox Reactions in Energy and Environmental Applications. *Advanced Materials*. 2020;32. doi:10.1002/adma.201905739
16. Aldrees A, Khan HR, Alzahrani A, Dan'azumi S. Synthesis and characterization of tungsten trioxide (WO3) as photocatalyst against wastewater pollutants. *Applied Water Science*. 2023;13. doi:10.1007/s13201-023-01938-x
17. Wei Z, Wang W, Li W, *et al*. Steering Electron–Hole

Migration Pathways Using Oxygen Vacancies in Tungsten Oxides to Enhance Their Photocatalytic Oxygen Evolution Performance. *Angewandte Chemie International Edition*. 2021;60:8236-8242. doi:10.1002/anie.202016170
18. Santato C, Odziemkowski M, Ulmann M, Augustyński J. Crystallographically Oriented Mesoporous WO3 Films: Synthesis, Characterization, and Applications. *Journal of the American Chemical Society*. 2001;123:10639-10649. doi:10.1021/ja011315x
19. Harini S, Aswini A, Kale SC, *et al*. Microwave-Assisted Solvothermal Synthesis of Tungsten Oxide (WO3) Nanoparticles for Microbial Inhibition. *International Journal of Current Research and Review*. 2021;13:76-79. doi:10.31782/ijcrr.2021.13226
20. Elaouni A, Ouardi ME, BaQais A, *et al*. Bismuth tungstate Bi2WO6: a review on structural, photophysical and photocatalytic properties. *RSC Advances*. 2023;13:17476-17494. doi:10.1039/d3ra01987j
21. Wang Y, Tian W, Chen C, *et al*. Tungsten Trioxide Nanostructures for Photoelectrochemical Water Splitting: Material Engineering and Charge Carrier Dynamic Manipulation. *Advanced Functional Materials*. 2019;29. doi:10.1002/adfm.201809036
22. Pastor E, Sachs M, Selim S, *et al*. Electronic defects in metal oxide photocatalysts. *arXiv (Cornell University)*. 2022;7:503-521. doi:10.1038/s41578-022-00433-0
23. Kumar MS, Singh VP, Bhat S, Kumar R. Environmental risks of textile dyes and photocatalytic materials for sustainable treatment: current status and future directions. *Discover Environment*. 2025;3. doi:10.1007/s44274-025-00337-0
24. Yuan S, Chen J, Lin Z, *et al*. Nitrate formation from atmospheric nitrogen and oxygen photocatalysed by nano-sized titanium dioxide. *Nature Communications*. 2013;4:2249. doi:10.1038/ncomms3249
25. Khalifa ZS, Shaban M, Zayed MA. WO3 thin films by spin coating technique and their wettability. *Egyptian journal of solids*. 2022;44:81-98. doi:10.21608/ejs.2022.142284.1036
26. Sánchez-Martínez D, Hernández-Uresti DB. Nanostructured-based WO3 photocatalysts: Recent development, activity enhancement, perspectives and applications for wastewater treatment. In: *Elsevier eBooks*. Elsevier BV; 2021. p. 211-220.
