

# Photo Catalytic Degradation of Industrial Dyes Using Metal Oxide Nanoparticles

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## Abstract

Synthetic dyes, which originate from industrial textile & chemical manufacturing processes create permanent toxic pollution-based problems that conventional wastewater treatment methods cannot resolve in further. Metal oxide nanoparticles show their ability to treat water when they successfully destroy dye pollutants through photocatalytic processes. The semiconductor photocatalysts of copper oxide and zinc oxide and titanium dioxide use sunlight to convert complex dye molecules into safer and simpler chemical substances. The process effectiveness depends on several factors which include pH value catalyst amount dye solution strength and brightness level. The development of these eco-friendly synthesis methods has improved the environmental compatibility of nanoparticles. Photocatalytic treatment functions as a wastewater remediation technology which effectively protects the environment.

**Keywords:** Synthetic dyes, Metal oxide, pH value, Photocatalytic treatment, Titanium dioxide etc.

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## I. INTRODUCTION

### Industrial Dye Pollution Background

Industrial dyes find application in manufacturing sectors that include textile and paper and leather and plastic and cosmetic and food processing operations. The textile sector ranks as the primary consumer of synthetic dyes because of worldwide consumer demand for colored textiles and clothing [1]. Industrial processes release about 100 dye compounds into water bodies through wastewater which contains dyes from dyeing and finishing operations. The chemical stability of dyes maintains their colorant strength because the dyes contain mechanisms which prevent their deterioration. The substances maintain their presence in aquatic ecosystems because they remain intact without any form of decomposition. The presence of untreated wastewater containing dyes results in three negative impacts which increase water turbidity and decrease light transmission while reducing dissolved oxygen levels in the water body. The alterations to the environment create challenges for aquatic plants and algae because they need sunlight to perform photosynthesis which results in detrimental impacts on aquatic ecosystems. The synthetic dyes and their decomposition chemicals create health dangers through their toxic properties which lead to genetic mutations and cancer development [2]. The substances create health hazards which endanger both human life and environmental protection. The need for wastewater treatment becomes crucial because dye pollution creates a significant environmental challenge which affects all members of society.

### Conventional Treatment Environmental Impact and Limitations

Industrial dye pollution creates environmental damage which extends beyond its effect of changing water colors. The presence of complex aromatic structures together with heavy metals establishes resistance to natural degradation for many dye colors. As a result, the substances enter water bodies where they continue to exist and build up in both sediment and living organisms [3]. The common wastewater treatment methods for dye removal include coagulation-flocculation and membrane filtration together with biological treatment and adsorption. The methods can decrease dye levels but they create three major problems which include incomplete degradation and high operational costs together with sludge production. The presence of complex molecular structures prevents microbes from breaking down synthetic dyes which renders biological treatments ineffective. Researchers are now working to create treatment methods which can achieve better efficiency while maintaining environmental sustainability. The advanced oxidation techniques produce highly reactive molecules which transform complex organic pollutants into safe carbon dioxide and water that serve as potential alternative treatment methods.

### Metal Oxide Nanoparticle Photocatalysis

The wastewater treatment method for industrial dye removal which uses photocatalysis as an advanced oxidation process has become a subject of research. Light energy absorption by semiconductor materials initiates chemical reactions which result in the elimination of organic contaminants [4]. When photocatalysts

undergo UV or visible light exposure their surfaces generate electron–hole pairs which produce reactive oxygen species such as hydroxyl radicals and superoxide ions. The reactive species exhibit strong oxidative power which enables them to transform dye molecules into non-toxic substances. Researchers have studied metal oxide nanoparticles which include titanium dioxide zinc oxide iron oxide and copper oxide as photocatalysts because these materials exhibit high surface area and chemical stability and active catalytic properties [5]. Photocatalytic degradation with metal oxide nanoparticles serves as an effective solution for treating dye-contaminated wastewater while safeguarding aquatic environments.

