

Photocatalytic and Electrocatalytic Materials for Environmental Remediation: A Review of Recent Advances

Priyanka Gupta¹, Gaurav Tamrakar² and Dayanand Sharma³

¹Department of Chemistry, Kalinga University, Naya Raipur, C.G, INDIA.

²Department of Mechanical Engineering, Kalinga University, Naya Raipur, C.G, INDIA.

³Department of Civil engineering, Sharda University, Greater Noida, INDIA.



www.jrasb.com || June 2026

Date of Submission: 01-06-2026

Date of Publication: 12-06-2026

ABSTRACT

The growing contamination of the environment's water and air supply has led researchers to find effective yet environmentally friendly remediation strategies. Photo catalysis and electro catalysis rise as effective technologies because they efficiently eliminate various pollutants at mild environmental conditions. Nanostructured materials possessing high surface area together with stability and reactivity enable the activation of catalytic breakdown processes to convert dangerous substances into safer or non-hazardous final products. The research acknowledges modern advances in the production along with implementation of photocatalytic and electro catalytic materials for environmental cleanup efforts. The research explores material-based approaches alongside operational methods and performance evaluation of systems which eliminate organic dyes and heavy metals and persistent pollutants. The paper explains both the weaknesses of existing systems along with specific paths to develop durable and expandable catalytic systems for sustainable applications.

Keywords- Photo catalysis, Electro catalysis, Nanomaterials, Dye Degradation, Wastewater Treatment, Green Technology.

I. INTRODUCTION

The fast industrialization together with urban expansion and growing population has transformed pollution of natural water bodies and air into a world-wide important issue. Multiple persistent organic pollutants along with heavy metals and dyes and emerging resistant contaminants continue their yearly release into the environment because of industrial waste and agricultural runoff and pharmaceutical residuals (Mandal et al., 2024). The environmental pollutants endanger marine ecosystems and create substantial health perils that hurt humans and animals.

The traditional coagulation filtration biological treatment purification techniques are unable to successfully process stable substances or those that do not degrade. Research now focuses on creating modern sustainable pollution reduction technologies which convert dangerous substances into safer compounds (Jain et al., 2023, Rath et al., 2024).

Photocatalysis and electrocatalysis have proven themselves as efficient clean technology methods for environmental pollution management. The activation of light exposes semiconducting materials to create reactive oxygen species which enable the decomposition of complex organic and inorganic pollutants (Liu et al., 2024). Electrocatalysis utilizes external electrical power to activate redox reactions that occur on catalytic surfaces which prompts pollutant destruction or modification according to Idris et al. (2023). The applications for both techniques demonstrate promising results suitable for wastewater purification along with air cleaning and energy-production purposes. Environmental pollutant degradation receives illustration through which shows fundamental operative mechanisms of both processes.

The efficiency of catalytic processes has experienced significant improvement because of nanostructured materials which include merges of metal oxides and carbon-based nanomaterials and 2D-layered structures. Their extensive surface area and flexible electronic features coupled with better charges transfer efficiency result in rapid and thorough contamination removal (Wang et al., 2025; Ye et al., 2024). A new line of investigation by researchers has generated hybrid catalysts and

metal-free alternatives together with cost-effective and sustainable materials for replacement of standard materials (Suppaso et al., 2023; Gao et al., 2023). Technical improvements in material development have produced stronger components that are easier to recycle and more discriminate in catalyst operations. This paper offers an extensive examination of current photocatalytic along with electrocatalytic materials used for environmental cleanup applications. This section reviews both the base principles while investigating multiple materials as well as essential performance criteria and effective rates. The paper presents both current difficulties and foreseeable opportunities for building large-scale environmentally friendly catalytic systems.

II. PHOTOCATALYTIC MATERIALS FOR ENVIRONMENTAL REMEDIATION

The practice of photocatalysis proves to be both a widely examined and a promising approach used to clean up the environment through the removal of organic pollutants in air and wastewater. Semiconducting materials which receive exposure to both UV and visible light use this technique to produce electron-hole pairs. Reactive oxygen species including hydroxyl radicals and superoxide ions form from charge carriers and actively transform pollutants into harmless end products including carbon dioxide and water as per Shee & Kim (2024) and Liu et al. (2024).

Multiple types of materials including TiO₂ metal oxides and biochar composites and advanced metal–organic frameworks have been created for various performance needs in changing environmental parameters. Photocatalytic materials have distinguishable bandgap energies alongside different characteristics for charge separation and resistance to degradation. The comparison table in Table 1 explores these materials together with their distinct capabilities and constraints according to Wang et al. (2025) and Ye et al. (2024).

