International Journal of Aquatic Research and Environmental Studies 6(S5) 383-391 2026

A review: Green Photocatalysis Advanced and Perspective-Solution for Environment Challenges

[1*]Ashvini V Meshram, [2]Indrani B Das Sarma, [3]Kishor M Hatzade

[1,3] Department of Chemistry, Dhote Bandhu Science College, Gondia 441614, India
[2]Department of Applied Science and Humanities, Jhulelal Institute of Technology, Nagpur 441111, India

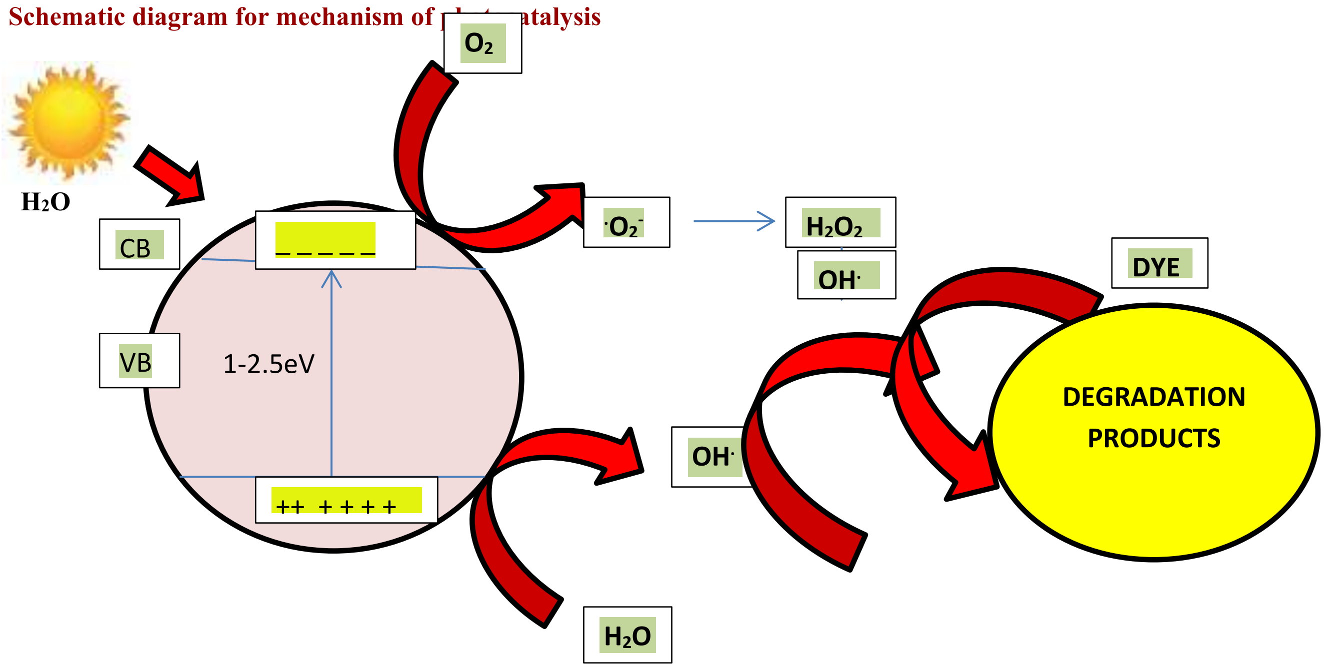
Abstract
In order to solve the world's energy and environmental problems, a new science called "green photocatalysis" blends the ideas of green chemistry with photocatalytic processes. With an emphasis on the creation of sustainable materials, environmentally friendly synthesis techniques, and their uses in energy conversion, organic transformations, and environmental remediation, this study examines the most recent developments in green photocatalysis. Designing non-toxic, economically viable photocatalysts using carbon-based, earth-abundant, and bioinspired materials is emphasized. The article also addresses how photocatalytic reactions can be fueled by renewable energy sources like solar light, which lessens the need for dangerous chemicals and fossil fuels. Critical analyses are conducted of issues like scalability, stability, and efficiency, as well as solutions such as reactor design, material optimization, and hybrid techniques. This analysis emphasizes the possibilities of green photocatalysis to support sustainable development objectives and stimulate creative thinking for a more environmentally friendly and clean future.

1. Introduction

By activating a photocatalyst substance, the process of photocatalysis uses light energy to propel chemical reactions. It involves the photocatalyst absorbing photons, which causes it to go through electrical excitation and produce reactive species that can start different chemical reactions. Due to its potential uses in fields including water splitting, pollutant degradation, and chemical synthesis, this environmentally benign technology has attracted a lot of attention recently.[1]

Here is a brief overview of the photocatalysis process:

Light absorption: The photocatalyst material absorbs photons from a light source, typically in the ultraviolet (UV) or visible range. The absorption depends on the bandgap energy of the photocatalyst, which determines the wavelengths of light it can absorb.[2]



Electron-hole generation: Upon photon absorption, electrons are promoted from the valence band to the conduction band, creating electron-hole pairs (excited state). These photoexcited charge carriers are responsible for the subsequent reactions.[3]

Redox reactions: The photoexcited electrons in the conduction band and the holes in the valence band can participate in various redox reactions. For example, the electrons can reduce a species, while the holes can oxidize another species. These reactions can result in the degradation of pollutants, generation of clean fuels, or synthesis of valuable chemicals.[4]

Recombination: In some cases, the photoexcited electrons and holes can recombine before participating in the desired reactions. Minimizing recombination is crucial for efficient photocatalysis, and several strategies such as doping, surface modification, and heterostructuring are employed to suppress it.