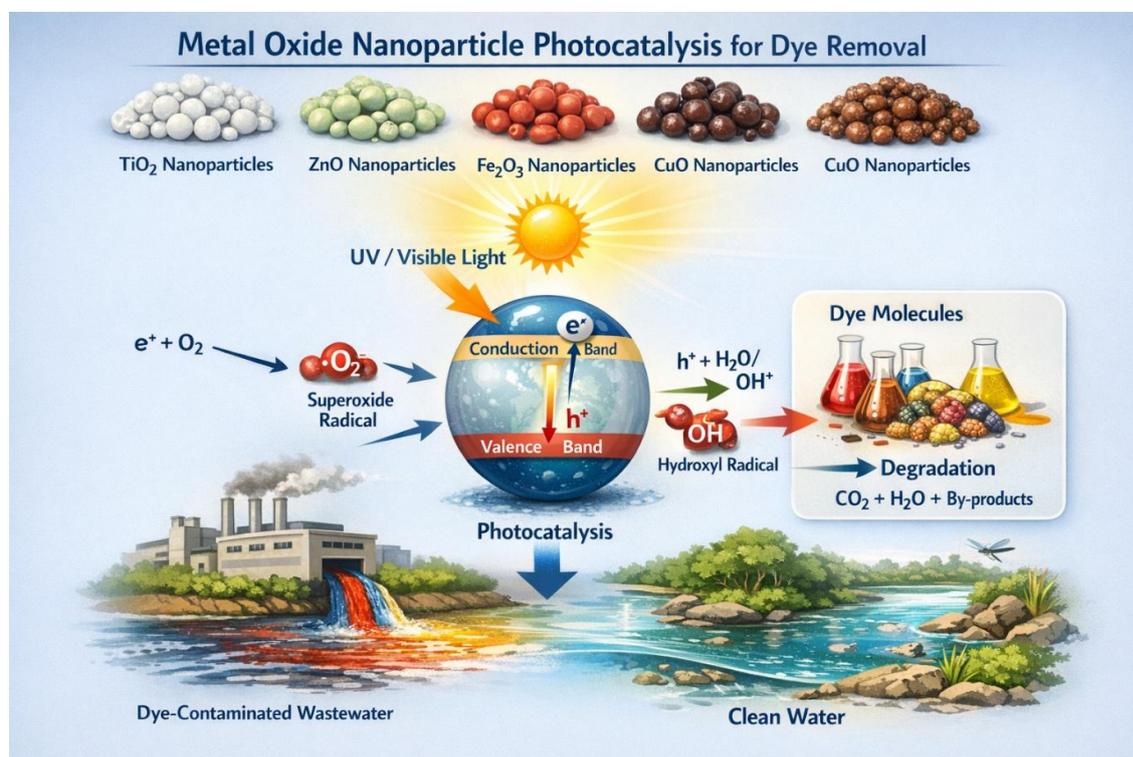


Figure 1: Photocatalysis for dye removal process, Source: Author Generated

### **Industrial Dyes and Environmental Issues**

Industrial dyes represent a diverse group of synthetic organic compounds which manufacturers use to color textiles and paper and leather and plastic and multiple consumer products. The dyes have been developed to maintain chemical stability since their colors will resist degradation from light exposure and washing processes and environmental conditions [6]. The substances become difficult to remove from wastewater treatment systems because their stable nature prevents proper disposal after they enter water bodies. The industrial sector primarily uses three major dye categories which include azo dyes reactive dyes and anthraquinone dyes. Azo dyes represent the most common dye type which contains one or more azo bonds that link together two aromatic rings. Textile manufacturers widely use these dyes for their capacity to produce different colors together with their affordable pricing. The reactive dye category creates permanent color bonds through its ability to form strong covalent connections with textile fibers, particularly cotton. The textile and printing industries use anthraquinone dyes because they produce bright blue and green colors [7].

Industrial facilities that produce textiles and conduct dyeing and chemical manufacturing processes release unprocessed wastewater which constitutes the main source of dye pollution in water bodies. During the dyeing process more than half of the used dyes end up in wastewater because they do not stick to the fabric. The discharges from industrial processes usually present high concentrations of color substances together with various industrial chemicals such as salts and surfactants and fixing agents [8]. Dyes present in water bodies create both visual pollution and harmful effects on the natural environment. Synthetic dyes present multiple dangers because they produce hazardous waste which results in carcinogenic and mutagenic substances during chemical or biological processing. The intense color of wastewater prevents light from further reaching underwater environments which results in the interruption of photosynthesis for both aquatic plants & algae. Industrial dyes hereby create a major environmental dilemma because they overly maintain their existence in nature for extended periods without breaking down [9].