2.1 Metal Oxide Photocatalysts

The photocatalytic material titanium dioxide (TiO₂) stands out as a preferred choice because it demonstrates exceptional chemical stability and non-toxicity properties together with strong oxidative power. The connected wide band gap value of approximately 3.2 eV defines the UV region as the main operating area for photocatalysis. The development of visible light response in TiO₂ occurs through dopant incorporation of metals (Fe, Cu) together with non-metal additives (N, C) according to Wang et al. (2025) and Ye et al. (2024). The modifications of TiO₂ alter the absorption spectrum to include visible light which enhances the photoreactivity under solar illumination. Photocatalytic performance improvement has occurred through heterojunction formation and surface engineering techniques which also help decrease electron-hole recombination (Mohd Zaki et al., 2023).

Zinc oxide (ZnO) stands out as a metal oxide material because its band gap matches well with its excellent photocatalytic capabilities. Ultimate exposure to UV light reduces the stability and also causes photocorrosion of ZnO. Researchers address these challenges through surface modification approaches and core-shell structure implementations as well as heterojunction formation with other semiconductors according to Liu et al. (2024) and Rathi et al. (2024).

2.2 Carbon-Based and Composite Photocatalysts

The photocatalytic systems incorporate carbonaceous materials consisting of graphene oxide (GO) reduced graphene oxide (rGO) and carbon nanotubes (CNTs) which have proven effective in recent years. Their unique conductive electrical properties along with superior surface area and their ability to block electron-hole recombination make them outstanding support structures as well as co-catalysers. Due to their properties these materials allow better mobility of charge carriers which leads to enhanced pollutant degradation rates through photocatalysis (Gao et al., 2023; Ramalingam et al., 2022).

Composite photocatalysts such as TiO₂–GO and ZnO–rGO leverage the synergistic interactions between metal oxides and carbon materials. The metal oxide section of the compound uses light energy to produce electron-hole pairs combined with carbon material functions for separating and transferring charges. The combined features between components produce superior degradation outcomes for dyes and pesticides with pharmaceutical pollutants using visible illumination and solar light exposure (Liu et al., 2024; Kocijan et al., 2021). The composites present improved durability combined with multiple uses which makes them applicable to practical wastewater treatment systems (Wang et al., 2025; Jain et al., 2023).

2.3 Metal-Free Photocatalysts

Growth in the use of metal-free photocatalysts for depollution purposes occurred because these compounds provide both economical benefits and environmental safety. The wide investigation of graphitic carbon nitride (g-C₃N₄) photocatalysts occurs because of its suitable band gap (~2.7 eV) together with visible light response capabilities and chemical stability. G-C₃N₄ exhibits narrow light absorption efficiency due to its limited surface area alongside rapid electron-hole recombination.

Different strategies involving non-metal doping alongside exfoliation and heterojunction creation have been developed to address these restrictions. Research demonstrates that material treatment with sulfur and phosphorus elements enhances both photocatalytic reaction charge separation while improving light absorption capabilities (Mallick et al., 2024). The photocatalytic efficiency improves when g-C₃N₄ receives conductive nanostructure treatments such as carbon-based materials or nanodiamonds because these additions enhance charge transport (Gao et al., 2023).

Table 1: Comparison of Photocatalytic Materials for Environmental Applications

Material Type	Examples	Advantages	Limitations	Reference
Metal Oxide	TiO ₂ , ZnO	Stable, Widely studied, Strong oxidative power	UV-active only, Fast charge recombination	Wang et al., 2025
Carbon-Based Composite	TiO ₂ -GO, ZnO-CNT	High conductivity, Enhanced charge separation	Synthesis complexity, Costly	Ramalingam et al., 2022; Kocijan et al., 2021
Metal- Free Photocatalysts	g-C ₃ N ₄ , Doped Polymer	Visible light active, Environmentally friendly	Low surface area, Fast recombination	Mallick et al., 2024; Ullah et al. 2024

2.4. Factors Affecting Photocatalytic Efficiency

The operational efficiency of photocatalysis depends upon different interconnected components. The band gap energy stands as a critical element because it controls how well a material absorbs light. A reduced band gap enables better absorption of visible light spectra to better utilize solar energy potential (Ye et al., 2024). Quick electron–hole pair recombination processes can reduce reactive oxygen species (ROS) generation which decreases the degradation rates. The combination of heterojunctions with doping methods and cocatalyst introduction serves to improve photocatalytic properties by increasing charge separation rates while extending light absorption (Liu et al., 2024; Shee & Kim, 2024).