R. Jaiswal and et.yl. have been studied that the energy band gap of TiO_2 is decreased through doping with metals like Cr, Fe, V, Mn, Cu, Zn, and Ni, which also lowers the rate at which photogenerated electron-hole pairs recombine. However, at greater dopant concentrations, these metals start to recombine photogenerated electrons and holes on their own. Doping TiO2 with non-metallic anions, such as N, S, and C, produces energy levels slightly above the top of the valence band of TiO_2, decreasing the band gap. These anions replace O in the TiO_2 lattice. Low concentration monodoping (p-type or n-type) can lower the band gap to some amount, but not to the point where visible light can be used effectively.[5]

2. Mechanism of photocatalysis

Light absorption, charge separation, surface reactions, and charge recombination are just a few of the processes that make up the mechanism of photocatalysis. The general description of the photocatalysis mechanism is given below:

Light absorption: The photocatalyst absorbs photons with energy equal to or higher than its bandgap energy. This excitation leads to the promotion of electrons from the valence band to the conduction band, leaving behind holes in the valence band. The absorbed light can be in the UV, visible, or even near-infrared range, depending on the bandgap of the photocatalyst.[6]

Charge separation: The photoexcited electrons and holes are spatially separated within the photocatalyst material. This separation is crucial to prevent rapid recombination of the charges, which could decrease the efficiency of the photocatalytic process. The mechanisms for charge separation can vary depending on the type of photocatalyst and its specific characteristics.[7]

Surface reactions: The photoexcited electrons and holes participate in surface reactions with adsorbed reactants or species present in the surrounding environment. These reactions can include oxidation, reduction, and other chemical transformations, depending on the desired photocatalytic application. The surface reactions are facilitated by the presence of active sites on the photocatalyst surface and the appropriate energy levels of the photoexcited charges.[8]

Charge recombination: In some cases, the photoexcited electrons and holes may recombine before participating in surface reactions, leading to the loss of photocatalytic activity. Minimizing charge recombination is essential for efficient photocatalysis. Strategies such as surface passivation, doping, and heterostructuring are employed to suppress recombination and enhance charge transfer to the surface.[9]

Step	**Description**	**Factual Data**
1.Light Absorption	Photocatalysts absorb light (often UV or visible), leading to electronic excitation.	Many photocatalysts, such as TiO_2, have a bandgap of ~3.2 eV, allowing them to absorb UV light.
2. Electron-Hole Pair Generation	Absorption of light generates electron-hole pairs. The electrons are excited from the valence band to the conduction band.	A photon with energy greater than the bandgap energy generates these pairs; e.g., for TiO_2, this is ~380 nm (UV range).
3.Charge Separation	The excited electrons and holes separate, often due to the structure of the photocatalyst.	Effective charge separation is crucial; structures like mesoporous TiO_2 enhance this process.
4. Surface Reactions	Electrons and holes migrate to the surface where they react with adsorbed molecules (e.g., H_2O, O_2, organic pollutants).	Reactions can include oxidation of pollutants and reduction of O_2 to generate reactive species like hydroxyl radicals (•OH).
5.Product Formation	Redox reactions lead to the formation of products, such as H_2 gas or mineralization of organic compounds.	Example: The degradation of methylene blue using TiO_2 under UV light results in the formation of CO_2 and H_2O.
6.Charge Recombination	Some electron-hole pairs recombine before reacting, which decreases efficiency.	Recombination rates can be high in some catalysts; using co-catalysts (like Pt) can reduce these rates.
7. Cycle Repeat	The photocatalyst can be reused as long as it maintains its structural integrity and activity.	TiO_2 and other catalysts can be recycled multiple times without significant loss of activity, provided they are not deactivated.

3. **Key factors influencing photocatalytic reactions**

Several key factors influence photocatalytic reactions, and understanding these factors is crucial for optimizing the efficiency and performance of photocatalysts. Here are some key factors:

Photocatalyst material: The selection of the photocatalyst material is crucial because it affects the catalytic activity, band structure, and qualities of light absorption. The degree of photocatalytic activity varies across numerous substances, including titanium dioxide (TiO2), zinc oxide (ZnO), and several metal halide perovskites. Charge separation, surface reactions, and catalytic performance are all impacted by the photocatalyst material's characteristics.[10]

Bandgap energy: The range of light wavelengths that can be absorbed depends on the photocatalyst's bandgap energy. To guarantee effective absorption, the bandgap and light source should be well matched. Narrower bandgap materials, such metal halide perovskites, can absorb more of the visible and near-infrared spectrum of light.[11]

Surface area and morphology: More active sites for reactant adsorption are provided by higher surface areas, which also increases the contact area where reactions can take place. Light scattering, charge transfer, and accessibility to reactants can all be affected by the photocatalyst's morphology, which can include nanoparticles, nanowires, or hierarchical structures.[12]

Cocatalysts and co-catalytic reactions: Noble metals (like platinum or palladium) or metal oxides (like Co_3O_4 or NiO) can improve charge separation and facilitate particular surface reactions as cocatalysts. Cocatalytic interactions using cocatalysts can boost catalytic activity, stimulate the synthesis of desired products, and reduce unwanted side effects [13]

Reaction conditions and environment: Photocatalytic processes can be influenced by variables like temperature, pH, the presence of co-solvents, and reactant concentration. To obtain the desired product yield and selectivity, the best reaction conditions must be identified.[14]

4. Role of catalyst in photocatalyst:

In photocatalysis, a catalyst plays a crucial role in facilitating the desired chemical reactions by enhancing the efficiency of charge separation, promoting surface reactions, and reducing charge recombination. The catalyst can be introduced as a cocatalyst or integrated into the photocatalyst structure.

