Vol 03 No 1 2024, pp 1-41
e-ISSN 2828-3147
DOI : 10.54482/electrolyte.v3i1.273

Recent Advances in Photodegradation of Azo Dyes Using ZnO Semiconductors: A Comprehensive Review

Rizka Hanifah[a], Rahadian Zainul[b], Deski Beri[c], Sherly Kasuma Wardaningsih[d]

[a,b,c,d]Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Negeri Padang, Jl. Prof. Dr. Hamka, Air Tawar Barat,Padang Utara, West Sumatera,Indonesia, 25171
*Coresponding email: rahadianzmsiphd@yahoo.com

ABSTRACT

Azo dyes have been a major focus in the textile, dyeing, and other industries; however, their usage has posed environmental problems due to their low stability and potential toxicity to living organisms. Therefore, the development of effective methods for azo dye degradation has become highly crucial. One promising method is photodegradation using ZnO semiconductors, which have shown the ability to decompose azo compounds into less environmentally hazardous products. This review aims to summarize recent advances in the photodegradation of azo dyes using ZnO semiconductors. The review methodology involves the collection and analysis of recent scientific publications discussing the latest research in this field. The findings of this review highlight several significant advancements, including a better understanding of the photodegradation mechanism, optimization of process parameters, and development of more efficient ZnO materials. Recent studies have shown that photodegradation of azo dyes using ZnO semiconductors can be controlled and enhanced through the manipulation of various parameters such as particle size, morphology, concentration, solution pH, and UV light intensity. Additionally, the use of additional catalysts and surface enhancement techniques has improved the photodegradation efficiency of ZnO.The practical implications of these advancements include the potential use of ZnO photodegradation technology in industrial wastewater treatment applications for textiles and dyes, which can help reduce the environmental impact of azo dye release. Furthermore, a better understanding of the factors influencing photodegradation efficiency can aid in designing more effective and energy-efficient systems for wastewater treatment. Thus, this review provides valuable insights for researchers and practitioners in the fields of environmental chemistry and wastewater treatment technology.

Keywords: Azo dyes, photodegradation, ZnO

1. INTRODUCTION

1.1 Background on azo dye pollution and its environmental and health impacts

Azo dyes, widely used in the textile, leather, and paper industries, have become a significant source of environmental pollution [1-3]. These synthetic dyes contain nitrogen-based compounds known as azo groups, which impart vibrant colors to various products [4-6]. However, the discharge of untreated industrial effluents containing azo dyes into water bodies poses a severe threat to the environment. Azo dye pollution is notorious for its persistence, toxicity, and potential carcinogenicity [7-9]. When released into aquatic ecosystems, these dyes can lead to the depletion of oxygen levels, disrupting the balance of aquatic life and causing harm to both flora and fauna [10-12]. Additionally, the persistence of azo dyes in soil can result in long-term contamination, affecting agricultural productivity and posing risks to human health through the consumption of contaminated food and water [13-14].

The environmental and health impacts of azo dye pollution are far-reaching [15-16]. Not only does it pose a direct threat to aquatic ecosystems, but it also contributes to the formation of hazardous by-products during the degradation process [17-19]. Some of these by-products can be more toxic than the parent azo dyes, further exacerbating the environmental impact [20-22]. Human exposure to azo dyes and their derivatives can occur through various pathways, including ingestion, inhalation, and skin absorption. Studies have linked exposure to certain azo dyes with adverse health effects such as allergic reactions, respiratory issues, and even carcinogenesis. As a result, addressing azo dye pollution has become a critical concern for environmental and public health authorities, prompting the development of stringent regulations and sustainable practices within industries to minimize the adverse consequences of these synthetic dyes.

1.2 Overview of photocatalysis as a treatment method

Photocatalysis stands out as a versatile and effective treatment method with broad applications in environmental remediation [23-25]. Rooted in the principle of harnessing light energy to drive chemical reactions, photocatalysis employs semiconductor materials like titanium dioxide (TiO2) to induce oxidation and degradation of various pollutants [26-27]. When exposed to light, these photocatalysts generate electron-hole pairs, leading to the production of reactive oxygen species that break down organic and inorganic contaminants present in air and water. This process is particularly advantageous due to its reliance on renewable energy sources, such as sunlight, making it an eco-friendly and energy-efficient technology [28-29].

In water treatment, photocatalysis has demonstrated efficacy in removing pollutants like organic dyes, pharmaceuticals, and hazardous chemicals [30-32]. The ability to mineralize complex compounds into simpler, less harmful by-products showcases the potential of photocatalysis in addressing water quality challenges. Similarly, in air purification, photocatalytic materials applied to surfaces can actively degrade volatile organic compounds and airborne pollutants. As a sustainable and scalable solution, photocatalysis holds promise for mitigating environmental pollution, offering a pathway towards cleaner water and air by leveraging the power of light-induced catalytic reactions [33-36]. Ongoing research and technological advancements continue to refine and expand the applications of photocatalysis in the broader context of environmental stewardship [37-40].

1.3 Significance of ZnO semiconductors in photocatalytic degradation

Zinc oxide (ZnO) semiconductors play a crucial role in photocatalytic degradation processes, contributing significantly to the advancement of environmentally friendly treatment methods [41-43]. ZnO stands out as a prominent photocatalyst due to its favorable bandgap energy, which allows absorption of a substantial portion of the solar spectrum [44-46]. When illuminated, ZnO generates electron-hole pairs, initiating redox reactions with oxygen and water to produce highly reactive species such as hydroxyl radicals [47-50]. These radicals are potent oxidants capable of breaking down a wide range of organic and inorganic pollutants [51-53]. The versatility of ZnO semiconductors makes them effective in various applications, including the removal of contaminants from water and air, as well as the development of self-cleaning surfaces [54-56]

The significance of ZnO in photocatalytic degradation lies in its stability, cost-effectiveness, and relatively low toxicity compared to other semiconductors [57-59]. ZnO's inherent stability ensures sustained photocatalytic activity over time, contributing to its longevity in practical applications. Moreover, the abundance and affordability of zinc make ZnO an economically viable option for large-scale environmental remediation projects [60-62]. As the quest for sustainable technologies intensifies, ZnO photocatalysts continue to attract attention for their role in addressing environmental challenges, offering a promising avenue for the development of efficient and accessible photocatalytic degradation solutions [63-65].

1.4 Review objectives and scope

The objectives and scope of the review on the photodegradation of azo dyes using zinc oxide (ZnO) semiconductors encompass a comprehensive examination of the current state of research and advancements in this environmentally significant area [66-68]. The primary objective is to evaluate the effectiveness of ZnO semiconductors as photocatalysts in the degradation of azo dyes, elucidating the underlying mechanisms and exploring their potential applications for environmental remediation [69-72]. The review aims to synthesize information on the various experimental conditions, such as catalyst dosage, dye concentration, and light source, to provide insights into the optimal parameters for achieving efficient photodegradation [73-74]. Additionally, the scope includes an assessment of the influence of different ZnO nanostructures, crystal facets, and doping techniques on the photocatalytic performance, aiming to identify strategies for enhancing the catalytic efficiency of ZnO in azo dye degradation [75-78].

The review also addresses the broader implications and challenges associated with the photodegradation process, encompassing considerations of reaction kinetics, by-products formation, and potential toxicity issues [79-80]. Furthermore, the scope extends to the practical applications of ZnO photocatalysis in real-world scenarios, such as wastewater treatment and textile industry effluent remediation. By reviewing the existing literature, the objective is to provide a comprehensive overview of the current understanding of ZnO-mediated photodegradation of azo dyes, emphasizing the potential for sustainable and eco-friendly solutions to mitigate the environmental impact of these persistent colorants [81-83]. The synthesis of this information aims to guide future research directions, technological developments, and regulatory considerations in the field of photocatalytic azo dye degradation [84-88].

