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A Review on Properties, Types and Applications of Photocatalysts in Environmental Remediation

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Abstract

A comprehensive review of photocatalysts and their applications in environmental remediation is carried as photocatalysis has emerged as a promising technology for environmental cleanup due to its effectiveness in degrading various organic pollutants and its potential to generate clean energy. The review covers the properties of photocatalysts, such as band gap, crystallinity, morphology, surface area, and impact of these properties on photocatalytic performance. The paper also discusses various types of photocatalysts, including unitary, binary, ternary photocatalytic materials. Additionally, the review highlights the key factors affecting the photocatalytic efficiency, such as light intensity, pH, temperature etc. The paper concludes by discussing the current challenges and future prospects of photocatalysis in environmental remediation, emphasizing the need for developing cost-effective and sustainable photocatalysts for large-scale applications.

Keywords: Photocatalysis, photodegradation, coprecipitation, dye degradation, water treatment

1. Introduction

Photocatalysis is the process of accelerating a chemical reaction by using a catalyst and light [1] and photocatalysts are materials that can initiate a photochemical reaction in the presence of light. Photocatalysts are extensively used for a variety of applications, including environmental remediation, energy conversion, chemical synthesis etc. In recent years, significant research has been conducted to develop new photocatalysts with improved performance for various applications [2, 3]. Photocatalysts are materials that can absorb light energy and convert it into chemical energy, which can be used to drive a chemical reaction. Some commonly used photocatalysts are metal oxides such as titanium dioxide (TiO_2), zinc oxide (ZnO), iron oxide (Fe_2O_3) etc. These materials are low cost materials, chemically stable and inert under normal conditions, which makes them suitable for a variety of applications.

TiO_2 is an extensively employed photocatalyst owing to its remarkable photocatalytic efficiency, durability, and cost-effectiveness. Its utility in addressing environmental issues like the decomposition of organic contaminants in water and air, and also in energy conversion applications such as dye-sensitized solar cells is well known. With its adaptability in various reactions, TiO_2 stands out as a versatile photocatalyst capable of facilitating reactions such as the degradation of pollutants, water splitting, and organic compound synthesis [4]. Zinc oxide (ZnO) is a commonly employed photocatalyst, known for its effectiveness in breaking down organic pollutants. This photocatalyst exhibits remarkable photocatalytic activity and can be utilized to decompose diverse types of contaminants, such as pharmaceuticals, pesticides, and dyes. It is also stable and relatively cheap, making it an attractive material for various applications [5].$Fe_2O_3$is a promising photocatalyst that has been studied extensively in recent years [6]. It has a wide bandgap, which allows it to absorb visible-light, making it suitable for photocatalytic applications. The utilization of Fe_2O_3 has been observed in the breakdown of pollutants like dyes and pharmaceuticals, water splitting, and the production of organic compounds. It is also stable and relatively cheap, making it a potential alternative to TiO_2.

2. Properties of Photocatalysts

The properties of photocatalysts play a critical role in their performance for various applications. The key properties of photocatalysts include their bandgap, surface area, crystallinity, morphology etc. which are discussed here.

2.1. Bandgap: The term "bandgap" refers to the amount of energy required to move an electron from the valence band to the conduction band in a material. The bandgap of a photocatalyst determines the type of light that can be used to initiate the photocatalytic reaction. Materials with a wide bandgap can only absorb high-energy photons, such as UV light, while materials with a narrow bandgap can absorb low-energy photons, such as visible light. Materials with a wide bandgap, such as TiO_2, are typically used for UV photocatalysis, while materials

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with a narrow bandgap, such as Fe_2O_3, can be used for visible light photocatalysis [7, 8].