Enhancing charge separation: Charge separation can be improved in photocatalysis by catalysts acting as charge acceptors or donors. They can stop quick recombination by grabbing photoexcited electrons or holes from the photocatalyst. Cocatalysts are frequently employed to improve charge separation and facilitate particular surface reactions. These materials include noble metals (such as platinum, palladium) and metal oxides (such as Co3O4, NiO).[15]

Promoting surface reactions: Catalysts can provide active sites for surface reactions and facilitate the conversion of reactants into desired products. They can lower the activation energy of the reactions and increase the reaction rates. The presence of catalysts on the photocatalyst surface enhances the adsorption of reactants, improving the efficiency of the photocatalytic process.[16]

Reducing charge recombination: Catalysts can reduce charge recombination, which is harmful to the effectiveness of photocatalysis. Catalysts reduce the likelihood of recombination and improve overall charge transfer efficiency by collecting the photoexcited charges and transferring them to the reaction sites.[17]

Synergistic effects: Catalysts can exhibit synergistic effects with the photocatalyst, leading to enhanced photocatalytic performance. The combination of different catalysts, such as metal cocatalysts or co-catalysts, can create unique active sites and promote specific reactions, expanding the range of photocatalytic applications.[18]

5.1 Green photocatalysts - concept

Green photocatalysts are substances that prioritise environmental sustainability while utilising light energy to drive chemical processes. These catalysts are made with safety, non-toxicity, and the environment in mind.

Environmental sustainability: By utilising renewable energy sources, such as sunshine, and avoiding the use of poisonous or damaging ingredients, green photocatalysts seek to reduce the environmental impact of chemical processes. The goal is to create catalysts that are abundant, simple to recycle, and energy-efficient.[19]

Abundant and non-toxic materials: Green photocatalysts make use of components that are both safe for the environment and people's health. For instance, titanium dioxide (TiO_2), a popular green photocatalyst, is accessible, affordable, and safe.[20]

Applications: Green photocatalysts are used in many different industries, such as organic synthesis, water purification, air purification, and environmental remediation. They provide options that are both environmentally friendly and economical with energy.[21]

Photocatalytic mechanisms: Green photocatalysts function by absorbing light energy and producing electron-hole pairs. The participation of these excited charge carriers in various redox processes allows for the degradation of contaminants or the creation of desired chemicals.[21]

5.2 History of Photocatalysis and green catalyst

In the branch of research known as "photocatalysis," photons interact with a catalyst usually a semiconductor material to trigger chemical reactions. Although photocatalysis has been around since the early 20th century, substantial developments and discoveries have just recently been accomplished. Additionally, in order to increase the effectiveness and sustainability of the process, the creation of green catalysts has grown to be a crucial component of photocatalytic research.[22]

Early Discoveries: One of the earliest reports of photocatalytic activity was made by scientist Alexander Stoletov in 1912 when he noticed the phenomena of light-induced water electrolysis. Friedrich Gomberg, a German scientist, demonstrated the photochemical production of reactive intermediates in the 1920s, offering crucial insights into light-driven chemical reactions.[23]

Photoelectrochemistry: While researching water electrolysis in the 1970s, scientists Akira Fujishima and Kenichi Honda discovered the photocatalytic characteristics of titanium dioxide (TiO2). This discovery set the stage for current photocatalysis research. The Honda-Fujishima effect, which explains the splitting of water into hydrogen and oxygen using light energy on a TiO2 electrode, was developed as a result of the work of Fujishima and Honda.[24]

Semiconductor Photocatalysis: In-depth study on semiconductor-based photocatalysis, particularly using TiO2, as a promising catalyst for a variety of applications, including environmental rectification and solar energy conversion, was conducted during the 1980s and 1990s. For improved photocatalytic performance, researchers investigated the underlying mechanisms of charge separation, surface reactions, and semiconductor material optimisation.[25]

Green Catalysts in Photocatalysis: Researchers are looking into the creation of ecologically acceptable catalysts for photocatalytic reactions since the ideas of green chemistry and sustainability have gained popularity. Green catalysts, sometimes referred to as earth-abundant or non-toxic catalysts, seek to substitute more cost-effective or environmentally friendly materials for hazardous or expensive ones that are typically employed in photocatalysis without sacrificing performance. Metal-free carbon-based polymers, organic dyes, metal oxides, and hybrid nanocomposites are a few examples of green catalysts.[22,24]

5.3 Green synthesis route

Green synthesis is the process of creating different substances, such as organic molecules or nanoparticles, utilising techniques that are kind to the environment and sustainable raw materials. These natural resources can act as reducing agents, stabilisers, or catalysts for the production of desired chemicals in the setting of plant or biological extracts.[26]

Similar to the green production of other nanoparticles, ferrites are created utilising biological or plant extracts. A group of magnetic materials known as ferrites are made of iron oxide and additional metal ions like cobalt, nickel, or zinc. Depending on the extract of choice and the desired ferrite composition, the specific processes involved in the green synthesis of ferrites utilising plant or biological extracts can change.[26]

Selection of Plant or Biological Extract: Picking a Plant or Biological Extract Various plant or biological extracts can be utilised as reducing agents, stabilisers, or catalysts in the synthesis of ferrites, just like in the case of silver nanoparticles. The preferred ferrite composition and the availability of acceptable plant or biological sources determine the extract to use. Green tea, neem, or grapefruit extracts, which are frequently utilised in the manufacture of nanoparticles, may also be used to create ferrite.[27]

Preparation of Plant or Biological Extract: Plant or biological material is normally cleaned, dried, and ground into a fine powder for the preparation of the extract. After that, the powder is combined with an appropriate solvent, like water or ethanol, and extracted using techniques like maceration, sonication, or refluxing. This procedure aids in the extraction of bioactive substances that may function as stabilisers or reducing agents for the ferrite production.[28]