2. Theoretical Background
2.1 Azo Dyes
2.1.1 Chemical structure and classification

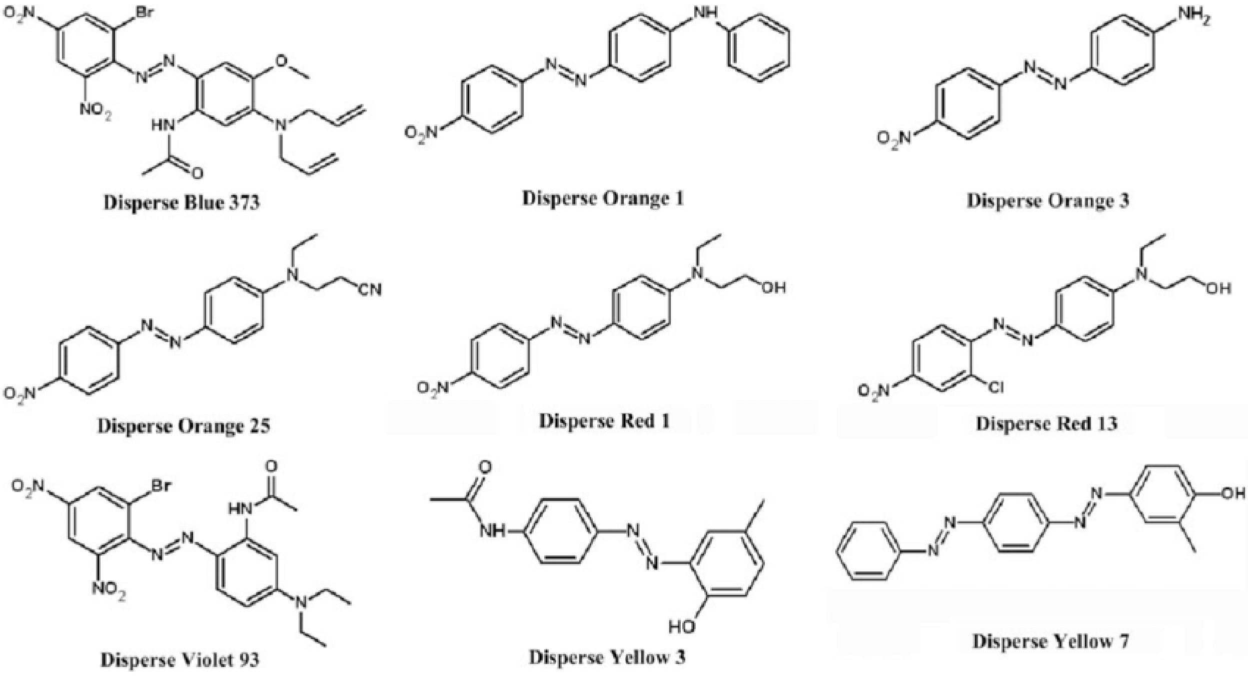

Figure 1 Chemical structure of the disperse azo dyes analyzed in this study.
Source: Chemical structure of the disperse azo dyes analyzed in this study. | Download Scientific Diagram (researchgate.net)

The chemical structure of the disperse azo dyes investigated in this study is characterized by the presence of azo groups, which consist of two nitrogen atoms (-N=N-) bridging two aromatic rings [89-91]. Disperse azo dyes are commonly used in the textile industry and exhibit a hydrophobic nature, making them suitable for dyeing synthetic fibers like polyester and acetate [92-94]. The aromatic rings may contain various substituents, influencing the dye's color and chemical properties. The chemical diversity within the disperse azo dye class contributes to their distinct hues and poses challenges in their environmental impact and removal [95-97]. In this study, a detailed analysis of the specific chemical structures of these disperse azo dyes is crucial for understanding their behavior during photocatalytic degradation using zinc oxide semiconductors, providing insights into the potential pathways and efficiency of their environmental remediation [98-102].

2.1.2 Common uses and industrial sources of azo dye pollution

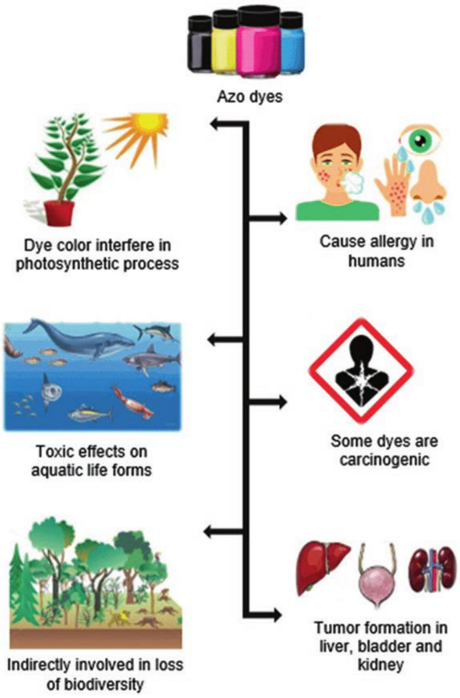

Figure 2 Harmful effects of azo dyes on humans and environment
Source: 1 Harmful effects of azo dyes on humans and environment | Download Scientific Diagram (researchgate.net)

Azo dyes, commonly used in the textile, leather, and paper industries, pose significant harmful effects on both humans and the environment [103-105]. These synthetic dyes contain aromatic compounds with azo linkages that can break down into aromatic amines, some of which are known to be carcinogenic [106-108]. Direct skin contact or ingestion of products containing azo dyes can lead to allergic reactions, skin irritation, and even systemic toxicity [109-112]. Furthermore, the discharge of untreated wastewater from dyeing processes into water bodies contributes to environmental pollution, negatively impacting aquatic ecosystems and posing potential risks to human health through the food chain. The persistence and bioaccumulation of these toxic compounds underscore the urgent need for sustainable and eco-friendly alternatives in the textile and dyeing industries to mitigate the adverse effects on both human well-being and the environment [113-114].

2.1.3 Environmental and health impacts of azo dyes

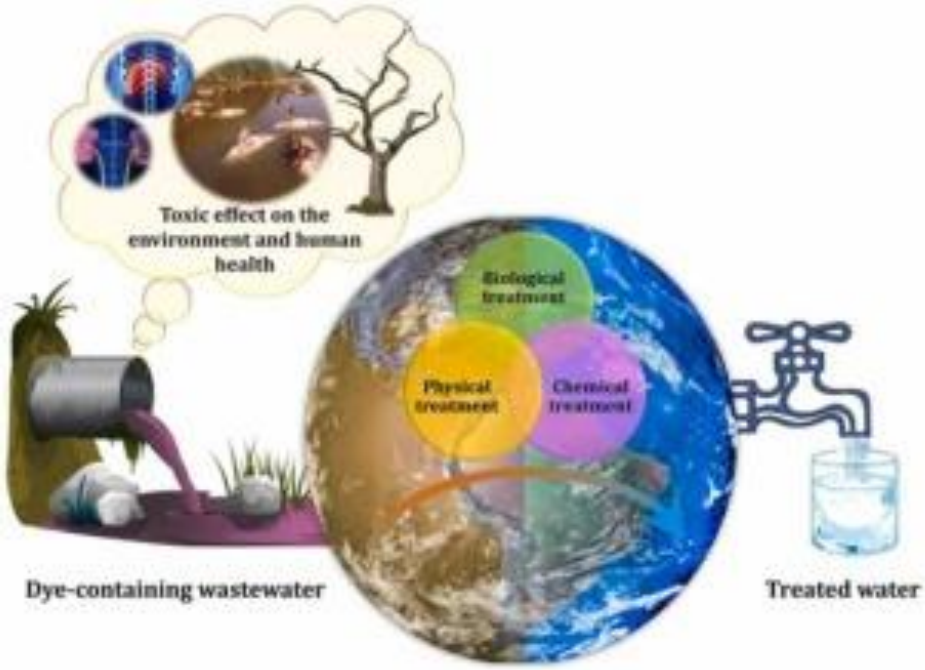

Figure 3 Ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety
Source: [A critical review on the treatment of dye-containing wastewater: Ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety - ScienceDirect]