The specific surface area and porous nature of the photocatalyst both determine the number of available active sites which directly affects the adsorptive properties toward pollutants. Properties of photocatalysts improve through nanostructuring and porous framework creation for enhancing their catalytic activity according to Kocijan et al. (2021). Photocatalysis driven by visible light receives current attention because scientists have emphasized better charge transport and photocatalytic interface optimization. The photocatalytic behavior of carbon-doped g-C₃N₄ synthesized from L-aspartic acid reached higher levels of charge separation and transportation because Ullah et al. (2024) had established this.

III. ELECTROCATALYTIC MATERIALS FOR ENVIRONMENTAL REMEDIATION

Electrocatalysis has emerged as a sustainable and efficient method for environmental remediation, especially for the degradation of organic pollutants in wastewater. It involves applying an electric potential to activate redox reactions on electrode surfaces, enabling the transformation of hazardous substances into less harmful compounds (Idris et al., 2023). The effectiveness of electrocatalytic systems depends on key properties of the electrode materials, including high conductivity, catalytic activity, chemical stability, and surface area. Materials such as metal oxides, carbon-based nanostructures, and hybrid composites have shown strong potential in pollutant degradation under ambient conditions (Ye et al., 2024). Recent research also highlights the use of metal-free materials like nanodiamonds, which offer excellent durability and tunable surface chemistry, making them attractive for long-term and eco-friendly applications in electrocatalysis (Gao et al., 2023). A comparison of different electrocatalytic materials and their performance is summarized in Table 2.

3.1 Metal-Based Electrocatalysts

Noble metals like platinum (Pt), ruthenium (Ru), and palladium (Pd) exhibit superior electrocatalytic activity due to their excellent conductivity and low activation barriers. Their market adoption stays limited due to high pricing and scarce availability. The field of alternative transition metals has expanded to include nickel (Ni) cobalt (Co) and iron (Fe) since these materials show promising low-cost alternatives with notable catalytic strength according to Liu et al. (2023).

The breakdown of complex organic compounds using electrochemical advanced oxidation (EAOPs) requires metal oxides like RuO₂, IrO₂ and MnO₂ which are stable and exhibit high redox activity according to Mallick et al. (2024). NiO/ZrO₂/Mn₃O₄ nanocomposites offer substantial potential for organic pollutant breakdown that transforms them into powerful tools for thriving environmental cleanup strategies (Zahra et al., 2023).

3.2 Carbon-Based Electrocatalysts

The electrochemical stability and excellent electrical conductivity and large surface area make carbon-based materials including graphene as well as carbon nanotubes (CNTs) activated carbon and carbon black stand out as preferred choices. The electrocatalytic properties of these materials become enhanced through heteroatom doping of nitrogen or sulfur and phosphorus alongside metal nanoparticle compositing according to Gao et al, (2023) and Ramalingam et al (2022).

The combination of nitrogen doping on graphene creates an effective catalyst system that performs highly effective electron transfer during dyes and pharmaceutical pollutant degradation processes. Stronger sustainable electrocatalysts can be developed with the introduction of metallic-free carbon nanomaterials such as nanodiamond and graphitic carbon nitride (g-C₃N₄) because their electronic structures are adjustable as well as their environmentally friendly nature (Gao et al., 2023; Mallick et al., 2024). The financial benefits of carbon-based materials together with their ability to reuse and safeguard the environment make them a strong candidate for industrial water purification systems.

3.3 Composite and Hybrid Electrocatalysts

The combination of composite and hybrid electrocatalysts attracts researchers because it allows for component integration to produce electrocatalysts which improve their operational efficiency alongside resistance properties and charge transport capabilities. The combination of carbon-based atomic structures including graphene along with carbon nanotubes (CNTs) together with metal oxides and bimetallic particles improves overall performance according to Raveendran et al. (2023) and Gao et al. (2023).

The degradation of dyes and heavy metal removal from wastewater shows high activity through Co₃O₄–CNT, Fe–graphene and Ni–TiO₂ composite materials. Their combined structures enable superior electron transport performance along with improved surface reactivity because the processes happen at reduced energy expenses (Liu et al., 2024). Research done in India throughout the previous year has stressed the significance of creating these hybrid systems. The research by Raveendran et al. (2023) showed hybrid electrodes perform better at water splitting and Ramalingam et al. (2022) studied graphene-based composite effectiveness toward pollutant destruction. The improvement in research of hybrid materials presents a promising route toward future electrocatalytic wastewater treatment methods (Ye et al., 2024).