27. Longobucco G, Pasti L, Molinari A, *et al*. Photoelectrochemical mineralization of emerging contaminants at porous WO3 interfaces. *Applied Catalysis B: Environmental*. 2016;204:273-282. doi:10.1016/j.apcatb.2016.11.007
28. Zhao Y, Balasubramanyam S, Sinha R, *et al*. Physical and Chemical Defects in WO3 Thin Films and Their Impact on Photoelectrochemical Water Splitting. *ACS Applied Energy Materials*. 2018;1:5887-5895. doi:10.1021/acsaem.8b00849
29. Nakrela A, Nehal MElF, Bouzidi A, *et al*. Comprehensive investigation of WO3-x thin films: Structural, optical, and electrical insights, with application in photodegradation of dyes. *Ceramics International*. 2025;51:16997-17006. doi:10.1016/j.ceramint.2025.02.009
30. Alruwaili M, Roy A, Alhabradi M, *et al*. Heterostructured WO3–TiVO4 thin-film photocatalyst for efficient photoelectrochemical water splitting. *Heliyon*. 2024;10. doi:10.1016/j.heliyon.2024.e25446
31. Ateş S, Ateş AE, Yurtsever A, Biçer Y. Recent advances in photocatalytic hydrogen evolution and oxidation performance of Ta2O5 based materials: A comprehensive review. *Journal of environmental chemical engineering*. 2026;14:124193. doi:10.1016/j.jece.2026.124193
32. Oladoye PO, Ajiboye TO, Omotola EO, Oyewola OJ. Methylene blue dye: Toxicity and potential elimination technology from wastewater. *Results in Engineering*. 2022;16:100678. doi:10.1016/j.rineng.2022.100678
33. Singh J, Kalamdhad AS, Koduru JR. Potential degradation of hazardous dye Congo red by nano-metallic particles synthesized from the automobile shredder residue. *Nanotechnology for Environmental Engineering*. 2017;2. doi:10.1007/s41204-017-0021-z
34. Tatarko M, Bumpus JA. Biodegradation of Congo Red by Phanerochaete chrysosporium. *Water Research*. 1998;32:1713-1717. doi:10.1016/s0043-1354(97)00378-3
35. Oda AM, Khudheyer FY, Obaid EK. Photocatalytic Decolorization of Crystal Violate Dye Solution by ZnO/MWCNT Nanocomposite. *Iraqi Journal of Science*. 2023:3748-3762. doi:10.24996/ijs.2023.64.8.3
36. Sifat M, Shin E, Schevon A, *et al*. Photocatalytic Degradation of Crystal Violet (CV) Dye over Metal Oxide (MOx) Catalysts. *Catalysts*. 2024;14:377. doi:10.3390/catal14060377
37. Davamani NS, Jarvin M, Samuel PP, Savariroyan SRI. The effect of Mg doping on structural and catalytic removal of malachite green using ZnO thin films fabrication by cost effective home-made spray pyrolysis technique. *Next Materials*. 2025;8:100884. doi:10.1016/j.nxmate.2025.100884
38. Adnan A, Nisar, Shah R, *et al*. Novel Ni/ZnO Nanocomposites for the Effective Photocatalytic Degradation of Malachite Green Dye. *Civil Engineering Journal*. 2024;10:2601-2614. doi:10.28991/cej-2024-010-08-011
39. Arutanti O, Nandiyanto ABD, Ogi T, *et al*. Influences of Porous Structurization and Pt Addition on the Improvement of Photocatalytic Performance of WO3 Particles. *ACS Applied Materials & Interfaces*. 2015;7:3009-3017. doi:10.1021/am507935j
40. Liu Z, Zhong Y, Shafei IH, *et al*. Tuning infrared plasmon resonances in doped metal-oxide nanocrystals through cation-exchange reactions. *Nature Communications*. 2019;10:1394. doi:10.1038/s41467-019-09165-2
41. Devi LG, Kavitha R. A review on non metal ion doped titania for the photocatalytic degradation of organic pollutants under UV/solar light: Role of photogenerated charge carrier dynamics in enhancing the activity. *Applied Catalysis B: Environmental*. 2013:559-587. doi:10.1016/j.apcatb.2013.04.035
42. Jeen H, Bi Z, Choi WS, *et al*. Orienting Oxygen Vacancies for Fast Catalytic Reaction. *arXiv (Cornell University)*. 2013;25:6459-6463. doi:10.1002/adma.201302919
43. Liu Y, Zeng X, Easton CD, *et al*. An in situ assembled WO3–TiO2 vertical heterojunction for enhanced Z-scheme photocatalytic activity. *Nanoscale*. 2020;12:8775-8784. doi:10.1039/d0nr01611j
44. Li J, Lou Z, Li B. Nanostructured materials with localized surface plasmon resonance for photocatalysis. *Chinese Chemical Letters*. 2021;33:1154-1168. doi:10.1016/j.cclet.2021.07.059
45. Wang Y, Tian W, Chen C, *et al*. Tungsten Trioxide Nanostructures for Photoelectrochemical Water Splitting: Material Engineering and Charge Carrier Dynamic Manipulation. *Advanced Functional Materials*. 2019;29. doi:10.1002/adfm.201809036