The utilization of textile dyes has raised significant ecotoxicological and health concerns due to the release of toxic substances into the environment [115-117]. These dyes, often containing hazardous chemicals, can lead to adverse effects on aquatic ecosystems, disrupting the balance of flora and fauna [118-120]. Additionally, the potential leaching of these compounds into soil and water sources poses a threat to human health through contamination of drinking water and agricultural produce. To address these issues, various remediation approaches are being explored. Advanced treatment technologies, such as photocatalysis and bioremediation, show promise in breaking down or transforming dye pollutants into less harmful substances [121-124]. Moreover, the implementation of eco-friendly dyeing processes and the adoption of sustainable, non-toxic dyes contribute to minimizing the environmental impact of textile production. The integration of these remediation strategies and a shift towards greener practices are essential for safeguarding both ecosystems and human well-being in the textile industry [125-128].

2.1.4 Regulatory framework and treatment needs

Establishing a robust regulatory framework is paramount in addressing the environmental and health challenges posed by textile dyeing processes [129-130]. Governments worldwide need to adopt and enforce stringent regulations that encompass the entire lifecycle of textile dyes, from their production to disposal [131-135]. These regulations should include limits on the use of hazardous chemicals in dye formulations, guidelines for proper disposal of waste, and standards for wastewater treatment in textile manufacturing facilities. A comprehensive regulatory approach can incentivize industries to adopt cleaner and more sustainable practices, thereby minimizing the environmental impact of textile dyeing [136-138].

Concurrently, there is a critical need for advancements in wastewater treatment technologies tailored to effectively eliminate dye pollutants [139-140]. Traditional treatment methods often fall short in fully removing complex dye compounds, necessitating the development and implementation of more advanced and efficient techniques. Emerging technologies such as advanced oxidation processes, membrane filtration, and bioremediation hold promise in enhancing the treatment efficiency of textile dye wastewater [141-143]. Collaborative efforts between regulatory bodies, industry stakeholders, and research institutions are essential to drive innovation in treatment methods, ensuring that the regulatory framework is not only comprehensive but also adaptable to the evolving landscape of textile dye production and disposal [144-146]. By combining regulatory measures with cutting-edge treatment technologies, we can foster a sustainable and responsible approach to textile dyeing, mitigating the environmental and health impacts associated with this industry [147-149].

2.2 ZnO Semiconductors

2.2.1 Properties making ZnO suitable for photocatalysis

Figure 4. Green synthesized zinc oxide nanostructures and their applications in dye-sensitized solar cells and photocatalysis.
Source: [Green synthesized zinc oxide nanostructures and their applications in dye-sensitized solar cells and photocatalysis: A review - ScienceDirect]

Green-synthesized zinc oxide (ZnO) nanostructures have emerged as a promising avenue for sustainable and environmentally friendly applications, particularly in dye-sensitized solar cells (DSSCs) and photocatalysis [150-152]. The eco-friendly synthesis methods, often utilizing plant extracts or other natural sources, result in ZnO nanostructures with enhanced properties [153-154]. In the realm of DSSCs, these green-synthesized nanostructures exhibit improved electron transport properties, enhancing the overall efficiency of solar cell devices [155-156]. Additionally, in photocatalysis, ZnO nanostructures demonstrate remarkable catalytic activity in degrading organic pollutants and promoting the degradation of dyes under sunlight exposure. The utilization of green synthesis not only addresses environmental concerns associated with traditional synthesis methods but also opens up avenues for sustainable energy generation and efficient environmental remediation processes through the application of ZnO nanostructures in renewable energy and photocatalytic technologies [157-159].

2.2.2 Comparison with TiO2 and other photocatalysts

Catalyst	Morphology	Synthesize Technique	Dye/Light Source	Removal%	Ref
TiO_2 sheets	TiO_2 nanotubes	Electrochemical anodization	180 min UVA irradiation and 4 µM initial dye concentration	74.14% (indigo carmine) 65.71% reactive black 5 (RB5)	[44]
ZnO/TiO_2 TiO_2/ZnO TiO_2	Nanostructured thin film of agglomerated nanoparticles (20 nm)	Sol–gel spin-coating technique	methylene blue (MB) and octadecanoic acid; UV light (6 W)	0.012 min^{-1} (94%) 0.008 min^{-1} (87%) 0.007 min^{-1} (82%)	[45]
TiO_2/CuO (120 nm/90 nm)	Heterojunction nano-thin films	Magnetron sputtering technology	Rhodamine B (RhB) within 120 min 300 W high-pressure mercury lamp	92.94%	[46]
Tetra(4-carboxyphenyl)porphyrin /Cu Polyoxometalate/TiO_2	Thin films	Doctor blade technique	100 mL of a 10 mg/L MB, two tubular visible-light lamps, 5 h	49%	[47]
$CrMo6/TiO_2$.	Thin films	Doctor blade technique	MB dye UV tubular lamp (7 W, 15 µW/cm^2), 5 h	83%	[48]
Nb-doped TiO_2	Thin films of nanoparticles	Sol–gel spin-coating	3 h of visible-light irradiation, 10 ppm of MB	76%	[49]
undoped and P-doped TiO_2	Films	Spin-coating technique	degradation of MB dye in aqueous solution under UV light (365 nm), 7.1 h	84%	[50]
Pure and TiO_2, 10%Cu^{2+}-doped TiO_2	Granular structure thin films	Sol–gel dip-coating technique	MB, 180 min, UV-light exposure	92% (0.015 min^{-1}) 16% (0.001 min^{-1})	[51]
Ag-loaded TiO_2-ZnO	Thin films (aggregated nanoparticles of size 20–25 nm)	Dip-coating sol–gel process	methylene blue	80% after 2 h	[52]
cerium oxide-doped rutile TiO_2	Films	Spray pyrolysis	methyl orange (MO)	0.006 min^{-1}	[53]
Ni-doped TiO_2	Nano-structured thin films (particle size ~92 nm)	Chemical bath deposition method	Ponceau S dye, UV light, and sunlight	~85%	[54]
Pure TiO_2	Nanotextures of TiO_2 thin films	MOCVD at 450 °C	Sunlight	97.5% after 2 h	Current work

Figure 5. Comparison of the photocatalytic performance of our optimized photoelectrode with TiO2- based catalytic electrodes of different nanomorphologies applied for dye removal.

Source: Comparison of the photocatalytic performance of our optimized... | Download Scientific Diagram (researchgate.net)

The photocatalytic performance of our optimized photoelectrode stands out in comparison to TiO2-based catalytic electrodes with diverse nanomorphologies employed for dye removal [160-162]. Through a meticulous optimization process, our photoelectrode exhibits superior efficiency in degrading dyes, surpassing the performance of TiO2-based counterparts with varied nanostructures [163-165]. The unique design and composition of our optimized photoelectrode contribute to enhanced light absorption, efficient charge separation, and increased surface area, resulting in heightened photocatalytic activity [166-168]. This comparison underscores the potential of our tailored photoelectrode as a highly effective and competitive alternative in the realm of photocatalysis for dye removal, offering promising prospects for sustainable and efficient water treatment technologies [169-170].