Synthesis of Ferrites: The extraction of biological or plant material, which is enriched with bioactive compounds, is combined with metal salts or precursors that contain the necessary metal ions, such as iron and other transition metals like cobalt, nickel, or zinc, to create ferrites. Redox processes may be involved in the reduction of metal ions and subsequent creation of ferrite nanoparticles. In these reactions, the bioactive substances in the extract function as reducing agents, converting metal ions to their corresponding metallic or oxide forms. The required ferrite nanoparticles are subsequently created by the reaction between these metallic or oxide forms.[27,28]

Characterization of Ferrite Nanoparticles: The size, shape, crystal structure, chemical composition, and magnetic properties of the synthesised ferrite nanoparticles can be examined using techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and Fourier-transform infrared spectroscopy (FTIR).[27,28]

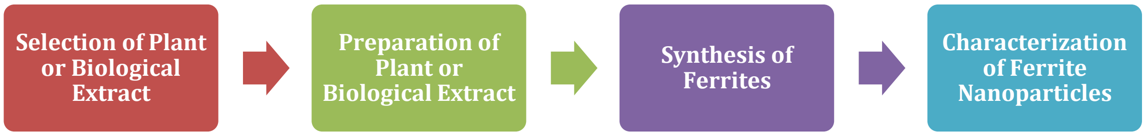


Fig: Green synthesis Route

5.4 Use of green photocatalysts in degradation of organic pollutants from water and air

Green photocatalysts have gained significant attention in recent years due to their potential for the degradation of organic pollutants from water and air.. They are usually made of sustainable and environmentally acceptable materials that can use solar energy to start photocatalytic reactions. Pesticides, dyes, and volatile organic compounds (VOCs) are three typical classes of organic pollutants that are targeted for degradation utilising green photocatalysts.[29]

a) Pestisides: Although pesticides are frequently employed in agriculture to manage pests, their leftovers can contaminate water sources and have a negative impact on ecosystems and human health. Photocatalysis has been used to degrade pesticides using green photocatalysts like titanium dioxide (TiO_2).[29]

The process by which pesticides degrade consists of multiple steps:

Photocatalyst excitation: Excitation of the photocatalyst results in the production of electron-hole pairs when the green photocatalyst is subjected to natural or artificial light.

Formation of reactive species: Reactive species can be produced by the photocatalyst's excited electrons reducing molecule oxygen (O2) to superoxide radicals (•O2-), and by the holes oxidising water molecules (H2O) to hydroxyl radicals (•OH). The breakdown of pesticides is greatly aided by these reactive organisms. Superoxide radicals (•O2-) typically have a reduction potential between -0.1 and -0.3 volts (V), which is considered to be moderate. This indicates that superoxide radicals serve as rather potent oxidising agents and have a tendency to take electrons. The oxidation potential of hydroxyl radicals (•OH), on the other hand, is extremely high, often between +2.7 and +2.8 V. Due to their high oxidation potential, hydroxyl radicals are shown to be highly reactive with a wide range of organic molecules and to be exceptionally potent oxidising agents.

Adsorption of pesticides: Pesticide molecules present in the water or air can adsorb onto the surface of the photocatalyst.

Degradation reactions: Pesticide molecules are broken down into smaller, less dangerous compounds like carbon dioxide (CO2) and water (H2O) when the adsorbed pesticides are exposed to oxidation reactions with the produced hydroxyl radicals (•OH) or by direct electron transfer from the excited photocatalyst.Alalm et. yl studies eight pesticides (azoxystrobin, hexaconazole, kresoxim-methyl, tebuconazole, pyrimethanil, triadimenol, primicarb, and propyzamide) were studied for photodegradation in leaching water using tandem ZnO/Na2S2O8 as photosensitizer/oxidant and compound parabolic collectors at pilot plant scale. Within 120 minutes, the insecticides completely disintegrated according to first-order kinetics based on the Langmuir curve. [29]

By completely mineralizing these pollutants, the overall photocatalytic breakdown of pesticides utilising green photocatalysts lessens their influence on the environment.

b) Dyes: Dye is widely utilised in many industries, such as the production of textiles, prints, and paper, which results in the discharge of coloured wastewater. Green photocatalysts present a viable approach for the photocatalytic degradation of dyes.[30]

The process by which colours degrade is comparable to that of insecticides. Upon light absorption, the activated photocatalyst produces electron-hole pairs, which in turn produce reactive species including hydroxyl radicals (•OH) and superoxide radicals (•O2-), among others. The dye molecules are subsequently degraded as a result of this interaction with the reactive species. The dye molecules go through structural changes and oxidation processes, which ultimately lead to the disintegration of complex dye molecules into less colourful and simpler chemicals.[30]

A complex mechanism that varies based on the particular type of ferrite and the reaction circumstances is involved in the photocatalytic degradation of methylene blue employing ferrites as the photocatalyst. A type of magnetic materials known as ferrites has the general formula MFe2O4, where M is one of a number of metal cations, including Fe, Co, Ni, Zn, Mn, etc.

Aubrey Makofane et. yl.in 2021 has been studied the degradation of methylene blue dye by zinc ferrite and about 67% dye degraded.

c) VOCs (Volatile Organic Compounds):

Volatile organic compounds, also known as VOCs, are a broad category of organic substances that can be emitted into the environment from a number of different sources, such as industrial emissions, car exhaust, and household items. Many VOCs are dangerous to human health, and they also contribute to smog production and air pollution. A proposed method for removing VOCs from the air is green photocatalysis.[31]

An excellent example of photocatalytic degradation of a volatile organic compound (VOC) is the breakdown of formaldehyde (HCHO) using a photocatalyst like titanium dioxide (TiO2). Formaldehyde is a common indoor air pollutant that can be emitted from various sources, including building materials, furniture, and household products has been studied by Guangxin Zhang et.yl in 2017.