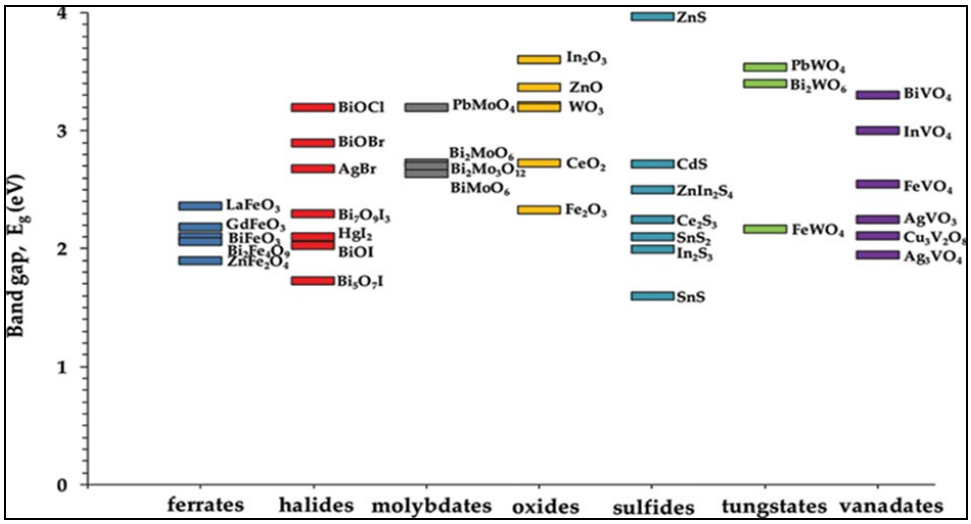

Fig 1: Band gap values for selected groups of photocatalyst [28]

2.2. Photocatalytic activity and Surface Area: Surface area is another critical property that affects the efficiency of the photocatalytic material. Materials possess a greater surface area offer more active sites for reactions to take place and lead to increased photocatalytic activity and efficiency [9], [10]. Further the activity is influenced by factors such as the bandgap, surface area, crystal structure, and doping of the photocatalyst material [11, 12]. Stability of photocatalysts under the conditions of the reaction, including in the presence of light, heat, resistant to corrosion and degradation over time, is also an important factor which affects the effectiveness of them [7-13].

2.3. Crystallinity: The crystallinity of a photocatalyst can have a significant impact on its performance. The crystallinity of TiO_2 affects its photocatalytic action by influencing factors such as band gap energy, surface area, stability, and reactivity. Anatase is preferred for many photocatalytic applications due to its high reactivity and surface area, while rutile and brookite phases have their own roles based on their stability and reactivity. The choice of crystalline phase depends on the specific photocatalytic reaction and conditions being considered. Additionally, there are methods to control the crystalline phase and morphology of TiO_2 nanoparticles, allowing researchers to tailor its properties for specific applications [14].

2.4. Morphology: The morphology of photocatalysts refers to their physical structure and shape. Common morphologies include nanoparticles, nanorods, nanowires, nanosheets, and porous structures. The size and shape of the photocatalyst affects its surface area, which in turn affects the efficiency of the photocatalytic reaction. Nanoparticle nature is the most commonly studied morphology for photocatalysts. The surface area to volume ratio is high in nanorods and nanowires, leading to more active sites for catalysis, while their elongated shape enhances charge transport and light absorption. Nanosheets have a 2-dimensional structure with a high aspect ratio, which also increases the surface area and provide more active sites. Porous structures, such as mesoporous materials, increase the accessibility of reactants to the active sites on the photocatalyst surface [15]. In addition to the shape and size, the crystalline structure of the photocatalyst also affects its performance. For example, the unique crystal structure of Anatase TiO_2 nanoparticles results in greater photocatalytic activity compared to rutile TiO_2 nanoparticles [16, 17]. Thus, researchers can tailor the morphology of photocatalysts to optimize their performance for specific applications.

2.5. Selectivity: Selectivity refers to the ability of the photocatalyst to initiate a specific chemical reaction without producing unwanted byproducts. This is an important property for many applications, such as in the synthesis of pharmaceuticals [18].

2.6. Optimal pH Range: The pH range in which the photocatalyst exhibits the highest photocatalytic activity is important, as it can affect the rate and selectivity of the reaction [19]. Table-1 illustrates effect of pH on organic pollutant degradation [20].

Table 1: Optimal pH for organic pollutant degradation

Type of catalyst	Organic Pollutant	Reaction Condition	Findings
DegussaP-25 TiO_2	Petroleum wastewater	Solarlight;170 min; pH = 3-9	Optimum pH = 6.8;76% reduction of COD.
TbxOy-TiO_2	Phenol	Visible light	Optimum pH = 4;100% of phenol Was degraded.
DegussaP-25 TiO_2	Petroleum Waste water	UV light (UVA-UVB);120 min; pH = 2-10	Optimum pH =3; COD was reduced by 72%.
Ptdoped-TiO_2	Methyl orange	UV light (365nm) ;30 min of irradiation time; pH=2.5, 6.2,and 11	Optimum pH = 2.5; 98% of Methyl orange was degraded.
Natural zeolites Supported TiO_2	Methyl orange	UV light;100 min; pH = 4-11	Optimum pH = 4; 96.58% of Methyl orange was degraded.