Table 2: Electrocatalytic Materials and Their Key Characteristics

Material Type	Examples	Advantages	Limitations	Reference
Nobel Metals	Pt, Pd, Ru	High conductivity, Strong redoxactivity, Efficient pollutants removal	Expensive, Scarce	Gao et al., 2023
Transition Metals	Fe, Co, Ni	Cost effective, Good catalytic performance	Less active than Nobel metals in some cases	Zahra et al., 2023
Metal Oxides	RuO ₂ , IrO ₂ , MnO ₂	Stable, efficient in oxidation reaction	May require high voltage	Mohd Zaki et al., 2023
Carbon-Based Material	Graphene, CNTs, Activated Carbon	High surface area, Conductive, Modifiable with doping	Sometimes requires combination with metals	Ramalingam et al., 2022; Kocijan et al., 2021
Hybrid Composite	Co ₃ O ₄ -CNT, Fe-Graphene, Ni-TiO ₂	Synergistic effects, Enhanced charge transfer, Scalable application	Synthesis complexity	Ullah et al., 2024; Raveendran et al., 2023

IV. MECHANISMS OF PHOTOCATALYTIC AND ELECTROCATALYTIC REMEDIATION

Transport of pollutants through photocatalytic and electrocatalytic reaction pathways depends on the fundamental operating principles that control degradation processes. The detoxification processes through redox reactions function dissimilarly in these two techniques due to their different sources of energy as well as catalyst activation methods. Researcher understanding of these mechanisms lets them create materials that possess better durability along with improved catalytic efficiency.

4.1 Photocatalytic Mechanism

The process of photocatalysis requires semiconductor materials which activate into photoactive substances after receiving exposure to visible or UV lighting. The semiconductor reacts to photons with suitable energy levels by promoting electrons from the valence band to the conduction band while creating positively charged holes in the valence band. When light strikes the semiconductor the creation of electron-hole pairs begins a sequence of redox reactions (Wang et al., 2023). A complete description of photocatalysis consists of these three fundamental steps:

1. Light Absorption: The semiconductor absorbs photons with energy equal to or greater than its bandgap. Electron promotion happens through the VB to the CB due to this process (Wang et al., 2023).
2. Photon absorption through the semiconductor creates electron-hole pairs whose electrons occupy the CB with high reactivity while holes remain positively charged at the VB (Liu et al., 2024).
3. Catalyst surface swells with electrons and holes after their generation. The photocatalytic efficiency depends heavily on the efficient separation of charges because this prevents recombination events (Zahra et al., 2023).
4. Surface redox process occurs when catalysts enable electrons to transform O₂ into •O₂⁻ while holes turn H₂O and OH⁻ into •OH radicals at the surface. Super reactive radicals on the surface serve to break down organic pollutants through their destructive power (Zahra et al., 2023; Gao et al., 2023).

5. The reactive oxygen species (ROS) consisting primarily of hydroxyl ($\bullet\text{OH}$) and superoxide ($\bullet\text{O}_2^-$) act to degrade pollutants through their attack of dyes and pharmaceuticals and pesticides before reducing them into non-hazardous final products CO_2 and H_2O (Gao et al., 2023).

Effective pollutant degradation during photocatalysis depends on light intensity together with bandgap energy and surface area and charge recombination rate because all these factors directly impact process efficiency (Liu et al., 2024). Representation of electrocatalytic remediation mechanisms according to Figure 3.

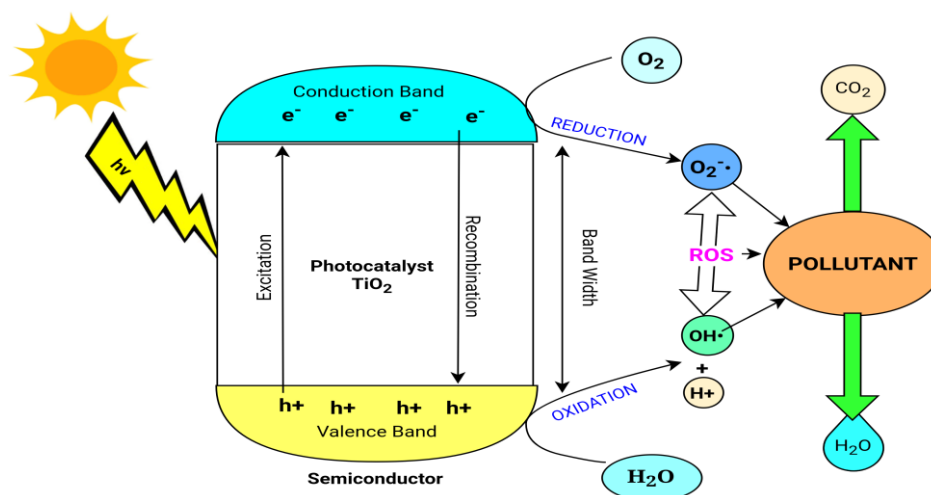


Figure 3. Photocatalytic Mechanism

4.2 Electrocatalytic Mechanism

Electrocatalytic remediation functions through external electric fields that apply between electrodes which are placed in electrolyte solutions to perform redox reactions as per Zhang et al.(2022). The two main degradation mechanisms operate at the anode during the treatment process.