Photocatalyst activation: Titanium dioxide becomes excited and produces electron-hole pairs when exposed to ultraviolet (UV) light with an energy larger than its bandgap, which activates the photocatalyst. The photocatalytic activity starts here.

Formation of hydroxyl radicals: Hydroxyl radicals (•OH) are extremely reactive molecules that are created when oxygen and water present in the surroundings react with excited electrons in TiO2.

Reaction with formaldehyde: The hydroxyl radicals produced in the preceding step can now interact with airborne formaldehyde molecules. The formaldehyde molecules are attacked by the hydroxyl radicals, which cause the molecules' carbon-hydrogen (C-H) and carbon-oxygen (C=O) bonds to break.

Formation of CO2 and water: Formaldehyde is completely mineralized into carbon dioxide (CO2) and water (H2O) as a result of the chemical reaction between hydroxyl radicals and formaldehyde. These leftovers can be safely disposed into the environment.

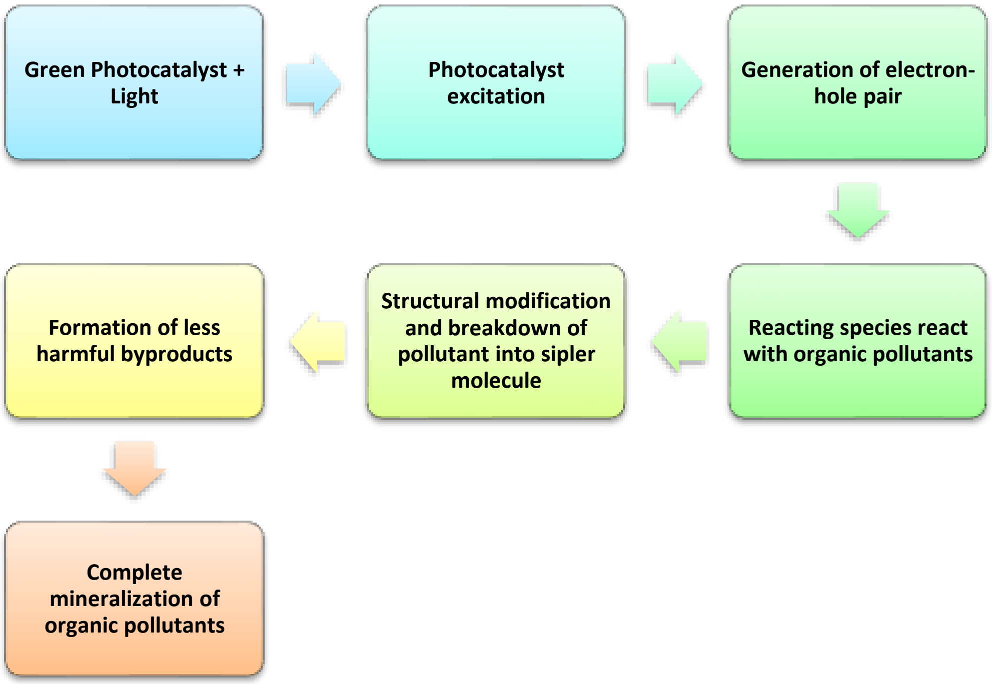
The following steps are part of the reaction process for the degradation of VOCs utilising green photocatalysts:

Photocatalyst excitation: The green photocatalyst absorbs photons and undergoes electronic excitation when exposed to light.

Activation of oxygen molecules: Superoxide radicals (•O2-) are produced as a result of the excited photocatalyst's transfer of electrons to molecular oxygen (O2). These radicals are very reactive and take part in the decomposition of VOCs[31]

Adsorption of VOCs: VOC molecules present in the air can adsorb onto the surface of the photocatalyst.

Oxidation reactions: The adsorbed VOC molecules engage in interactions with the reactive species (•O2- and •OH) that are produced. Through these processes, chemical bonds are broken and VOCs are converted into less hazardous and volatile byproducts like carbon dioxide (CO2) and water (H2O).[31]



Degradation of organic pollutant

5.5 Elucidate how the photocatalysts are sustainable

Due to a number of characteristics that contribute to their resource efficiency and environmental friendliness, photocatalysts are regarded as sustainable.[32]

Here are some key points explaining how photocatalysts exhibit sustainability:

Renewable Energy Utilization: Photocatalysts use solar energy, a plentiful and renewable source of energy, as the catalyst for photocatalytic reactions. Because of this reliance on solar energy, there is no need for non-renewable energy sources like electricity or fossil fuels.[33]

Particularly in the area of renewable energy, photocatalysts are essential for the use of sustainable energy. They are crucial in many applications because they can use solar energy to fuel chemical reactions. Titanium dioxide (TiO2) is a well-known example of a sustainable photocatalyst. Water splitting as a means of using renewable energy: Photocatalytic water splitting is a promising technique for creating sustainable hydrogen fuel from solar energy. A photocatalyst uses the energy it collects from the sun's rays to split water into hydrogen and oxygen in this process. Due to its availability, affordability, and stability, titanium dioxide (TiO2) is one of the most commonly utilised photocatalysts for water splitting.