2.7. Temperature: The effect of temperature on photocatalysts can vary depending on the specific material and the reaction being studied. However, in general, temperature can have both positive and negative effects on photocatalytic reactions. At lower

temperatures, photocatalytic activity may be reduced due to decreased reaction rates and lower mobility of reactant molecules. On the other hand, higher temperatures can increase the rate of photocatalytic reactions by providing more energy for reactant molecules to overcome activation barriers and promoting the formation of reactive intermediates. It is important to note that excessive temperatures can also lead to thermal degradation or deactivation of the photocatalyst. This can occur due to structural changes, loss of active sites, or sintering of nanoparticles. Overall, the effect of temperature on photocatalysts is a complex interplay between various factors such as reaction kinetics, surface chemistry, and material stability, and must be carefully considered and optimized for each specific application [21],[22].

2.8. Light Source and Dosage of Photocatalyst: The light source used to activate the photocatalyst can affect the photocatalytic activity. For example, some photocatalysts are more active under UV light, while others may require visible light or both [23-25]. Further catalyst dose also plays an important role in photocatalytic activity of the material. More active surface area is available for organic compound absorption when higher catalyst dosage is used. Besides, more oxidative radicals and ions can be generated as a result of higher concentration of electrons and holes. However, excess catalyst concentration can cause agglomerate ion of the catalyst, and as a result, inhibit the penetration of UV/visible light/solar light into the effluent. Therefore, photocatalytic activity is hindered when the light irradiation is not sufficient [9]. Table 2 illustrates the effect of photocatalyst on organic pollutant degradation [26].

Table 2: Effect of TiO_2 dosage on different organic pollutants

Type of Catalyst	Organic Pollutant	Reaction Condition	Findings
Pd-TiO_2	Methylene blue & methyl orange	Visible light; 120min; Pd-TiO_2 concentration at 0.25, 0.5, 0.75,and 1.0wt. %.	Optimum loading dosage is 0.5wt.%and 0.75wt. % of Pd-TiO_2 for Methylene blue & methyl orange, respectively; 99.4 and 92.6% were degraded.
ZnO-TiO_2	Azo Dye	UV–Vislight;180min;TiO_2dosage from0.5to1.5g/L	Optimum loading dosage is 1g/L; 99% of Azo dye was degraded.
Ag-TiO_2	Orange II	UV light; 60min; 0.5, 0.8, and 1.3% of Ag	Optimum loading dosage is 0.5% of Ag-TiO_2; 20ppm of orange II was degraded
Zr^{+4}-TiO_2	4-chlorophenol	UV-Vis; 480min; TiO_2 dosage from100-500mg/100mL;Zr^{+4} concentration from 0.5-7.0 mo l%	Optimum TiO_2 dosage is 200mg/100mL; Optimum Zr^{+4} concentration I s3.0mol%; Almost 100% of 4-chlorophenol was degraded.
Natural zeolites supported TiO_2	Methyl orange	UVlight;100min;TiO_2 dosage from0.006to0.04g/10 mL	Photocatalytic degradation rate increased from 0.025 min^{-1} to 0.060 min^{-1} with thecatalystdosageincreasingfrom0.006to 0.04g/10mL.

3. Types of Photocatalysts

Various types of photocatalysts are known and are being synthesized now a days. Metal based photocatalysts utilizing metals like titanium, zinc, and iron are available. Amongst them, titanium dioxide (TiO_2) is the most preferred due to its remarkable stability and efficiency [4-6]. Photocatalysts that are based on semiconductors such as silicon, cadmium sulfide, and gallium nitride are also known. These photocatalysts have high electron mobility and can generate highly reactive radicals [28]. Photocatalysts based on carbon materials such as graphene, carbon nanotubes, and activated carbon are also prepared and used. These materials have high surface area and can be functionalized to enhance their photocatalytic properties [29]. Photocatalysts that are made by combining two or more different materials are known as composite photocatalysts. For example, a composite photocatalyst could be made by combining titanium dioxide with carbon nanotubes to enhance its photocatalytic activity [30].

Photocatalyst are widely used in many applications, including water treatment [31], air purification [32], and energy production [33]. There are various ways to categorize photocatalysts, taking into account factors such as their composition, structure, and properties. This has led to the classification of photocatalysts into different groups, including unitary, binary, ternary, and quaternary photocatalysts, which have recently gained considerable interest. [28, 34].