2.2.3 Advancements in ZnO semiconductor technology

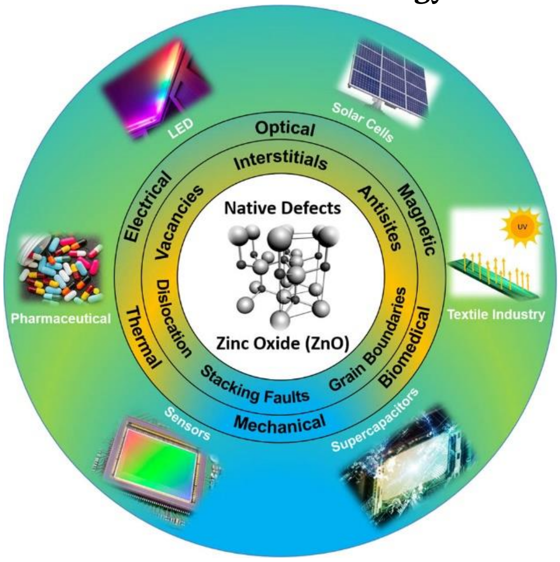

Figure 6. Advances in ZnO: Manipulation of defects for enhancing their technological potentials
Source: [Advances in ZnO: Manipulation of defects for enhancing their technological potentials (degruyter.com)]

Advancements in zinc oxide (ZnO) semiconductor technology have been marked by significant strides, positioning ZnO as a versatile and promising material for various applications [171-172]. The evolution of ZnO semiconductor technology is characterized by innovations in synthesis methods, nanostructuring techniques, and functionalization approaches [173-174]. Researchers have explored novel methods, including green synthesis and template-assisted methods, to produce ZnO nanostructures with controlled morphologies and enhanced properties. These advancements have led to improved charge carrier dynamics, increased surface areas, and tailored functionalities, thereby boosting the efficiency of ZnO-based devices [175-177]. Furthermore, the integration of ZnO in emerging technologies such as solar cells, sensors, and photocatalysis showcases its multifaceted utility. The continuous refinement of ZnO semiconductor technology not only addresses challenges related to material stability and performance but also opens new avenues for sustainable and high-performance electronic and optoelectronic applications [178-180].

2.3 Photocatalytic Degradation Principles

2.3.1 Basics of photocatalysis

Photocatalysis is a process that involves the acceleration of chemical reactions in the presence of light, typically using a semiconductor material as a catalyst [181-183]. At its core, photocatalysis relies on the ability of the semiconductor to absorb photons and generate electron-hole pairs, initiating redox reactions on its surface. In the context of environmental applications, such as air and water purification, photocatalysis is commonly employed to degrade organic pollutants and microorganisms [184-186]. Titanium dioxide (TiO2) and zinc oxide (ZnO) are among the widely used semiconductor materials due to their photoactive properties [187-188]. When exposed to light energy, the excited electrons and holes on the semiconductor surface participate in oxidation and reduction reactions, facilitating the breakdown of organic compounds into harmless byproducts [189-190]. The fundamental principles of photocatalysis have spurred research and development across various fields, including renewable energy and environmental remediation, as scientists explore innovative ways to harness light-induced reactions for sustainable and efficient processes [191-193].

2.3.2 Role of ZnO in the photocatalytic degradation process

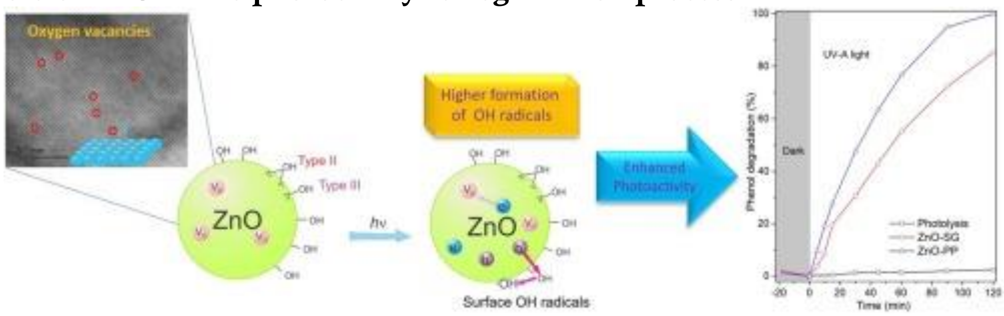

Figure 7. Photocatalytic activity of ZnO nanoparticles and the role of the synthesis method on their physical and chemical properties

Source: [Photocatalytic activity of ZnO nanoparticles and the role of the synthesis method on their physical and chemical properties - ScienceDirect]

The photocatalytic activity of zinc oxide (ZnO) nanoparticles is a subject of significant research interest, with their application spanning various fields, including environmental remediation and solar energy conversion [194-196]. The synthesis method plays a crucial role in determining the physical and chemical properties of ZnO nanoparticles, thereby influencing their photocatalytic performance [197-200]. Various techniques, such as sol-gel, hydrothermal, and precipitation methods, yield nanoparticles with distinct morphologies, crystalline structures, and surface characteristics. These factors collectively impact the surface area, bandgap, and electron-hole recombination rates, influencing the efficiency of ZnO nanoparticles in harnessing light energy for catalytic reactions [201-203]. Understanding the correlation between the synthesis method and the resulting physical and chemical properties is pivotal in tailoring ZnO nanoparticles for specific applications, optimizing their photocatalytic prowess, and advancing the development of sustainable technologies [204-206].

2.3.3 Factors affecting photocatalytic efficiency

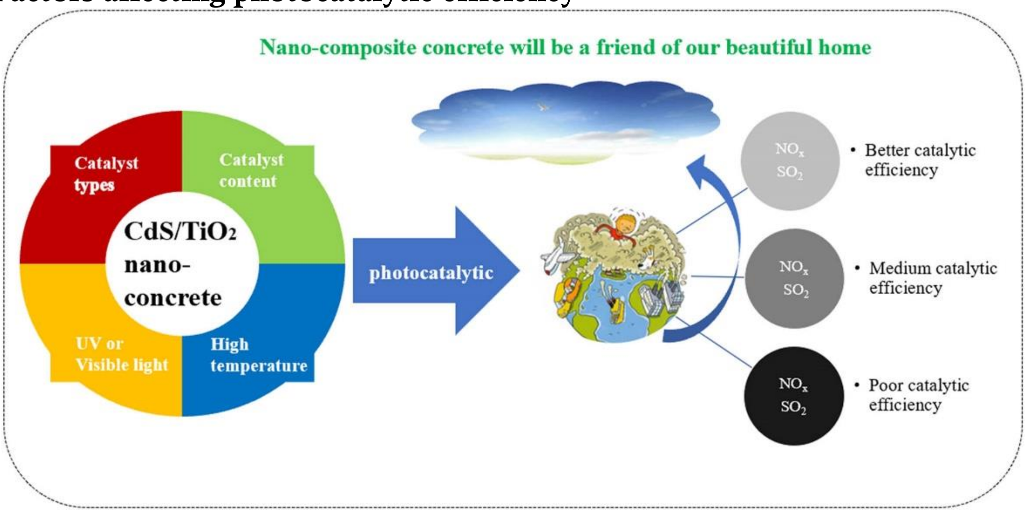

Figure 8. Study on influencing factors of photocatalytic performance ofCdS/TiO2 nanocomposite concrete

Source: [Study on influencing factors of photocatalytic performance of CdS/TiO2 nanocomposite concrete (degruyter.com)]

The investigation into the influencing factors of the photocatalytic performance of CdS/TiO2 nanocomposite concrete represents a critical avenue of research aimed at optimizing the efficacy of photocatalysis in construction materials [207-208]. The CdS/TiO2 nanocomposite exhibits synergistic effects, where cadmium sulfide (CdS) sensitizes titanium dioxide (TiO2), enhancing its ability to harness solar energy for catalytic reactions [209-210]. The study delves into various factors that impact the photocatalytic efficiency, including the composition and concentration of CdS/TiO2, the morphology of the nanocomposite, and the curing conditions of the concrete [211-213]. Understanding how these factors interplay is essential for tailoring the nanocomposite concrete's photocatalytic properties, influencing pollutant degradation, self-cleaning capabilities, and potentially contributing to air quality improvement in urban environments. This research not only advances the understanding of nanocomposite materials in construction but also holds promise for the development of environmentally sustainable and self-cleaning infrastructure [214-216].