1. The anode surface directly receives pollutants through Direct Oxidation which results in electron loss from the pollutants.
2. The indirect pathway of oxidation produces hydroxyl radicals from water oxidation which then attack contaminants based on research by Zahra et al. (2023).
3. The cathode mainly conducts reduction processes. These may include:
4. The reduction of toxic metal ions (e.g., Cr^{6+} to Cr^{3+}),
5. The reduction process of oxygen dissolution creates hydrogen peroxide (H_2O_2).
6. The production of additional reactive species that further aid in the degradation process (Gao et al., 2023; Idris et al., 2023).
7. Electrocatalysis stands out because researchers can manipulate reaction performance with various adjustable factors including voltage strength and density along with electrode types and solution acidity levels. The system operates under darkness which allows it to perform when photocatalytic methods become limited (Liu et al., 2024).

The stepwise process includes:

1. Upon activating the electrode surfaces with an electric current flow electric stimulation phase starts.
2. Reactive Species Generation: Formation of $\bullet\text{OH}$ and H_2O_2 via direct oxidation or electron transfer.
3. Pollutant Interaction: Reactive species attack contaminants through oxidation or reduction.
4. The system finishes by decomposing pollutants into harmless end-products consisting of CO_2 alongside H_2O .

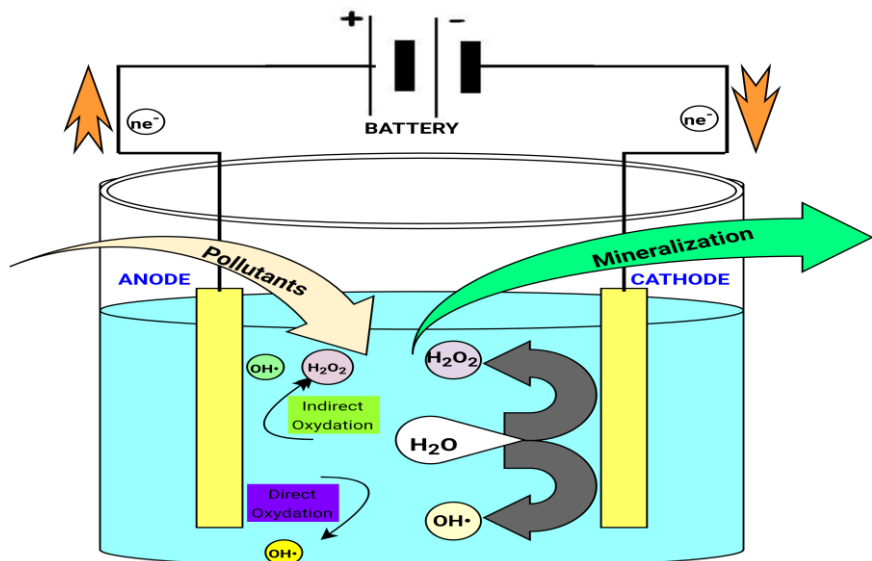


Figure 4. Electrochemical Mechanism

Semiconductor-based photocatalysis and electrocatalysis operate as paramount advanced oxidation technologies specifically designed for wastewater treatment of long-lasting organic pollutants. The processes create reactive oxidants for contaminant mineralization although they use different operational methods.

The photocatalytic process generates electron-hole pairs from semiconducting materials including TiO_2 , ZnO and $\text{g-C}_3\text{N}_4$ when these substances interact with appropriate light (UV or visible). The generated charge carriers make possible the formation of reactive oxygen species (ROS) including hydroxyl radicals ($\bullet\text{OH}$) and superoxide anions ($\text{O}_2^{\bullet-}$) that destroy various organic contaminants (Chen et al., 2021; Zhao et al., 2023). Efforts to enhance visible light absorption and recombination rates have been achieved through doping techniques as well as the development of hybrid photocatalysts (Li et al., 2023; Bhatti & Parikh, 2022).

The electrocatalytic process requires electrodes and electrolytes subjected to external voltage applications. An applied external voltage triggers redox reactions directly on electrode surfaces which produce radical species including $\bullet\text{OH}$ and H_2O_2 that perform oxidation or reduction of pollutants. The catalytic process of electrocatalysis operates successfully under dark conditions with precise control enabled through adjustments of current and voltage and electrode composition (Zhao et al., 2023).

Photocatalysis provides green potential through photovoltaic assistance yet electrocatalysis leads to controlled pollutant breakdown along with operation in dark conditions. The decision to use photocatalysis or electrocatalysis depends on the nature of pollutant substances and illumination sources as well as operational system needs.