Category	Description	Key Characteristics	Environmental Impact
Industrial Dyes	Synthetic organic compounds used to impart color to various industrial and consumer products such as textiles, paper, leather, and plastics.	Chemically stable, resistant to light, washing, and environmental conditions.	Persistence in wastewater and difficulty in removal during conventional treatment processes.
Azo Dyes	The most widely used class of industrial dyes containing one or more azo (-N=N-) bonds linking aromatic rings.	Wide range of colors, cost-effective, high stability.	Can break down into toxic aromatic amines which may be carcinogenic and harmful to aquatic life.
Reactive Dyes	Dyes capable of forming strong covalent bonds with textile fibers, especially cotton.	High color durability, strong chemical bonding with fabrics.	Large percentage remains unbound during dyeing and enters wastewater systems.
Anthraquinone Dyes	Dyes derived from anthraquinone structures commonly used for bright blue and green coloration.	High color intensity, good chemical stability.	Resistant to natural degradation and may persist in aquatic environments.
Major Sources of Dye Pollution	Industrial activities such as textile manufacturing, dyeing units, and chemical processing plants.	Large-scale water consumption and dye discharge.	Release of untreated or partially treated wastewater into rivers and lakes.
Dye Loss During Processing	Significant portion of dyes does not attach to fibers during dyeing operations.	Up to 50% of dyes may be lost in wastewater streams.	Leads to high concentrations of colored pollutants in effluents.
Associated Chemicals in Effluents	Wastewater often contains salts, surfactants, fixing agents, and other processing chemicals.	Complex mixture of organic and inorganic compounds.	Increases toxicity and complicates wastewater treatment.
Environmental Effects	Presence of dyes in water affects both physical and biological properties of aquatic systems.	Reduced light penetration and water discoloration.	Inhibits photosynthesis in aquatic plants and algae, disrupting ecosystems.
Health and Toxicity Concerns	Some synthetic dyes and their degradation products are hazardous to living organisms.	Mutagenic and carcinogenic compounds may form during chemical or biological transformation.	Potential risks to aquatic organisms and human health through contaminated water sources.
Persistence in Environment	Many industrial dyes resist natural biodegradation processes.	High chemical stability and complex molecular structures.	Long-term accumulation in water bodies and sediments, creating persistent environmental pollution.

Table 1: Industrial Dyes and Environmental Issues, Source:> Author Generated

## **Metal Oxide Nanoparticles Utilized as Photocatalysts**

### **Prevalent Metal Oxide Nanoparticles Employed in Photocatalysis**

Researchers have found that metal oxide nanoparticles function as effective photocatalysts which can remove organic pollutants from wastewater, particularly industrial dyes. The material exhibits strong photocatalytic performance because its unique physicochemical characteristics create a high surface area and nanoscale dimensions which boost its catalytic efficiency [10]. The main metal oxide photocatalysts which researchers studied are titanium dioxide ( $\text{TiO}_2$ ) and zinc oxide ( $\text{ZnO}$ ) and iron oxide ( $\text{Fe}_2\text{O}_3$ ) and copper oxide ( $\text{CuO}$ ). Researchers consider titanium dioxide the most studied photocatalytic substance because it delivers both chemical stability and non-toxic safety and strong ultraviolet light oxidation power. The substance exists in multiple crystal forms which include anatase and rutile and brookite, with anatase demonstrating the strongest ability for photocatalytic activities.

Zinc oxide nanoparticles show reliable performance because their band gap energy matches the properties of  $\text{TiO}_2$  while their materials block ultraviolet radiation. The first advantage of  $\text{ZnO}$  exists because it enables achievement of superior quantum efficiency with reduced expenses. The system operates effectively for operation at commercial scale because it provides efficient methods for waste material processing. Researchers investigate hematite which consists of iron oxide nanoparticles that form  $\text{Fe}_2\text{O}_3$  because its visible light absorption and magnetic properties enable easy catalyst separation from purified water. Copper oxide nanoparticles possess a limited band gap energy which enables them to absorb visible light more effectively than most metal oxides. The system operates effectively for solar energy powered photocatalytic applications.