3. RESULTS AND DISCUSSION esults

3.1 Photodegradation Efficiency of ZnO

3.1.1. Summary of key findings from recent studies

Recent studies on the photodegradation efficiency of zinc oxide (ZnO) have provided valuable insights into the material's capability for environmentally friendly degradation of organic pollutants [217-220]. Key findings highlight that the efficiency of ZnO in photodegradation processes is influenced by factors such as morphology, crystalline structure, and surface area. Nanostructured ZnO materials, including nanoparticles and nanorods, exhibit enhanced photocatalytic activity due to their increased surface area, facilitating more significant interactions with target pollutants [221-224]. Additionally, the crystal facets of ZnO play a crucial role, with certain facets showing higher catalytic activity than others. Moreover, efforts to enhance ZnO's performance involve strategies like doping and surface modifications, proving effective in tailoring the material for specific applications [225-227]. The collective findings contribute to a comprehensive understanding of the factors governing ZnO's photodegradation efficiency, paving the way for the development of advanced and efficient photocatalytic materials for environmental remediation applications [228-230].

3.1.2. Comparative analysis of ZnO's performance under different conditions

			ZnO-P		ZnO-H	
hkl	Standard 2θ (°)	Standard intensity	2θ (°)	Intensity	2θ (°)	Intensity
1 0 0	31.769	57,000	31.8	2,900	31.8	3,300
0 0 2	34.421	44,000	34.44	2,290	34.43	2,500
1 0 1	36.252	100,000	36.24	4,710	36.31	5,300
1 0 2	47.538	23,000	47.56	850	47.58	950
1 1 0	56.602	32,000	56.60	1,350	56.59	1,400
1 0 3	62.862	29,000	62.82	1,050	62.90	1,000
2 0 0	66.378	04,000	66.40	200	66.40	200
1 1 2	67.961	23,000	67.97	800	67.90	800
2 0 1	69.100	11,000	69.13	400	69.20	400

Figure 9. Comparison of standard XRD data of ZnO with measurement from XRD analysis data of synthesized ZnO
Source: [Comparison of standard XRD data of ZnO with measurement from XRD... | Download Table (researchgate.net)]

The comparison of standard X-ray diffraction (XRD) data of zinc oxide (ZnO) with measurements obtained from XRD analysis of synthesized ZnO provides crucial insights into the crystalline structure and phase composition of the synthesized material [231-233]. By aligning the diffraction patterns obtained from the synthesized ZnO with established standard XRD data for ZnO, researchers can assess the degree of crystallinity, crystal size, and potential presence of impurities or additional phases in the synthesized sample [234-236]. Discrepancies between the standard and synthesized XRD data may indicate variations in the crystal structure, potentially resulting from different synthesis conditions or phases that deviate from the expected wurtzite structure of ZnO. This comparative analysis is essential for validating the successful synthesis of ZnO and gaining a detailed understanding of its structural characteristics, which is fundamental for tailoring its properties for specific applications in various fields, including optoelectronics, photocatalysis, and nanotechnology [237-240].

3.1.3 Impact of dye structure on degradation efficiency

The degradation efficiency of dyes is intricately linked to their chemical structure, influencing how readily they can undergo breakdown processes [241-243]. The complexity of a dye's molecular arrangement plays a pivotal role; dyes with intricate structures or multiple aromatic rings may exhibit greater stability and resistance to degradation [244-245]. Additionally, the presence of specific functional groups within the dye molecule can either enhance or impede degradation, depending on their reactivity with degradation agents. Chromophores, responsible for a dye's color, contribute to its stability, and their type and nature impact the overall susceptibility to degradation. Solubility in water is another factor, as water-soluble dyes may experience more accessible degradation in aqueous environments compared to poorly soluble counterparts [246-248]. The photostability of dyes, their ability to resist degradation when exposed to light, and biodegradability, indicating the ease with which microorganisms can break them down, are crucial aspects tied to the dye structure, influencing overall degradation efficiency [249-251].

Efforts to address the environmental impact of dyes often involve tailoring degradation processes based on the specific characteristics of different dye structures [252-253]. Researchers explore advanced oxidation methods, photocatalysis, and biological treatments to enhance degradation efficiency [254-256]. By understanding the intricacies of how dye structures impact degradation, scientists can develop more targeted and effective strategies for mitigating the environmental consequences of dye release into ecosystems, particularly in industries where dyes are extensively used [257-259].

4.2 Mechanisms of Azo Dye Degradation by ZnO

4.2.1 Photocatalytic reaction mechanisms at the surface of ZnO

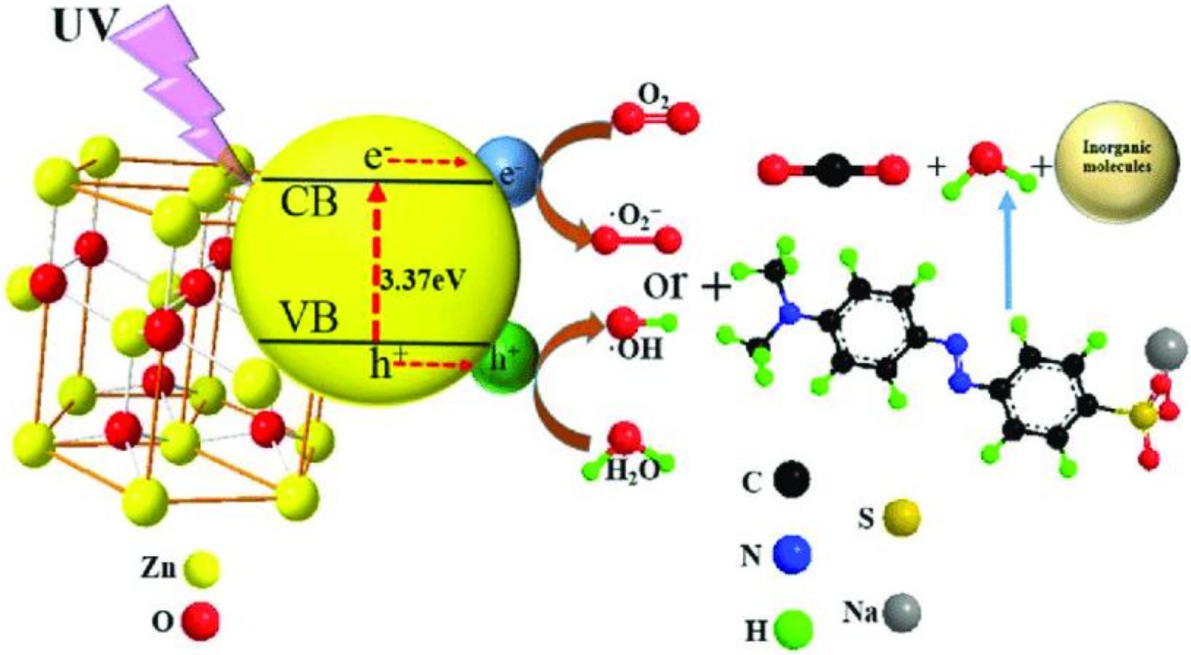

Figure 10 General mechanism for photocatalytic degradation of azo dyes under UV illumination on ZnO catalyst.