Figure 5 shows that comparative degradation efficiency of Photocatalytic and Electrocatalytic for different pollutants.

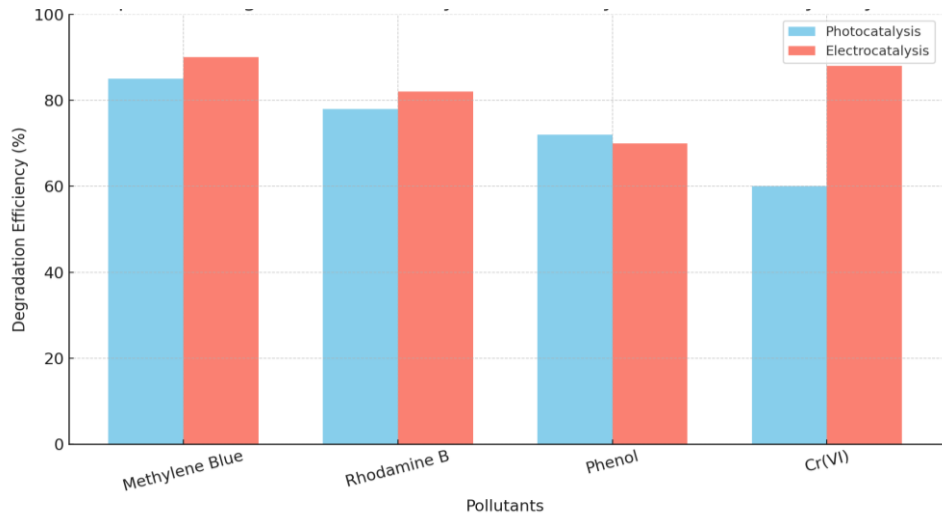


Figure 5. compares the degradation efficiency of photocatalytic and electrocatalytic systems for different pollutants.

V. APPLICATIONS IN ENVIRONMENTAL REMEDIATION

Highly efficient environmental pollution mitigation tools have developed as photocatalytic and electrocatalytic materials for using water and air purification applications. The catalytic systems show effective degradation abilities toward a wide range of persistent pollutants involving synthetic dyes together with pharmaceutical residues and heavy metal ions throughout traditional treatment methods.

The semiconductor-based photocatalysts TiO_2 and BiVO_4 and $\text{g-C}_3\text{N}_4$ serve as wastewater purification chemicals that degrade dyes such as methylene blue and rhodamine B under UV or visible light conditioning. The materials exploit solar power together with air oxygen to maintain an operation which combines sustainability with economic viability. Doped TiO_2 photocatalysts together with their hybrid advanced oxidation processes receive major interest because they optimize organic pollutant removal efficiency (Bhatti & Parikh, 2022). The photocatalytic activities of modified TiO_2 materials become stronger through doping procedures and creating composites according to Li et al. (2023).

The electrochemical performance of toxic pollutant oxidation reaches exceptional levels when boron-doped diamond (BDD) electrodes alongside Ti/IrO_2 electrodes are used as electrocatalytic materials. The operational control abilities of these materials excel because adjustment of voltage and current density parameters enables optimal performance in low-light and dark conditions. The process of electrocatalysis enables faster degradation of persistent conductive media pollutants that prove difficult for alternative techniques (Raveendran et al., 2023).

The process of air purification employs photocatalysts incorporated into different materials like coatings and surfaces and filters which break down contaminants like nitrogen oxides (NO_x) and volatile organic compounds (VOCs) under light exposure according to Zahra et al. (2023). The application of electrocatalytic methods continues to increase within advanced air filtration technology because they deliver high industrial efficiency and operational control capabilities.

The combination of photocatalysis and electrocatalysis into photoelectrocatalytic systems turns out to be increasingly popular. The combination of photocatalysis with electrocatalysis in hybrid systems allows synergistic operation for enhanced charge separation and degradation efficiency with applications in varied environmental conditions according to Gao et al. (2023).

The primary application of photocatalytic systems exists in water treatment while hybrid photoelectrocatalytic systems have emerged as an expanding segment for integrated remediation technologies.

VI. CHALLENGES AND FUTURE PROSPECTS

Multiple barriers stand between photocatalytic and electrocatalytic materials and their practical use on a broad scale for environmental clean-up operations. Many photocatalysts function inefficiently under visible light due to poor quantum efficiency rates. The efficiency of TiO_2 material as a photocatalyst deteriorates significantly because it responds only to ultraviolet rays. To enhance visible light-induced charge separation and redox activity, researchers employ three techniques of doping, heterojunctions and nanostructuring (Li et al., 2023; Bhatti & Parikh, 2022; Mallick et al., 2024; Xu et al., 2023).