### **Structural Attributes, Band Gap Properties, and Benefits**

The structural characteristics and electrical characteristics of metal oxide nanoparticles determine their photocatalytic performance which depends on these two fundamental properties. The nanoscale materials exhibit a surface-to-volume ratio which exceeds the surface-to-volume ratio of their bulk counterparts. The increased surface area of the material provides more active sites which facilitate catalytic reactions thus creating better contact between the catalyst and pollutant substances. The nanoscale system design improves light capture abilities while it boosts efficient charge movement during photocatalytic processes.

The photocatalytic effectiveness of semiconductor materials always depends on their band gap energy here. The band gap quantifies here the energy distinction between the valence and conduction bands of a catalyst based always. Photocatalysts enable electron transfer from the valence band to the conduction band when the incoming light energy exceeds their band gap value [11]. The bandwidth between  $\text{TiO}_2$  and  $\text{ZnO}$  is approximately 3.2 eV which corresponds to the voltage differential between the two materials.  $\text{Fe}_2\text{O}_3$  &  $\text{CuO}$  demonstrate reduced band gaps always which enable them to absorb visible light more efficiently than other materials here. Metal oxide nanoparticles shows more exhibit photocatalytic degradation abilities which make them more suitable for environmental remediation projects that demand high operational efficiency and effectiveness.

### **Mechanism of Photocatalytic Degradation**

The process of photocatalytic degradation requires light energy to interact with semiconductor photocatalysts and the pollutants which exist in wastewater. The semiconductor materials which metal oxide nanoparticles use include titanium dioxide and zinc oxide and iron oxide because these materials can absorb light energy to initiate oxidation-reduction chemical reactions. The process of these chemical reactions results in the breakdown of complex dye molecules into simpler chemicals, which have less harmful effects. Photocatalytic degradation processes typically include several connected stages which begin with light absorption by the catalyst and then proceed through electron-hole pair formation and reactive oxygen species production until dye molecules are fully broken down [12].

The first stage of the photocatalytic process begins when the semiconductor photocatalyst absorbs light. When the catalyst receives ultraviolet or visible light which has energy that matches or exceeds its band gap energy, its valence band electrons enter an active state through light absorption. The process causes electrons to transfer from the valence band into the conduction band. This process results in the creation of positively charged areas which emerge from the valence band. The process enables the photocatalyst to generate electron-hole pairs which develop on its surface. The charge carriers that are made in this process become the essential components which create chemical reactions that eliminate pollutants. The electrons and holes need to complete their photocatalytic process because their immediate recombination would decrease the process efficiency through heat generation.

The electron-hole pairs that form during the process immediately start to interact with surface molecular redox reactions which occur through the aqueous environment of their surroundings. The electrons with a positive charge in the conduction band create superoxide radical anions when they interact with liquid oxygen molecules. The valence band herein holes with a positive charge create a more highly reactive hydroxyl

radicals when they react with water-based molecules & hydroxide ions in the solution based. Organic pollution disintegrates because reactive oxygen species function as powerful oxidizing agents.