3.1. Unitary Photocatalysts: Unitary photocatalyst are generally oxides, sulphides etc. of metal and are referred to a type of material that can initiate or facilitate chemical reactions using light energy, such as photons from the sun or a light source. These materials typically consist of a semiconductor that absorbs light and creates an electron-hole pair, which can then interact with a nearby molecule to initiate a chemical reaction. Some common examples of unitary photocatalysts include titanium dioxide and zinc oxide [4, 5, 28]. For example, ZnO is commonly used photocatalyst for dye degradation. The photocatalytic mechanism involves the formation of electron-hole pairs, which interact with oxygen to form superoxide radicals, leading to the degradation of the dye [5].

Research studies have demonstrated the efficient degradation of dyes using visible light irradiation by the Fe_2O_3 photocatalyst. The photocatalytic mechanism involves the generation of hydroxyl radicals from the reaction between the Fe_2O_3 surface and water, leading to the degradation of the dye [6]. CuO photocatalyst has been shown to degrade dyes effectively under visible light irradiation. The dye degradation occurs through the reaction of electron-hole pairs with oxygen to form superoxide radicals in the photocatalytic mechanism [35]. Researchers have utilized ZnS to decompose dyes when exposed to visible light. The process of photocatalysis involves the generation of pair of electron-hole that interacts with oxygen, generating superoxide radicals that decompose the dye [36].

3.2. Binary Photocatalyst: A binary photocatalyst refers to a type of photocatalyst that consists of two components: a semiconductor material and a co-catalyst. The semiconductor material is typically a metal oxide that can

absorb light and produce electron-hole pairs, which can initiate chemical reactions. However, the efficiency of the photocatalytic process can be limited by the recombination of these electron-hole pairs before they can participate in a reaction. To tackle this issue, a co-catalyst is often introduced into the semiconductor material to help transfer electrons or holes to the reactants [28]. For example, platinum (Pt) is a commonly used co-catalyst for water splitting reactions, as it can facilitate the transfer of electrons from the TiO_2 to water molecules [39].The combination of the semiconductor material and co-catalyst in a binary photocatalyst can lead to improved photocatalytic efficiency and selectivity for certain reactions. There are several mechanisms by which binary photocatalysts can remove pollutants [40-43]. There are several benefits of using combination of materials in photocatalysis like:

i). **Charge Separation:** When a binary photocatalyst absorbs light, it generates pairs of electrons and holes. These electrons can move from one semiconductor's conduction band to another's, creating a separation of charges that triggers redox reactions and pollutant degradation.

ii). **Synergetic Effect:** When two dissimilar semiconductor photocatalysts are used together, they can produce a synergistic outcome, where the overall efficiency of the photocatalyst is greater than the sum of its individual parts. This effect can be attributed to improved light absorption, increased surface area, and enhanced charge separation.

iii). **Band Alignment:** The energy levels of the two semiconductor photocatalysts in the binary photocatalyst must be properly aligned in order to create an efficient photocatalyst. The conduction and valence bands of the two semiconductors should be offset such that the electrons and holes can move freely between the two materials. This allows for the efficient transfer of charge and the promotion of redox reactions.

iv). **Selectivity:** The use of binary photocatalysts can also increase the selectivity of the photocatalytic reaction. By selecting two different semiconductor photocatalysts with different properties, it is possible to create a photocatalyst that is selective for certain types of pollutants.

3.3. Ternary Photocatalyst: Ternary photocatalysts are a type of photocatalyst composed of three different materials that work together to enhance their photocatalytic properties. These materials typically consist of two semiconductor materials, such as titanium dioxide and zinc oxide, and a third material such as a metal oxide, metal sulfide, or carbon-based material. Ternary photocatalysts are gaining popularity as they exhibit superior photocatalytic efficiency compared to binary photocatalysts. This is because the combination of three materials allows for a greater surface area for light absorption, improved charge separation, and enhanced stability [28].

The mechanism involves the cooperation of three distinct components to enhance the efficiency of photocatalytic reactions, particularly in processes like water splitting or pollutant degradation. By employing three different materials and facilitating charge carrier transfer between them, ternary photocatalysts operating via the Z-scheme mechanism exhibit synergistic effects that lead to improved photocatalytic performance, such as higher reaction rates, increased stability, and enhanced selectivity for desired products [44].