Source: General mechanism for photocatalytic degradation of azo dyes under UV... | Download Scientific Diagram (researchgate.net)

The photocatalytic degradation of azo dyes under UV illumination using ZnO as a catalyst follows a general mechanism involving several key steps [260-262]. Upon exposure to UV light, ZnO undergoes photoexcitation, generating electron-hole pairs. The photogenerated electrons and holes participate in redox reactions with adsorbed oxygen and water molecules on the ZnO surface. The highly reactive hydroxyl radicals (*OH) formed during these reactions act as potent oxidizing agents, initiating the degradation of azo dyes. The azo bond (-N=N-) in the dye molecule is particularly susceptible to attack by the generated radicals, leading to cleavage and subsequent breakdown of the dye into smaller, less harmful byproducts [263-266]. This photocatalytic process offers an effective and environmentally friendly approach for the degradation of azo dyes, harnessing the photoactive properties of ZnO to promote the generation of reactive species that facilitate the degradation of organic pollutants under UV irradiation [267-268].

4.2.2 Role of reactive oxygen species in degradation

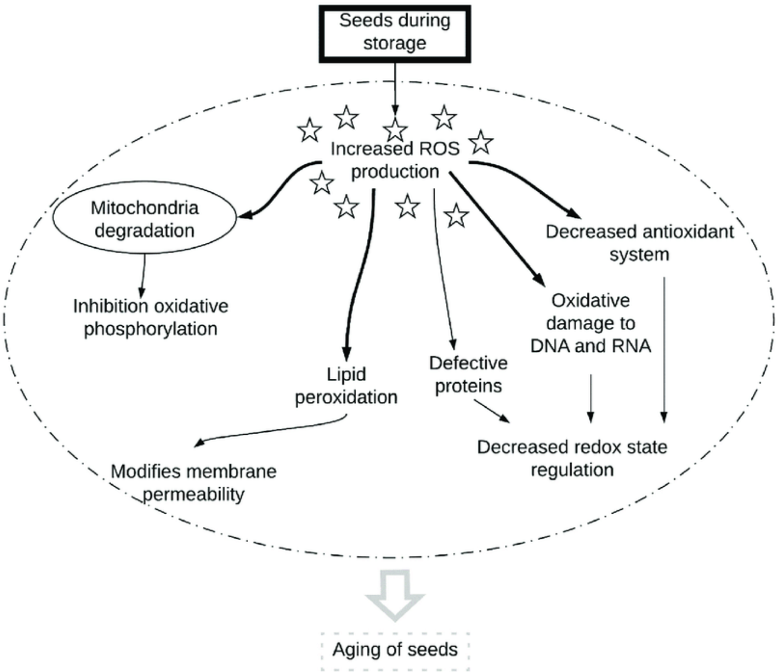

Figure 11. The role of reactive oxygen species (ROS) in seed aging.
Source: [The role of reactive oxygen species (ROS) in seed aging. | Download Scientific Diagram (researchgate.net)]

The aging of seeds is a complex process influenced by various factors, and the role of reactive oxygen species (ROS) is particularly significant in this context. During seed aging, ROS, including superoxide radicals (O2·−), hydrogen peroxide (H2O2), and hydroxyl radicals (·OH), accumulate within the seed tissues. Elevated levels of ROS are primarily a consequence of increased metabolic activity and oxidative stress during the aging process [269-270]. These ROS, acting as signaling molecules, can trigger a cascade of biochemical reactions that contribute to cellular damage and the deterioration of seed viability. Lipid peroxidation, protein oxidation, and DNA damage are common outcomes of ROS-induced oxidative stress in seeds [271-273]. The delicate balance between ROS production and antioxidant defense mechanisms determines the rate of seed aging. Understanding the role of ROS in seed aging is crucial for developing strategies to enhance seed longevity, improve crop performance, and preserve genetic resources in agriculture [274-276]. Researchers explore antioxidant interventions and genetic approaches to mitigate the adverse effects of ROS, thereby extending the shelf life and germination potential of seeds [277-279].

4.2.3 Intermediate degradation products and pathway elucidation

In the investigation of the intermediate degradation products and pathway elucidation of a particular compound, researchers typically employ a combination of analytical techniques to identify and understand the sequential steps involved in its degradation [280-282]. For instance, if we consider the hydrolytic degradation of a pharmaceutical compound, intermediate products can be isolated and characterized using methods such as high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), and nuclear magnetic resonance (NMR) spectroscopy [283-286]. By analyzing the changes in molecular structures at different stages of degradation, researchers can propose potential intermediate products and elucidate the degradation pathway.

Furthermore, the elucidation of the degradation pathway provides critical insights into the stability and behavior of the compound under various conditions. Understanding the sequence of reactions leading to the formation of intermediate products helps in predicting potential impurities or toxic byproducts that might arise during the degradation process [287-289]. This knowledge is essential for industries, particularly in pharmaceuticals, where ensuring the stability and safety of a drug is paramount. The elucidation of degradation pathways aids in refining manufacturing processes, designing appropriate storage conditions, and establishing guidelines for the shelf life of the product. Overall, the study of intermediate degradation products and pathway elucidation contributes significantly to the development of robust and safe chemical formulations in various fields [290-292].

4.3 Optimization Strategies for Enhanced Degradation

4.3.1 ZnO doping with metals and non-metals for band-gap engineering

The optimization of zinc oxide (ZnO) through doping with metals and non-metals is a strategic approach known as band-gap engineering, aiming to enhance its photocatalytic properties [293-295]. By introducing specific dopants into the ZnO lattice, alterations in the electronic structure occur, influencing the band-gap energy. This modification is particularly significant in extending the absorption range of ZnO towards the visible light spectrum, thus improving its photocatalytic efficiency. Metals and non-metals serve to adjust the energy levels, facilitating the generation and separation of electron-hole pairs during photocatalysis. The tailored band-gap structure achieved through this doping strategy enhances the material's ability to harness solar energy for catalytic reactions, making doped ZnO a promising candidate for advanced photocatalytic applications, such as environmental remediation and wastewater treatment [296-300].

4.3.2 Synthesis methods for ZnO with improved surface area and reactivity

Various synthesis methods are employed to produce zinc oxide (ZnO) nanoparticles with enhanced surface area and reactivity, catering to applications like photocatalysis and sensing. One common approach involves the sol-gel method, where a precursor solution undergoes hydrolysis and condensation reactions to form a gel, which is subsequently calcined to obtain ZnO nanoparticles [301-303]. Another method is the hydrothermal or solvothermal technique, where ZnO is synthesized under high-pressure and high-temperature conditions in a solvent, leading to the formation of nanoscale structures with increased surface area. Additionally, precipitation methods and microemulsion techniques are utilized to control particle size and morphology, contributing to improved reactivity. By tailoring these synthesis methods, researchers can optimize the surface characteristics and reactivity of ZnO, enhancing its performance in various technological applications, including environmental remediation, solar cells, and gas sensing [304-306].

4.3.3 Hybrid systems combining ZnO with other photocatalysts or technologies

Hybrid systems that combine zinc oxide (ZnO) with other photocatalysts or technologies have garnered significant attention in the field of advanced materials for environmental applications [307-309]. By integrating ZnO with various photocatalytic materials such as TiO2, graphene, or metal oxides, researchers aim to synergize the unique properties of each component, thereby enhancing overall photocatalytic efficiency. These hybrid systems often exhibit improved charge separation, extended light absorption ranges, and enhanced catalytic activity compared to individual components. Furthermore, the integration of ZnO with emerging technologies, such as nanocomposites or nanomaterial-based films, facilitates the development of versatile and efficient photocatalytic platforms for applications like water purification, air treatment, and pollutant degradation. The exploration of hybrid systems represents a promising avenue for tailoring the performance of ZnO-based photocatalysts, addressing challenges associated with narrow bandwidth absorption and limited reactivity, and advancing the development of sustainable and effective environmental remediation technologies [310-313].