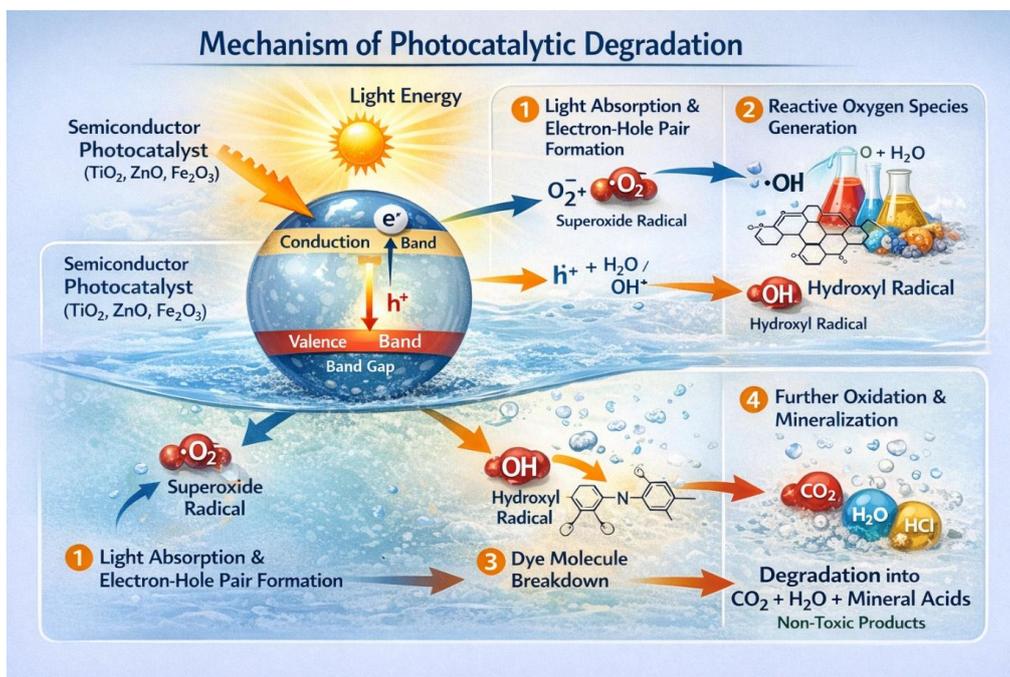


Figure 2: Photocatalytic degradation process diagram, Source: Author Generated

The catalyst surface contains color molecules which hydroxyl and superoxide radicals produced during the process attack. The oxidation process begins when the complex aromatic structures of the color molecule start to break down. This process produces intermediate chemical compounds. The intermediates undergo oxidation until they become basic solid substances which include mineral acids and carbon dioxide and water. Weathering processes eliminate all dyes from the environment which leads to their harmful effects being removed. The process of photocatalytic degradation using metal oxide nanoparticles provides an efficient and environmentally friendly solution for dye-contaminated wastewater treatment.

### Determinants of Photocatalytic Efficiency

The photocatalytic degradation of industrial dyes demonstrates efficient results through testing various operational conditions which affect the physical and chemical characteristics of tested samples. The established parameters show how dye molecules behave when they encounter both photocatalysts and light energy sources which leads to complete degradation assessment. The process outcomes always depend on five main elements, which include more or less on solution pH, catalyst dosage, dye concentration, light intensity, and the structural characteristics of nanoparticles, which include their size & surface area. The reaction of medium pH level interacts with various dye molecules by altering photocatalyst surface charge properties & dye molecule ionization processes. The catalyst surface shows different dye adsorption patterns at various pH levels, which leads to changes in the degradation process efficiency [13].

The photocatalytic activity increases when pH levels reach slightly acidic to neutral because these conditions lead to higher reactive oxygen species production and better electrostatic interactions between catalyst and dye molecules. The catalyst dosage constitutes a fundamental factor which determines the extent of photocatalytic activity. The photocatalyst quantity here always increase leads to more active surface sites which enable more with light absorption & chemical reactions, resulting in better dye degradation. The photocatalytic process becomes less effective because excess catalyst particles beyond the acceptable concentration limit led to light scattering which reduces radiation penetration.

Reaction Mechanisms of Photocatalytic Dye Degradation

$$(1) \text{ Degradation Efficiency (\%)} = \frac{C_0 - C_t}{C_0} \times 100$$

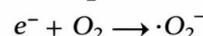
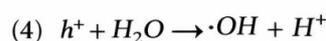
$C_0$  = Initial dye concentration  
 $C_t$  = Dye concentration at time  $t$

$$(2) A = \epsilon l C$$

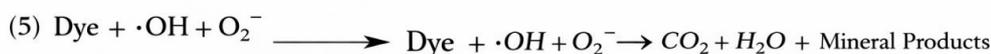
$A$  = Absorbance  
 $\epsilon$  = Molar absorptivity  
 $l$  = Path length of cuvette  
 $C$  = Concentration of dye

$$(3) \ln(C_0) = kt$$

$k$  = Apparent rate constant  
 $t$  = Reaction time



Reactive Oxygen Species Formation



Overall Mineralization Reaction

Overall Mineralization Reaction

Figure 3: Photocatalytic dye degradation mechanisms, Source: Author Generated

The initial dye concentration present in wastewater determines the speed at which it will decompose. The solution shows improved degradation speed because light can cross through the solution and make contact with the catalyst when dye concentrations reach their lower levels. The photocatalyst activation will be limited because high dye concentrations absorb most of the incoming light.