3.4. Quaternary Photocatalysts: Quaternary photocatalysts are advancement beyond ternary photocatalysts, involving four different components or materials. These complex photocatalytic systems offer even greater potential for improving efficiency and performance in various photocatalytic applications [56]. These components include semiconductors, metals, metal oxides, carbon-based materials, or other nanomaterials with photocatalytic activity. Each component in the quaternary photocatalyst serves a unique role in enhancing photocatalytic activity, such as light absorption, charge separation, surface reactions, or cocatalyst functions. By combining multiple materials with complementary properties, quaternary photocatalysts exploit synergistic effects to achieve superior performance compared to single-component or binary systems. The selection of materials in quaternary photocatalysts is often guided by the desired band structure to facilitate efficient charge carrier generation, separation, and utilization. By carefully engineering the energy levels of each component, quaternary photocatalysts can promote favorable redox reactions and minimize charge recombination, thereby improving overall efficiency. Interface engineering strategies, such as controlling crystalline orientation, interfacial defects, or surface modification further enhance photocatalytic performance by promoting efficient electron and hole migration. Synergistic Effects also amplify photocatalytic activity, stability, and selectivity. For example, one component may act as a sensitizer to broaden the absorption spectrum, while another component serves as a cocatalyst to accelerate surface reactions. In summary, quaternary photocatalysts represent a sophisticated approach to photocatalysis by integrating four different components to achieve synergistic effects and enhance overall performance in various applications. Their multifunctionality, optimized band structure, interface engineering, and synergistic interactions make them promising candidates for advancing photocatalytic technology [54, 55].

4. Advantages of Binary, Ternary and Quaternary Photocatalysts

Binary, ternary, and quaternary photocatalysts have several advantages over unitary photocatalysts. They offer enhanced efficiency, improved stability, and greater selectivity, making them ideal for a wide range of applications.

4.1. Advantages of Binary Photocatalysts: Binary photocatalysts are composed of two different materials that work together to produce the desired reaction. The advantages of binary photocatalysts are [28], [40-43]:

i). Enhanced photocatalytic activity of the system leading to better efficiency and faster reaction rates.

ii). Tunable properties by changing the ratio of the two components, allowing for more precise control over the reaction.

iii). Reduced cost as compared to unitary photocatalysts because the materials used are more abundant and less specialized.

4.2. **Advantages of Ternary Photocatalysts:** Ternary photocatalysts are composed of three different materials that work together to produce the desired reaction. The advantages of ternary photocatalysts are [28],[44],[45]:

i). Enhanced stability because three components work together to prevent degradation of the material.

ii). Material can be designed to have improved selectivity for specific reactions, leading to higher yields and fewer byproducts.

iii). Can be used in a wider range of applications due to their diverse compositions and properties.

4.3. Advantages of Quaternary Photocatalysts: Quaternary photocatalysts are composed of four different materials that work together to carry the desired reaction. The advantages of quaternary photocatalysts are [28],[54]:

i). Superior efficiency of all the types of photocatalysts due to their complex composition and the interactions between the components.

ii). Can be designed to have high selectivity, specific properties, such as improved stability, higher activity, or greater selectivity for specific reactions, leading to better yields and fewer byproducts.

5. Mechanism of Photocatalytic Reactions

The mechanism of pollutant removal by unitary photocatalysis involves several steps. First, the photocatalyst absorbs light energy, creating electron-hole pairs. The movement of electrons and holes towards the photocatalyst surface enables them to engage in redox reactions with contaminants. The electrons reduce the pollutants by donating an electron, while the holes oxidize the pollutants by accepting an electron. The reactions between the photocatalyst and the pollutants can be classified into two types: direct and indirect. In direct reactions, the pollutants are adsorbed onto photocatalyst surface, and the electron-hole pairs react with them directly. In indirect reactions, the photocatalyst generates reactive species, such as hydroxyl radicals (•OH), which react with the pollutants. Several factors affect the success of photocatalysis in removing pollutants, including photocatalyst properties, pollutant type and concentration, light intensity and wavelength, and substrate geometry and surface area etc. Different substrates, such as TiO_2-coated glass fibers, metal foils, and ceramic honeycomb structures, have been studied by researchers and found to effectively eliminate various pollutants, such as bacteria, nitrogen oxides, and volatile organic compounds [28].TiO_2here is considered as role model to discuss the mechanism involved in photocatalysis.