The following chemical formula can be used to photocatalyze the water splitting process utilising TiO2:

$2 H2O + \text{Photons (solar energy)} \rightarrow 2 H2 + O2$

As it allows the use of solar energy, a clean and renewable resource, to make hydrogen fuel without creating damaging greenhouse gases or depleting finite resources, TiO2 is a sustainable choice for this application.[34]

Reduced Energy Consumption: Compared to conventional methods of pollutant degradation, photocatalysis often operates under ambient settings and uses less energy. By reducing energy use and related carbon emissions, this trait that conserves energy supports sustainability.[35]

Example: Photocatalytic degradation of organic pollutants

Water supplies can get contaminated by organic pollutants from industrial processes, agriculture, and urban activities, and their cleanup requires energy-intensive methods. Energy-intensive conventional techniques like chemical oxidation or activated carbon adsorption are frequently used. However, a method known as photocatalytic oxidation can be utilised to breakdown organic contaminants in water using photocatalysts such titanium dioxide (TiO2). Reactive oxygen species (ROS) are formed when the photocatalyst is exposed to ultraviolet (UV) or visible light because it produces electron-hole pairs. When organic contaminants are exposed to these ROS, they can be converted into innocuous byproducts like carbon dioxide and water. Using photocatalysts in this situation has the advantage of utilising sunshine as a plentiful and sustainable energy source to accelerate the degradation process. As a result, compared to conventional techniques that rely on electricity or chemical agents, the energy usage is significantly decreased. [36]

Environmental Impact: A number of photocatalysts, including titanium dioxide (TiO2), are made of plentiful, naturally occurring, non-toxic minerals. They do not significantly endanger human health or ecosystems, ensuring their continued use.[37]

Example: Photocatalytic air purification

A major environmental worry that has an impact on ecosystems and human health is air pollution. Traditional air cleaning techniques frequently entail the use of chemicals that can have a negative environmental impact or energy-intensive processes. Utilising photocatalysts, such as titanium dioxide (TiO2), will provide for a sustainable solution to this problem. These photocatalysts produce reactive oxygen species (ROS) when exposed to UV or visible light, which can break down dangerous air pollutants like nitrogen oxides (NOx) and volatile organic compounds (VOCs).[38]

Potential for Water Conservation: Photocatalysis can be used to destroy organic contaminants in water treatment systems. Water treatment techniques like filtering or distillation that use a lot of chemicals or energy can be reduced or even eliminated by using photocatalysis. The sustainability of photocatalytic water treatment is improved by this element of water conservation.[33-39]

Example: Photocatalytic water purification and wastewater treatment

Global concerns about water scarcity are growing, and conventional water treatment techniques frequently use a lot of energy and chemicals. To address these issues sustainably, photocatalysts like titanium dioxide (TiO2) can be used in water purification and wastewater treatment. Reactive oxygen species (ROS), which are produced when photocatalysts are exposed to UV or visible light, can efficiently breakdown a variety of water contaminants, including organic chemicals, heavy metals, and even some viruses.[40]

Reusability and Longevity: Some photocatalysts have a high degree of stability and can be utilised repeatedly without significantly losing their photocatalytic characteristics. This reusability decreases the requirement for frequent photocatalyst synthesis or replacement, minimising waste formation and resource usage.[36-39]

Example: Reusable photocatalysts for water treatment

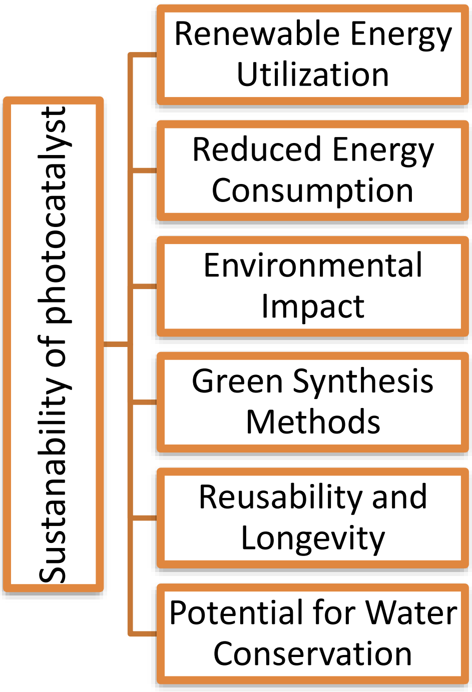
As previously indicated, photocatalysts like titanium dioxide (TiO2) can be used in water treatment to remove contaminants through photocatalytic reactions. These photocatalysts' potential for reusability and long-term performance is one of their sustainable advantages. The photocatalyst can be immobilised on a substrate or supporting material in a continuous flow water treatment system. Pollutants are destroyed as contaminated water passes over the photocatalyst surface and engages in the photocatalytic reaction. After that, the cleaned water can be gathered for disposal or reuse. The photocatalyst can be renewed by being exposed to UV or visible light after each treatment cycle, which reactivates its photocatalytic capabilities. An effective and long-lasting water treatment solution is provided by the reusing of the photocatalyst for consecutive treatment cycles.[41]

Green Synthesis Methods: Researchers are actively looking for environmentally friendly ways to make photocatalysts. Utilising ecologically friendly precursors, renewable resources, or eco-friendly production techniques, green synthesis techniques lessen the environmental impact of their manufacture.[39]

Example: Green synthesis of silver nanoparticles using plant extracts

The green synthesis of Ag NPs offers several sustainable benefits:

Natural sources that are typically non-toxic and biocompatible, such as plant extracts, are preferable to the dangerous chemical reducing agents utilised in conventional production procedures. Plant extracts are made from renewable plant a source, which lessens the need for non-renewable resources in the production of photocatalysts.[42]



Degussa TiO_2

The terms Degussa TiO2 or Evonik TiO2 refer to a particular type of titanium dioxide (TiO2) photocatalyst produced by Degussa, a German speciality chemicals business that is now a part of Evonik Industries. Due to its high purity, specific surface area, and regulated particle size, Degussa TiO2 has been utilised extensively in a variety of applications, including photocatalysis.