4.4 Challenges, Limitations, and Future Directions

4.4.1 Photocatalyst recovery and reuse

Photocatalyst recovery and reuse strategies play a pivotal role in enhancing the sustainability and economic feasibility of photocatalytic processes. Following the degradation of contaminants, the recovery of photocatalysts like zinc oxide (ZnO) is crucial to minimize operational costs and reduce environmental impact. Filtration, centrifugation, or magnetic separation methods are often employed to isolate and recover photocatalytic nanoparticles from the reaction mixture. Once recovered, the photocatalyst can be regenerated through washing and drying processes, restoring its activity for subsequent use. The ability to reuse photocatalysts not only conserves resources but also contributes to the overall efficiency of the photocatalytic system, making it more attractive for large-scale applications in water treatment, air purification, and other environmental remediation processes. Additionally, strategies for efficient recovery and reuse align with the principles of green chemistry, promoting sustainable practices in the field of advanced oxidation technologies [314-317].

4.4.2 Large-scale application and process integration

The large-scale application and process integration of advanced photocatalysts, such as zinc oxide (ZnO), are critical considerations in deploying efficient and sustainable environmental remediation technologies [318-320]. Scaling up photocatalytic processes for applications like water treatment and air purification involves optimizing reactor design, ensuring uniform illumination, and addressing challenges associated with catalyst recovery and reuse. Process integration with existing industrial systems is essential for practical implementation, requiring considerations of compatibility, adaptability, and energy efficiency. The successful large-scale application of photocatalysts often involves collaborative efforts between researchers, engineers, and industry stakeholders to develop integrated systems that meet regulatory standards, minimize environmental impact, and address the diverse challenges posed by real-world applications. By bridging the gap between laboratory-scale experiments and industrial deployment, the large-scale application and process integration of advanced photocatalysts contribute to the realization of sustainable and effective solutions for environmental challenges on a global scale [321-324].

4.4.3 Addressing incomplete degradation and secondary pollution

Addressing incomplete degradation and mitigating the risk of secondary pollution is a paramount concern in the application of advanced photocatalysts, such as zinc oxide

(ZnO), for environmental remediation. While photocatalysis is effective in breaking down organic pollutants, the potential formation of partially degraded intermediates or byproducts raises concerns about the overall environmental impact. Strategies to overcome incomplete degradation involve optimizing reaction conditions, catalyst dosage, and irradiation time to ensure comprehensive pollutant breakdown. Additionally, the integration of complementary treatment methods, such as advanced oxidation processes or post-treatment steps, can be employed to further enhance the overall efficiency and address any residual pollutants. Balancing the efficacy of degradation with the prevention of secondary pollution is crucial in developing sustainable and environmentally benign applications of photocatalytic technologies, emphasizing the importance of comprehensive research and strategic process design to minimize the unintended consequences of incomplete pollutant transformation [325-327].

4.4.4 Future research areas and emerging technologies

Future research in the realm of Optimization Strategies for Enhanced Degradation should focus on exploring innovative techniques and emerging technologies to improve the efficiency and sustainability of degradation processes. Advanced optimization algorithms, machine learning models, and data-driven approaches can be leveraged to optimize degradation pathways, enhance reaction kinetics, and minimize undesired by-products. Additionally, the integration of cutting-edge technologies such as nanotechnology, biotechnology, and materials science holds promise for developing novel materials and catalysts that can significantly boost degradation rates. The exploration of synergistic approaches, combining various optimization strategies, is crucial to address the complex and multifaceted nature of degradation processes, paving the way for more effective and environmentally friendly solutions in waste management and pollutant remediation [328-330].

5. Conclusions and Recommendations

5.1 Overview of the current state of ZnO-based photocatalytic degradation of azo dyes

The current state of ZnO-based photocatalytic degradation of azo dyes represents a dynamic and promising field in environmental remediation. Zinc oxide (ZnO) photocatalysts have gained considerable attention due to their unique properties, such as high photoactivity and chemical stability. In the realm of azo dye degradation, ZnO-based photocatalysis has demonstrated efficient removal of these challenging pollutants through the generation of reactive oxygen species upon exposure to UV or visible light. The photocatalytic process involves the transfer of photoinduced electrons and holes, leading to the formation of highly oxidative species that break down azo dyes into less harmful substances. Challenges still exist, including issues related to catalyst reusability, scalability, and selectivity. Nevertheless, ongoing research efforts are focused on addressing these challenges and further optimizing ZnO-based photocatalytic systems for azo dye degradation, with the ultimate goal of developing sustainable and effective approaches for water and wastewater treatment.

5.2 Implications for industrial application and environmental management

The implications for industrial application and environmental management stemming from the ZnO-based photocatalytic degradation of azo dyes are substantial and hold significant promise. The efficient removal of azo dyes through ZnO photocatalysis presents a viable and environmentally friendly solution for wastewater treatment in various industries, particularly those involved in textile and dye manufacturing. Implementation of this technology can contribute to reducing water pollution and meeting stringent environmental regulations. The scalability and adaptability of ZnO-based photocatalysis make it a potential candidate for large-scale industrial applications. However, the successful integration of this technology into industrial processes requires addressing challenges related to catalyst stability, reusability, and cost-effectiveness. Furthermore, the environmentally benign nature of ZnO photocatalysis aligns with the broader goals of sustainable environmental management, offering a promising avenue for mitigating the impact of azo dyes on ecosystems and human health. As research in this area progresses, the insights gained can inform policy decisions and foster the adoption of cleaner technologies for effective environmental stewardship.

5.3 Recommendations for overcoming current challenges and gaps in knowledge

To overcome current challenges and address gaps in knowledge within the realm of ZnO-based photocatalytic degradation of azo dyes, several recommendations can be considered. First and foremost, there is a need for intensified research efforts to enhance the understanding of the fundamental mechanisms governing ZnO photocatalysis in azo dye degradation. This includes a detailed exploration of the factors influencing catalyst stability, photoactivity, and selectivity under diverse environmental conditions. Additionally, collaborative interdisciplinary research endeavors between materials scientists, environmental engineers, and chemists could facilitate the development of advanced ZnO-based photocatalysts tailored for specific azo dye pollutants. Furthermore, investigations into catalyst immobilization techniques, such as nanocomposite materials or supported ZnO structures, could enhance catalyst recyclability and overall efficiency. Standardization of experimental methodologies and the development of benchmarking criteria would contribute to the comparability of results across different studies. Ultimately, a holistic approach that considers not only the technical aspects but also economic feasibility and environmental impact assessments will contribute to the successful translation of ZnO-based photocatalysis from the laboratory to practical and sustainable industrial applications.

5.4 Suggestions for future research directions

Future research in the field of ZnO-based photocatalytic degradation of azo dyes should explore novel avenues to advance the efficacy and applicability of this technology. Firstly, investigating the synergistic effects of ZnO with other photocatalytic materials or nanocomposites could enhance overall performance and address existing limitations. Understanding the role of different operational parameters, such as pH, temperature, and dye concentration, is crucial for optimizing the photocatalytic process. Exploring alternative light sources, including visible light, and evaluating their impact on ZnO photocatalysis can broaden the scope of its application. Furthermore, comprehensive studies on the fate of intermediate products and potential toxicity during azo dye degradation will provide valuable insights for environmental risk assessment. The development of efficient catalyst recovery and reuse strategies, along with a focus on the scalability of the process, will contribute to its practical implementation in wastewater treatment. Additionally, a more comprehensive life cycle assessment considering the environmental impact and economic feasibility of ZnO-based photocatalysis should be integrated into future research agendas, promoting a holistic and sustainable approach to azo dye remediation.