TiO_2 uses light energy equal to or greater than its 3.2 eV bandgap, exciting electrons to the conduction band (CB) and leaving behind positively charged holes(h^+) in the valence band(VB).When excited, electrons and holes move towards the surface of TiO_2, where they can either take part in redox reactions or interact with adsorbed species. Effective charge separation is crucial to avoid electron-hole recombination, which ultimately hinders the photocatalytic process's efficiency. Further when electrons in the conduction band (CB) become excited, they may interact with adsorbed O_2(oxygen molecules) to createO_2^- (superoxide radicals). On the other hand, holes present in the valence band (VB) can trigger the oxidation of water molecules (H_2O), generating hydroxyl radicals (OH•).These ROS are highly reactive and can attack organic and inorganic pollutants adsorbed on the TiO_2 surface, leading to their degradation. These can oxidize and degrade a wide range of pollutants, including volatile organic compounds, sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter. The pollutants are converted into harmless products, such as CO_2, H_2O, and nitrates.

The mechanism for pollution removal can be summarized as follows [37, 38]

$$TiO_2 \longrightarrow \; + hv \quad (1)$$

$$e_{CB} \longrightarrow TR \quad (2)$$

$$hv^{+}_{VB} \longrightarrow TR \quad (3)$$

$$e_{TR} \; VB(h^{+}TR) \longrightarrow e_{CB} \quad (4)$$

The photo-excitation mechanism of ternary composites remains poorly comprehended, but outline of the mechanism of ternary photocatalyst involves several steps that lead to the degradation of pollutants [28, 44, 45].

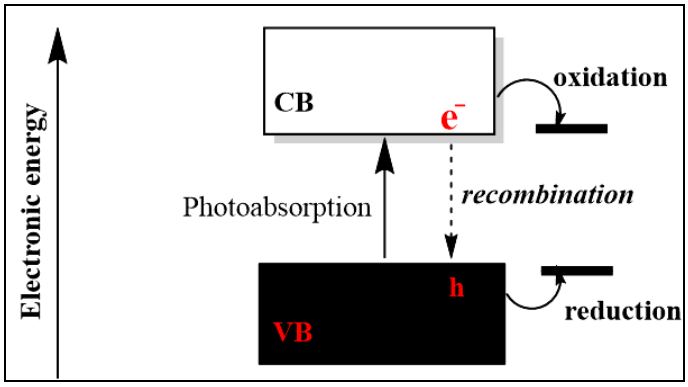

Fig 2: Electronic structure of semiconductor photocatalysts and processes in photocatalytic reactions [56]

6. Applications of Photocatalysts

Photocatalysts are used now a day for removal of pollutants, hydrogen production, water splitting, in solar cells etc. and many other environmental remediation. The Sunlight activated S-scheme ZnO-CoTe binary photocatalyst is used to effectively degrade dye pollutants from wastewater. Cobalt telluride [CoTe] when combined with ZnO in an S-scheme configuration, work together to create a more efficient photocatalyst. In an S-scheme configuration, the ZnO and CoTe are in close proximity to each other, and the electrons generated by the ZnO are transferred to the CoTe, which can then use the energy to activate further reactions. Subsequent advancements and research in this field could potentially result in the creation of even more efficient and effective photocatalytic materials that can be utilized for purifying polluted water [46].

The combination of$CuNb_2O_6$ and g-C_3N_4 has several advantages over single-component photocatalysts, such as improved photoactivity, enhanced stability, and extended spectral response range [47].$CuNb_2O_6$ and g-C_3N_4 are two semiconductor materials with band gaps of 2.7 eV, making them appropriate for visible light photocatalysis. The former is an n-type semiconductor material, while the latter is a 2D carbon nitride-based material. By incorporating both of these materials, a wide range of wavelengths can be absorbed and the efficiency of photocatalysis is enhanced. Several studies have reported the preparation and characterization of $CuNb_2O_6$/g-C_3N_4 binary photocatalysts. The performance of the photocatalyst in reducing Cr (VI) under visible light was outstanding. The effectiveness can be traced to the efficient separation of the electron-hole pairs generated by light, as well as the powerful oxidation-reduction capabilities of the

$CuNb_2O_6$/g-C_3N_4 binary photocatalyst. In addition, the $CuNb_2O_6$/g-C_3N_4 binary photocatalyst has been used for the decomposition of various dyes, such as rhodamine B and methylene blue which can be attributed to its large surface area, efficient electron transfer, and the creation of reactive oxygen species.