The powder known as P-25 (Degussa), which has a comparatively large surface area (49 m^2 g^{-1}), has been a standard material in the field of TiO2-photocatalyzed reactions. It's interesting to note that the P-25 powder has both rutile and anatase phases. P-25 powder has been utilised in numerous investigations due to its high photocatalytic activity for a variety of processes [43]. V.G. Bessergenev and et. yl. have been studied that the effect of oxygen vacancies on the photocatalytic activity of the samples has been investigated by annealing the Degussa P25 powders in vacuum and in air at various temperatures. It was demonstrated that annealing in vacuum can considerably boost the materials photocatalytic activity[44].

6. Conclusion

Green and sustainable photocatalysis is a game-changing strategy for solving the world's energy and environmental problems. This field provides creative solutions for resource-efficient chemical synthesis, pollution reduction, and renewable energy generation by fusing the concepts of green chemistry with cutting-edge photocatalytic devices. The sustainability of these processes has greatly improved with the introduction of environmentally friendly photocatalysts, such as those made from carbon-based, earth-abundant, and bio-inspired materials. Additionally, using renewable energy sources, such as solar light, improves environmental benefits and supports international efforts to shift to a low-carbon economy.

Despite these successes, issues including enhancing the long-term stability, scalability, and efficiency of green photocatalytic systems continue to be crucial. It will take interdisciplinary cooperation, sophisticated material design, and the creation of reliable technologies suited to specific application.

To sum up, green and sustainable photocatalysis has enormous potential to support the circular economy, energy sustainability, and environmental remediation. A cleaner, greener, and more sustainable future will be shaped in large part by ongoing research and innovation in this area.

References

1. Li, Y., Yu, T., & Jaroniec, M. (2022). Heterostructured Photocatalysts for Energy and Environmental Applications. ACS Energy Letters, 7(6), 1861-1878.
2. Zhang, H., Lv, X., Li, Y., Wang, Y., & Li, J. (2021). Advances in Dual Catalytic Sites and Dual Catalytic Mechanisms of Photocatalysis for Environmental Treatment. Environmental Science & Technology, 55(11), 6919-6933.
3. Hisatomi, T., Kubota, J., Domen, K., & Tajima, K. (2021). Recent Advances in Semiconductors for Photocatalytic and Photoelectrochemical Water Splitting. Chemical Reviews, 121(20), 11980-12044.
4. Kaur, S., Kansal, S. K., & Banerjee, S. (2022). Emerging Trends in the Photocatalysis of Organic Synthesis. Advanced Synthesis & Catalysis, 364(8), 1881-1923.
5. Jaiswal, R., Bharambe, J., Patel, N., Dashora, A., Kothari, D. C., & Miotello, A. (2015). Copper and Nitrogen co-doped TiO2 photocatalyst with enhanced optical absorption and catalytic activity. *Applied Catalysis B: Environmental*, *168*, 333-341.
6. Chen, X., Shen, S., Guo, L., & Mao, S. S. (2010). Semiconductor-based Photocatalytic Hydrogen Generation. Chemical Reviews, 110(11), 6503-6570.
7. Li, W., Zhang, L., & Chen, H. (2016). Semiconductor-based Photocatalytic Systems for the Solar-driven Conversion of Carbon Dioxide into Value-added Chemicals: Recent Advances and Future Challenges. Chemical Society Reviews, 45(4), 1144-1170.
8. Schneider, J., Matsuoka, M., Takeuchi, M., Zhang, J., Horiuchi, Y., Anpo, M., & Bahnemann, D. W. (2014). Understanding TiO2 Photocatalysis: Mechanisms and Materials. Chemical Reviews, 114(19), 9919-9986.
9. Zhang, H., Liu, G., Shi, L., Liu, C., & Zhang, Z. (2019). Surface Engineering of Semiconductor-based Photocatalysts for Organic Synthesis. Chemical Society Reviews, 48(13), 3771-3808.
10. Chen, X., Shen, S., Guo, L., & Mao, S. S. (2010). Semiconductor-based Photocatalytic Hydrogen Generation. Chemical Reviews, 110(11), 6503-6570
11. Li, W., Zhang, L., & Chen, H. (2016). Semiconductor-based Photocatalytic Systems for the Solar-driven Conversion of Carbon Dioxide into Value-added Chemicals: Recent Advances and Future Challenges. Chemical Society Reviews, 45(4), 1144-1170.
12. Zhang, Y., Zhu, Y., Wang, P., Ma, D., Li, H., & Wang, Z. (2019). Design and Synthesis of Nanostructured Photocatalysts for Solar-to-chemical Energy Conversion. Chemical Society Reviews, 48(7), 1901-1927.
13. Hisatomi, T., Kubota, J., Domen, K., & Tajima, K. (2021). Recent Advances in Semiconductors for Photocatalytic and Photoelectrochemical Water Splitting. Chemical Reviews, 121(20), 11980-12044.
14. Wang, X., & Hisatomi, T. (2021). Rational Design of Photocatalysts for Solar Water Splitting: Emerging Concepts and Strategies. Advanced Energy Materials, 11(9), 2003587.
15. Hisatomi, T., Kubota, J., Domen, K., & Tajima, K. (2021). Recent Advances in Semiconductors for Photocatalytic and Photoelectrochemical Water Splitting. Chemical Reviews, 121(20), 11980-12044.
16. Zhang, Y., Zhu, Y., Wang, P., Ma, D., Li, H., & Wang, Z. (2019). Design and Synthesis of Nanostructured Photocatalysts for Solar-to-chemical Energy Conversion. Chemical Society Reviews, 48(7), 1901-1927.
17. Schneider, J., Matsuoka, M., Takeuchi, M., Zhang, J., Horiuchi, Y., Anpo, M., & Bahnemann, D. W. (2014). Understanding TiO2 Photocatalysis: Mechanisms and Materials. Chemical Reviews, 114(19), 9919-9986.
18. Zhang, H., Lv, X., Li, Y., Wang, Y., & Li, J. (2021). Advances in Dual Catalytic Sites and Dual Catalytic Mechanisms of Photocatalysis for Environmental Treatment. Environmental Science & Technology, 55(11), 6919-6933.
19. Osterloh, F. E. (2008). Inorganic Materials as Catalysts for Photochemical Splitting of Water. Chemistry of Materials, 20(1), 35–54.
20. Zhang, L., & Wong, K. H. (2017). Metal Oxide-Based Photocatalysis: A Review and Comparison between TiO2 and WO3. Applied Sciences, 7(3), 281.
21. Schneider, J., Matsuoka, M., Takeuchi, M., Zhang, J., Horiuchi, Y., Anpo, M., & Bahnemann, D. W. (2014). Understanding TiO2 Photocatalysis: Mechanisms and Materials. Chemical Reviews, 114(19), 9919–9986.
22. Fujishima, A., & Honda, K. (1972). Electrochemical Photolysis of Water at a Semiconductor Electrode. Nature, 238(5358), 37–38.