The essential problem which must be solved is the instability of catalysts and their limited reuse capability. The lifespan of photocatalysts decreases through photochemical corrosion or agglomeration in multiple cycles. The integration of catalysts into membranes or support matrices serves as a solution to improve durability and recovery while immobilization becomes important (Kocijan et al., 2021; Ramalingam et al., 2022). Photocatalytic systems experience rapid electron-hole recombination as an important challenge that affects their performance similarly to electrocatalytic systems which encounter electrode fouling that reduces operational lifespan. Wider applications in photoelectrocatalysis involve hybrid nanostructure constructs and carbon material backings and anti-fouling surface protection designs (Gao et al., 2023; Mohd Zaki et al., 2023).

New hybrid photoelectrocatalytic systems unite photocatalysis and electrocatalysis benefits by improving charge carrier behaviors to increase the degradation efficiency. Complex and persistent pollutants can be effectively treated through these systems that prove beneficial under genuine environmental settings according to Ullah et al. (2024) and Zahra et al. (2023). Metal-nonmetal composites with graphene-based electrodes lead the research in useful water splitting and pollutant degradation through high-efficiency pathways (Raveendran et al., 2023).

The future research sector combines artificial intelligence with machine learning for improving catalyst design and performance along with process modeling applications. Research lab achievements need to tackle cost factors together with energy usage requirements and system integration obstacles to become applicable to genuine treatment methods. For the development of effective solutions to remediate the environment both interdisciplinary collaboration and scalable production methods should continue through research.

VII. CONCLUSION

Industrial and urban operations have produced environment pollution which demands immediate effective solutions for remediation. The combination of photocatalytic and electrocatalytic materials represents a powerful solution due to their

operations efficiency together with low costs and environment-friendly characteristics. TiO_2 and $\text{g-C}_3\text{N}_4$ functions as photocatalysts that break down organic pollutants under light illumination and BDD electrodes act as electrocatalysts which remove toxic chemicals by performing redox reactions. The performance of water remediation processes gets additional gains from systems which integrate vital elements from both photocatalytic and electrocatalytic technologies. The key barriers to overcome include weak responsiveness to visible light together with catalyst breakdown and elevated material expenses. Scientists need to prioritize the research development of durable materials which will operate both efficiently and at a large scale. These technologies present excellent possibilities for sustainable air and water purification through advanced design methods and applications of renewable energy systems.