The degradation of Orange G dye is investigated using photocatalysis under UV light in the presence of a catalyst consisting of TiO_2 mixed with 20% chromium oxide. To achieve the highest level of dye degradation, various factors including catalyst quantity, dye concentration, pH, and reaction time were systematically optimized. The degradation of the dye followed a pseudo first-order kinetics pattern. Monitoring the process through LC-MS/MS analysis allowed for the identification of numerous intermediate products that emerged as the dye underwent degradation. Notable intermediate products that were identified include substituted phenols, aromatic hydroxylamine, nitroso hydroxyl aromatic amines, and dicarboxyl aromatic compounds. By examining these intermediates alongside minor byproducts, it was possible to propose a potential degradation pathway for Orange G. The degradation of the dye appeared to be predominantly driven by three distinct pathways: hydroxylation of the aromatic ring, desulfonation, and oxidative cleavage of the azo bond [48].

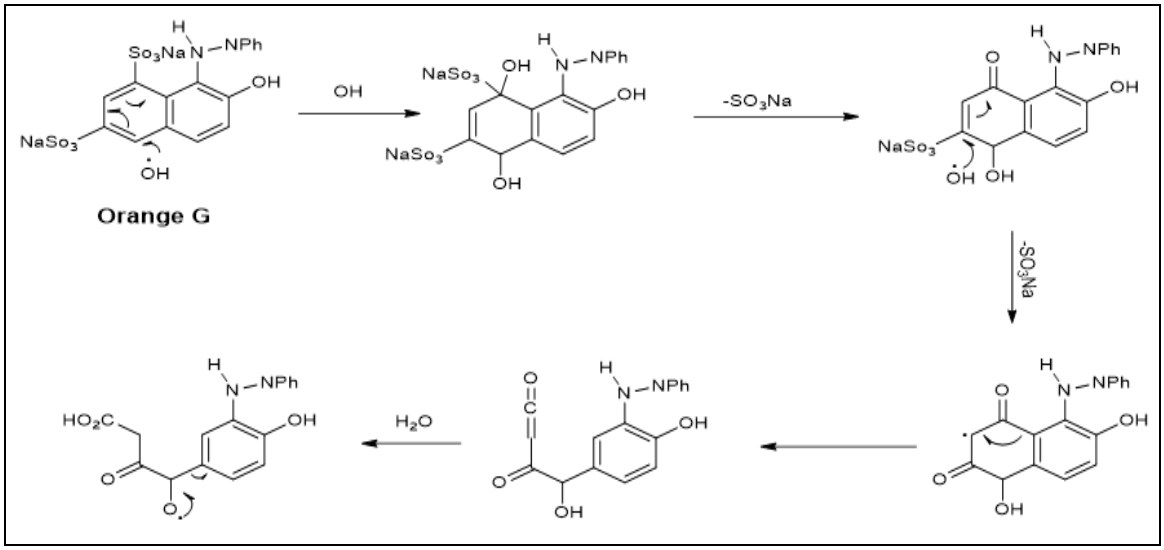

Fig 3: Mechanism of the oxidation of Organic G dye [48]

Scheme 1Mechanism of the Oxidation of Organic G Dye

The CeO_2/SiO_2 binary composite exhibits photocatalytic properties in dye degradation. It is observed that CeO_2 is a renowned photocatalyst with UV light absorption and reactive oxygen species generation capabilities, while SiO_2 is a stable and high surface area support material. The presence of CeO_2 nanoparticles on the SiO_2 surface enhances the adsorption capacity of dye molecules by creating numerous active sites. Under light exposure, the CeO_2 nanoparticles generate electron-hole pairs through the absorption of photons. These electrons and holes come into contact with oxygen, they combine to create superoxide radicals (O_2^-). These radicals have the ability to break down dye molecules and lead to their degradation. Here, the SiO_2 support enhances the stability of the CeO_2 nanoparticles and prevents their agglomeration, resulting in improved photocatalytic activity. It is environmentally friendly and can be easily synthesized using simple and low-cost methods [49].