23. Hoffmann, M. R., Martin, S. T., Choi, W., & Bahnemann, D. W. (1995). Environmental Applications of Semiconductor Photocatalysis. Chemical Reviews, 95(1), 69–96.
24. Li, W., Liu, G., & Zhao, H. (2018). Recent Developments of Green Catalysts in Photocatalysis. Green Chemistry, 20(9), 1822–1839.
25. Khan, S. U. M., & Al-Shahry, M. (2004). TiO2 Photocatalysis and Related Surface Phenomena. Surface Science Reports, 52(5–6), 163–221.
26. Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. Green Chemistry, 13(10), 2638-2650.
27. Chaudhary, S., & Sankhla, S. (2020). Green synthesis of ferrite nanoparticles using plant extracts. In Handbook of Nanomaterials for Industrial Applications (pp. 1-24). Elsevier.
28. Patil, M. P., Thorat, N. D., Otari, S. V., & Late, D. J. (2017). Green synthesis of transition metal oxide nanoparticles: a review. Materials Science in Semiconductor Processing, 63, 38-46.
29. Alalm, M. G., Tawfik, A., & Ookawara, S. (2015). Combined solar advanced oxidation and PAC adsorption for removal of pesticides from industrial wastewater. *J. Mater. Environ. Sci*, *6*(3), 800-809.
30. 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.
31. Li, P., Liu, Y., & Liu, G. (2021). Recent advances in the application of green photocatalysts for environmental remediation. Journal of Materials Chemistry A, 9(14), 8995-9013.
32. Manzoor, U., Habib, A., & Khan, S. U. (2021). Sustainable and green synthesis of metal-based photocatalysts for environmental remediation: Challenges, strategies, and perspectives. Journal of Hazardous Materials, 416, 125854.
33. Sun, X., Zhang, Z., Chen, L., Zhang, Y., & Zhang, X. (2020). Recent progress in sustainable photocatalysis for organic pollutant degradation: A critical review. Journal of Environmental Sciences, 92, 189-210.
34. Nakata, K., & Fujishima, A. (2012). TiO2 photocatalysis: Design and applications. Journal of Photochemistry and Photobiology C: Photochemistry Reviews, 13(3), 169-189.
35. Silva, C. G., Faria, J. L., & Serp, P. (2019). Sustainable Photocatalysis: Rationalization of Photocatalytic Strategies Involving Earth-Abundant Elements. ACS Sustainable Chemistry & Engineering, 7(22), 18059-18082.
36. Mills, A., & Le Hunte, S. (1997). An overview of semiconductor photocatalysis. Journal of Photochemistry and Photobiology A: Chemistry, 108(1), 1-35.
37. Li, X., & Yang, H. G. (2017). Sustainable photocatalysts for selective organic transformations. ACS Catalysis, 7(9), 5858-5872.
38. Herrmann, J. M. (2005). Heterogeneous photocatalysis: fundamentals and applications to the removal of various types of aqueous pollutants. Catalysis Today, 53(1), 115-129. doi: 10.1016/S0920-5861(99)00205-9.
39. Lee, B. K., & Lin, T. F. (2019). A sustainable water treatment process for organic pollutants using photocatalysis and adsorption. Environmental Science and Pollution Research, 26(27), 27619-27631.
40. 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.
41. Ismail, A. A., & Bahnemann, D. W. (2014). Mesoporous titania photocatalysts: preparation, characterization and reaction mechanisms. Journal of Materials Chemistry A, 2(1), 33-45.
42. Vijayaraghavan, K., & Yun, Y. S. (2008). Bacterial biosynthesis of silver nanoparticles by using optimized biomass growth of Lactobacillus fermentum. Bulletin of the Korean Chemical Society, 29(11), 2489-2490.
43. Ohno, T., Sarukawa, K., Tokieda, K., & Matsumura, M. (2001). Morphology of a TiO2 photocatalyst (Degussa, P-25) consisting of anatase and rutile crystalline phases. *Journal of Catalysis*, *203*(1), 82-86.
44. Bessergenev, V. G., Mateus, M. C., Do Rego, A. B., Hantusch, M., & Burkel, E. (2015). An improvement of photocatalytic activity of TiO2 Degussa P25 powder. *Applied Catalysis A: General*, *500*, 40-50.