The light intensity functions as an essential factor for photocatalysis because this process depends on light energy. The process of increasing light intensity leads to a higher production rate of electron-hole pairs which creates more reactive radicals. The two factors of nanoparticle size and surface area distribution determine how well the nanoparticles will perform as catalysts. The smaller size of nanoparticles increases their surface-to-volume ratio which allows more active sites to be accessible for photocatalytic processes and results in better overall degradation performance.

Recent Developments and Case Analyses

In recent years scientists developed new metal oxide nanoparticle photocatalysts which destroy industrial dyes with effective results. Researchers have worked to improve photocatalytic performance through three methods, which involve changing nanoparticle shapes, adding dopants, and developing environmentally friendly production methods. The experimental studies proved that ultraviolet and visible light irradiation could achieve complete degradation of common dyes, which included methylene blue and rhodamine B and methyl orange [14]. The sol-gel & hydrothermal methods for producing titanium dioxide nanoparticles result in materials-based perspective shown demonstrate strong photocatalytic performance because they achieve here more than 90% dye molecule destruction within multiple hours of light exposure here. Zinc oxide nanoparticles show high photocatalytic performance because they always possess high electron mobility and they effectively generate reactive oxygen species.

The field of metal oxide nanoparticles has achieved a significant advancement through the development of sustainable eco-friendly methods for their sustainable production. Scientists are using plant extracts and bacteria together with other natural biomaterials more often instead of using hazardous chemicals to produce nanoparticles because the natural materials are less harmful to the environment. The natural chemicals in plant extracts from leaves and fruits and roots contain flavonoids and phenols and alkaloids which help to produce nanoparticles through size reduction and stability maintenance [15]. The environmental benefits of green-synthesized nanoparticles lead to their superior photocatalytic performance because of their improved surface properties. The case studies demonstrate that green-synthesized ZnO and Fe<sub>2</sub>O<sub>3</sub> nanoparticles can effectively break down multiple textile colors when exposed to sunlight, which shows its potential as a sustainable solution for wastewater treatment.

## **Problems and Possible Futures**

The application of all of the metal oxide nanoparticles for photocatalytic dye degradation at industrial scale remains unfeasible because of its presents multiple operational difficulties to despite its overall potential benefits. The primary challenge of this technique in here originates from the difficulty of retrieving mainly nanoparticles that remain suspended in water after all of the processing because this problem hinders effective recycling operations. Nanoparticles require thorough investigation because they represent a significant environmental hazard which needs assessment to determine their potential health effects on humans and aquatic species. The current issue involves developing a method to scale up laboratory photocatalytic systems so they can operate in industrial wastewater treatment plants. Future research should focus on developing recyclable catalysts while improving visible-light performance and creating cost-effective and eco-friendly photocatalytic systems for real-world applications.

## **II. CONCLUSION**

Metal oxide nanoparticles operating through photocatalytic breakdown offer an environmentally friendly solution for removing industrial wastewater color. The process achieves chemical destruction through its operational mechanism. The technology here enables rapid environmental & water body restoration through its overly ability to produce reactive oxygen species, with which, under light conditions, decompose on intricate color compounds.