The visible active reduced graphene oxide-$BiVO_4$-ZnO ternary photocatalyst is a type of material that can efficiently remove ciprofloxacin from water or wastewater by utilizing the power of light [50]. $BiVO_4$ is a semiconducting material that can absorb visible light and generate electron-hole pairs, while ZnO is a wide-bandgap semiconductor that can generate electron-hole pairs when exposed to UV light. When these components are combined to form the ternary photocatalyst, they work together to produce a strong oxidizing agent that can break down ciprofloxacin molecules. The absorption of light by $BiVO_4$ and ZnO results in the creation of electron-hole pairs, which are subsequently transferred to the reduced graphene oxide component. The reduced graphene oxide acts as a conductor, allowing the electrons and holes to move freely and react with water and oxygen molecules to generate highly reactive hydroxyl radicals. These hydroxyl radicals then react with ciprofloxacin molecules, breaking them down into smaller, less harmful compounds.

The BiOI/Fe_3O_4@graphene oxide ternary photocatalyst has shown promising photocatalytic performance for the degradation of 2, 4-DNP (2,4-dinitrophenol) under irradiation of visible light. The presence of graphene oxide (GO) in the ternary catalyst improves the adsorption and photocatalytic performance of the catalyst due to its large surface area and excellent electronic properties. Adding Fe_3O_4 nanoparticles to the ternary catalyst improves its magnetic separation, simplifying the recycling and reuse process. The BiOI/Fe_3O_4@GO photocatalyst showed a quick recovery of its photocatalytic activity after repeated use due to the synergistic effect of the three components. According to the research findings, after 120 minutes of irradiation, the degradation efficiency of 2, 4-DNP was 93.6%, which is noticeably greater than that of pure BiOI/Fe_3O_4 (86.7%) and BiOI (74.9%). In addition to the greater photocatalytic performance, the BiOI/Fe_3O_4@GO photocatalyst also showed excellent stability and reusability. The researchers were able to separate the catalyst easily using a magnetic field and it retained its photocatalytic activity even after five cycles of use [51].

In recent years, there has been a growing interest in the development of highly-efficient dual Z-scheme heterojunction photocatalysts for pollutant removal. Increasing the effectiveness of tetracycline degradation through visible light was achieved by employing a ternary photocatalyst consisting

of Ag_3PO_4, AgBr, and g-C_3N_4 with a dual Z-scheme heterojunction. Yu *et al.* [52] proposed a dual Z-scheme heterojunction design to increase the performance of the photocatalytic process. The ternary photocatalyst of Ag_3PO_4/AgBr/g-C_3N_4 was chosen because of the unique properties of each material. Ag_3PO_4 and AgBr are proven to be efficient photocatalysts with visible light, and g-C_3N_4 is a reliable and widely available substance that can boost the photocatalytic performance of both materials. The study found that the photocatalyst dual Z-scheme heterojunction design resulted in better photocatalytic activity in breaking down tetracycline than using single materials or binary combinations.

Photocatalysts, such as CdS/$ZnWO_4$/ZnS system, have demonstrated superior photocatalytic activity when compared to single-component photocatalysts. This is due to the unique properties of dual Z-scheme heterojunctions, which have made them a promising area of research in the field of photocatalysis. In particular, CdS/$ZnWO_4$/ZnS heterojunction photocatalysts have shown excellent performance in pollutant removal due to their unique 0D/1D/0D structure and dual Z-scheme mechanism. Under light irradiation, the CdS nanoparticles are stimulated to absorb photons and subsequently produce electron-hole pairs. The photogenerated electrons are transferred to the $ZnWO_4$ nanorods, which serve as the electron transfer channel due to their excellent electron transport properties. The electrons then move to the 0D ZnS nanoparticles, which act as the electron acceptor and co-catalyst, and are involved in the redox reactions that degrade pollutants. The use of ZnS nanoparticles can improve the photocatalytic activity of heterojunction photocatalysts by effectively reducing electron-hole pair recombination [53].

7. Conclusion

In conclusion, photocatalysts have emerged as a promising solution for environmental remediation. These materials offer unique properties such as high stability, efficient light absorption, and facile synthesis, which make them ideal for a variety of applications. Thus, different types of photocatalysts, their properties, and their applications in environmental remediation are discussed here. Photocatalysts have demonstrated tremendous potential for addressing environmental issues such as water and air pollution. Further research is necessary to optimize the efficiency and effectiveness of photocatalysts in different applications, and to scale up their production for practical use. Despite various advantages, designing and synthesizing these complex materials (i.e. Binary, ternary, and quaternary photocatalyst) can be challenging, and more research is needed to fully understand their properties and potential applications.

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