REFERENCES

- [1] Mandal, A., Kumar, P. S., Poorva, C. S., Raju, L. S., Balasubramani, S. R., & Rangasamy, G. (2024). Research progress of persistent organic pollutants in water: Classification, sources, potential risks, and treatment approaches. *Water Practice & Technology*, 19(3), 937–959. <https://doi.org/10.2166/wpt.2024.031>
- [2] Rath, B. S., Kumar, P. S., Kishore, V., Sridhar, S., & Rangasamy, G. (2024). Conventional technologies and recent developments in the nanotechnological approach for the remediation of persistent organic pollutants. *Water Practice & Technology*, 19(5), 1849–1877. <https://doi.org/10.2166/wpt.2024.070>
- [3] Jain, T., Kumar, P. S., Parmar, A., Arora, V., Abdul-Zahra, D. S., & Nagpal, A. (2023). Sustainable materials for water treatment: A comprehensive review. *E3S Web of Conferences*, 430, 01103. <https://doi.org/10.1051/e3sconf/202343001103>
- [4] Liu, Y., Dai, X., Li, J., Cheng, S., Zhang, J., & Ma, Y. (2024). Recent progress in TiO_2 -biochar-based photocatalysts for water contaminants treatment: Strategies to improve photocatalytic performance. *RSC Advances*, 14(1), 478–491. <https://doi.org/10.1039/D3RA06910A>
- [5] Idris, A. O., Orimolade, B., & Dennany, L. (2023). A review on monitoring of organic pollutants in wastewater using electrochemical approach. *Electrocatalysis*, 14(5), 659–687. <https://doi.org/10.1007/s12678-023-00834-x>
- [6] Gao, X.-W., Zhao, Z.-W., He, Y., Jiao, K.-R., Lou, S.-Y., Han, X.-Y., Zhang, S.-S., & Zhu, J.-Q. (2023). Nanodiamond: A promising metal-free nanoscale material in photocatalysis and electrocatalysis. *Rare Metals*. <https://doi.org/10.1007/s12598-023-02513-8>
- [7] Suppaso, C., Khamdang, C., Wannasen, L., Kanazawa, T., Miyoshi, A., Nishioka, S., Chotiwan, N., & Khaorapapong, N. (2023). Visible-light driven H_2 evolution over a precious metal-free hybrid photocatalyst constructed from CuO and NiFe layered double hydroxide. *Catalysis Science & Technology*, 13(3), 675–683. <https://doi.org/10.1039/D2CY00958G>
- [8] Wang, L., Liu, Y., & Liu, C. (2025). Green catalysis in nanomaterials—Photocatalysis and electrocatalysis. *Nanomaterials*, 15(1), Article 5. <https://doi.org/10.3390/nano15010005>
- [9] Ye, J.-Q., Xu, S.-Y., Liang, Q., Dai, Y.-Z., & He, M.-Y. (2024). Metal-organic frameworks-derived nanocarbon materials and nanometal oxides for photocatalytic applications. *Chemistry – An Asian Journal*, 19(10), e202400161. <https://doi.org/10.1002/asia.202400161>
- [10] Shee, N. K., & Kim, H.-J. (2024). Recent Developments in Porphyrin-Based Metal-Organic Framework Materials for Water Remediation under Visible-Light Irradiation. *International Journal of Molecular Sciences*, 25(8), 4183. <https://doi.org/10.3390/ijms25084183>
- [11] Mohd Zaki, R. S. R., Jusoh, R., Chanakaewsomboon, I., & Setiabudi, H. D. (2023). Recent advances in metal oxide photocatalysts for photocatalytic degradation of organic pollutants: A review on photocatalysts modification strategies. *Materials Today: Proceedings*, 66, 3294–3301. <https://doi.org/10.1016/j.matpr.2023.07.102>
- [12] Ramalingam, G., Perumal, N., Priya, A. K., & Rajendran, S. (2022). A review of graphene-based semiconductors for photocatalytic degradation of pollutants in wastewater. *Chemosphere*, 300, 134391. <https://doi.org/10.1016/j.chemosphere.2022.134391>
- [13] Kocijan, M., Čurković, L., Ljubas, D., Mužina, K., Bačić, I., Radošević, T., Podlogar, M., Bdikin, I., Otero-Irurueta, G., & Hortigüela, M. J. (2021). Graphene-Based TiO_2 Nanocomposite for Photocatalytic Degradation of Dyes in Aqueous Solution under Solar-Like Radiation. *Applied Sciences*, 11(9), 3966. <https://doi.org/10.3390/app11093966>
- [14] Mallick, P., Sahoo, S. K., & Satpathy, S. K. (2024). Different strategies to improve photocatalytic activity of graphitic carbon nitride ($\text{g-C}_3\text{N}_4$) semiconductor nanomaterials for hydrogen generation. *Journal of Molecular Liquids*, 406, 125071. <https://doi.org/10.1016/j.molliq.2024.125071>
- [15] Ullah, I., Qin, N., Zhao, P., Li, J., Chen, S., & Xu, A. (2024). Improved charge separation and transport with L-aspartic acid derived carbon-doped $\text{g-C}_3\text{N}_4$ for efficient visible-light photocatalytic H_2 production. *Sustainable Energy & Fuels*, 8(13), 5868–5877. <https://doi.org/10.1039/D4SE01264J>
- [16] Zahra, T., Ahmad, K. S., & Sharif, S. (2023). Facile synthesis of $\text{NiO/ZrO}_2/\text{Mn}_2\text{O}_4$ nanocomposites for catalytic degradation of organic pollutants: Characterization and performance evaluation. *Environmental Nanotechnology, Monitoring & Management*, 20, 100789. <https://doi.org/10.1007/s13762-022-04396-1>

-
- [17] Raveendran, A., Selvam, M., Vairakannu, M., & Narayanan, T. N. (2023). Facile fabrication of hybrid electrocatalyst for efficient water splitting applications. *Materials Today: Proceedings*, 84, 35–40. <https://doi.org/10.1039/D2RA07642J>
 - [18] Bhatti, D. T., & Parikh, S. P. (2022). Recent progress in doped TiO₂ photocatalysis and hybrid advanced oxidation processes for organic pollutant removal from wastewater. *Current World Environment*, 17(1), Article 13. <https://doi.org/10.12944/CWE.17.1.13>
 - [19] Li, X., Wei, H., Song, T., Lu, H., & Wang, X. (2023). A review of the photocatalytic degradation of organic pollutants in water by modified TiO₂. *Water Science & Technology*, 88(6), 1495–1507. <https://doi.org/10.2166/wst.2023.288>
 - [20] Xu, R., Wei, G., Xie, Z., Diao, S., Wen, J., Tang, T., Jiang, L., Li, M., & Hu, G. (2023). V2C MXene-modified g-C₃N₄ for enhanced visible-light photocatalytic activity. *arXiv preprint arXiv:2310.16414*. <https://arxiv.org/abs/2310.16414>