## **REFERENCES**

- [1]. Hoffmann, M. R., Martin, S. T., Choi, W., & Bahnemann, D. W. (1995). Environmental applications of semiconductor photocatalysis. *Chemical Reviews*, 95(1), 69–96. <https://doi.org/10.1021/cr00033a004>
- [2]. Fujishima, A., Rao, T. N., & Tryk, D. A. (2000). Titanium dioxide photocatalysis. *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, 1(1), 1–21. [https://doi.org/10.1016/S1389-5567\(00\)00002-2](https://doi.org/10.1016/S1389-5567(00)00002-2)
- [3]. Konstantinou, I. K., & Albanis, T. A. (2004). TiO<sub>2</sub>-assisted photocatalytic degradation of azo dyes in aqueous solution: An overview. *Applied Catalysis B: Environmental*, 49(1), 1–14. <https://doi.org/10.1016/j.apcatb.2003.11.010>
- [4]. Daneshvar, N., Salari, D., & Khataee, A. R. (2004). Photocatalytic degradation of azo dye acid red 14 in water: Investigation of the effect of operational parameters. *Journal of Photochemistry and Photobiology A: Chemistry*, 162(2–3), 317–322. [https://doi.org/10.1016/S1010-6030\(03\)00378-2](https://doi.org/10.1016/S1010-6030(03)00378-2)
- [5]. Chen, X., & Mao, S. S. (2007). Titanium dioxide nanomaterials: Synthesis, properties, modifications, and applications. *Chemical Reviews*, 107(7), 2891–2959. <https://doi.org/10.1021/cr0500535>
- [6]. Byrappa, K., & Adschiri, T. (2007). Hydrothermal technology for nanotechnology. *Progress in Crystal Growth and Characterization of Materials*, 53(2), 117–166. <https://doi.org/10.1016/j.pcrysgrow.2007.04.001>
- [7]. Gupta, V. K., & Suhas. (2009). Application of low-cost adsorbents for dye removal – A review. *Journal of Environmental Management*, 90(8), 2313–2342. <https://doi.org/10.1016/j.jenvman.2008.11.017>
- [8]. Chong, M. N., Jin, B., Chow, C. W. K., & Saint, C. (2010). Recent developments in photocatalytic water treatment technology: A review. *Water Research*, 44(10), 2997–3027. <https://doi.org/10.1016/j.watres.2010.02.039>
- [9]. Wang, C., Yin, L., Zhang, L., Xiang, D., & Gao, R. (2010). Metal oxide gas sensors: Sensitivity and influencing factors. *Sensors*, 10(3), 2088–2106. <https://doi.org/10.3390/s100302088>
- [10]. Ahmed, S., Rasul, M. G., Martens, W. N., Brown, R., & Hashib, M. A. (2011). Advances in heterogeneous photocatalytic degradation of phenols and dyes in wastewater. *Water, Air, & Soil Pollution*, 215(1–4), 3–29. <https://doi.org/10.1007/s11270-010-0456-3>
- [11]. Pelaez, M., Nolan, N. T., Pillai, S. C., Seery, M. K., Falaras, P., Kontos, A. G., & Dionysiou, D. D. (2012). A review on the visible light active titanium dioxide photocatalysts for environmental applications. *Applied Catalysis B: Environmental*, 125, 331–349. <https://doi.org/10.1016/j.apcatb.2012.05.036>
- [12]. Kamat, P. V. (2012). TiO<sub>2</sub> nanostructures: Recent physical chemistry advances. *Journal of Physical Chemistry Letters*, 3(5), 663–672. <https://doi.org/10.1021/jz201710h>
- [13]. Zhang, Y., Chen, Z., Wang, S., & Liu, W. (2008). Photocatalytic degradation of methylene blue using ZnO nanoparticles. *Journal of Hazardous Materials*, 152(2), 649–655. <https://doi.org/10.1016/j.jhazmat.2007.07.028>
- [14]. Katheresan, V., Kansedo, J., & Lau, S. Y. (2015). Efficiency of various recent wastewater dye removal methods: A review. *Journal of Environmental Chemical Engineering*, 3(3), 1549–1560. <https://doi.org/10.1016/j.jece.2015.06.032>
- [15]. Malato, S., Fernández-Ibáñez, P., Maldonado, M. I., Blanco, J., & Gernjak, W. (2009). Decontamination and disinfection of water by solar photocatalysis: Recent overview and trends. *Catalysis Today*, 147(1), 1–59. <https://doi.org/10.1016/j.cattod.2009.06.018>