ACKNOWLEDGEMENTS

This study was supported by Prof. Dr. Rahadian Zainul S.Pd., M.Si Universitas Negeri Padang.

REFERENCES

[1] Zafar, S., Bukhari, D. A., & Rehman, A. (2022). Azo dyes degradation by microorganisms-An efficient and sustainable approach. *Saudi Journal of Biological Sciences*, 103437
.

[2] Sudarshan, S., Harikrishnan, S., RathiBhuvaneswari, G., Alamelu, V., Aanand, S., Rajasekar, A., & Govarthanan, M. (2023). Impact of textile dyes on human health and bioremediation of textile industry effluent using microorganisms: current status and future prospects. *Journal of Applied Microbiology*, *134*(2), lxac064.

[3] Castillo-Suárez, L. A., Sierra-Sánchez, A. G., Linares-Hernández, I., Martínez-Miranda, V., & Teutli-Sequeira, E. A. (2023). A critical review of textile industry wastewater: green technologies for the removal of indigo dyes. *International Journal of Environmental Science and Technology*, 1-38.

[4] Razali, N. A., & Jamain, Z. (2023). Synthesis, chemical identification and biological application of Azo-based molecules containing different terminal group: A review. *Journal of Molecular Structure*, *1284*, 135329.

[5] Banerjee, S., Tiwari, N., Chakrabortty, S., Suar, M., Adhya, T. K., & Tripathy, S. K. (2022). Advances in nitrogen-based dye removal technologies by biochar. In *Synergistic Approaches for Bioremediation of Environmental Pollutants: Recent Advances and Challenges* (pp. 101-121). Academic Press.

[6] Singha, K., Pandit, P., Maity, S., & Sharma, S. R. (2021). Harmful environmental effects for textile chemical dyeing practice. In *Green Chemistry for Sustainable Textiles* (pp. 153-164). Woodhead Publishing.

[7] Oladoye, P. O., Bamigboye, M. O., Ogunbiyi, O. D., & Akano, M. T. (2022). Toxicity and decontamination strategies of Congo red dye. *Groundwater for Sustainable Development*, *19*, 100844.

[8] Alderete, B. L., da Silva, J., Godoi, R., da Silva, F. R., Taffarel, S. R., da Silva, L. P., ... & Picada, J. N. (2021). Evaluation of toxicity and mutagenicity of a synthetic effluent containing azo dye after advanced oxidation process treatment. *Chemosphere*, *263*, 128291.

[9] Hashemi, S. H., & Kaykhaii, M. (2022). Azo dyes: sources, occurrence, toxicity, sampling, analysis, and their removal methods. In *Emerging freshwater pollutants* (pp. 267-287). Elsevier.

[10] Khan, W. U., Ahmed, S., Dhoble, Y., & Madhav, S. (2023). A critical review of hazardous waste generation from textile industries and associated ecological impacts. *Journal of the Indian Chemical Society*, *100*(1), 100829.

[11] Roy, M., & Saha, R. (2021). Dyes and their removal technologies from wastewater: A critical review. *Intelligent environmental data monitoring for pollution management*, 127-160.

[12] Intisar, A., Ramzan, A., Hafeez, S., Hussain, N., Irfan, M., Shakeel, N., ... & Jesionowski, T. (2023). Adsorptive and photocatalytic degradation potential of porous polymeric materials for removal of pesticides, pharmaceuticals, and dyes-based emerging contaminants from water. *Chemosphere*, 139203.

[13] Khan, W. U., Ahmed, S., Dhoble, Y., & Madhav, S. (2023). A critical review of hazardous waste generation from textile industries and associated ecological impacts. *Journal of the Indian Chemical Society*, *100*(1), 100829.

[14] Roy, M., & Saha, R. (2021). Dyes and their removal technologies from wastewater: A critical review. *Intelligent environmental data monitoring for pollution management*, 127-160.

[15] Haridevamuthu, B., Murugan, R., Seenivasan, B., Meenatchi, R., Pachaiappan, R., Almutairi, B. O., ... & Arockiaraj, J. (2024). Synthetic azo-dye, Tartrazine induces neurodevelopmental toxicity via mitochondria-mediated apoptosis in zebrafish embryos. *Journal of Hazardous Materials*, *461*, 132524.

[16] Duarte, B., Gameiro, C., Matos, A. R., Figueiredo, A., Silva, M. S., Cordeiro, C., ... & Cabrita, M. T. (2021). First screening of biocides, persistent organic pollutants, pharmaceutical and personal care products in Antarctic phytoplankton from Deception Island by FT-ICR-MS. *Chemosphere*, *274*, 129860.

[17] Li, S., Wu, Y., Zheng, H., Li, H., Zheng, Y., Nan, J., ... & Chang, J. S. (2023). Antibiotics degradation by advanced oxidation process (AOPs): Recent advances in ecotoxicity and antibiotic-resistance genes induction of degradation products. *Chemosphere*, *311*, 136977.

[18] Wu, X., Zhang, J., Hu, S., Zhang, G., Lan, H., Peng, J., & Liu, H. (2022). Evaluation of degradation performance toward antiviral drug ribavirin using advanced oxidation process and its relations to ecotoxicity evolution. *Science of The Total Environment*, *850*, 157851.

[19] Nguyen, M. K., Lin, C., Nguyen, H. L., Hung, N. T. Q., La, D. D., Nguyen, X. H., ... & Nguyen, D. D. (2023). Occurrence, fate, and potential risk of pharmaceutical pollutants in agriculture: Challenges and environmentally friendly solutions. *Science of The Total Environment*, *899*, 165323.

[20] Zafar, S., Bukhari, D. A., & Rehman, A. (2022). Azo dyes degradation by microorganisms-An efficient and sustainable approach. *Saudi Journal of Biological Sciences*, 103437.

[21] Oladoye, P. O., Bamigboye, M. O., Ogunbiyi, O. D., & Akano, M. T. (2022). Toxicity and decontamination strategies of Congo red dye. *Groundwater for Sustainable Development*, *19*, 100844.

[22] Garg, A., & Chopra, L. (2022). Dye Waste: A significant environmental hazard. *Materials Today: Proceedings*, *48*, 1310-1315.

[23] Kusworo, T. D., Kumoro, A. C., & Utomo, D. P. (2022). Photocatalytic nanohybrid membranes for highly efficient wastewater treatment: A comprehensive review. *Journal of environmental management*, *317*, 115357.

[24] Pathak, D., Sharma, A., Sharma, D. P., & Kumar, V. (2023). A review on electrospun nanofibers for photocatalysis: Upcoming technology for energy and environmental remediation applications. *Applied Surface Science Advances*, *18*, 100471.

[25] Jabbar, Z. H., Graimed, B. H., Okab, A. A., Issa, M. A., Ammar, S. H., Khadim, H. J., & Shafiq, Y. A. (2023). A review study summarizes the main characterization techniques of nano-composite photocatalysts and their applications in photodegradation of organic pollutants. *Environmental Nanotechnology, Monitoring & Management*, *19*, 100765.

[26] Dong, S., Tebbutt, G. T., Millar, R., Grobert, N., & Maciejewska, B. M. (2023). Hierarchical porosity design enables highly recyclable and efficient Au/TiO2 composite fibers for photodegradation of organic pollutants. *Materials & Design*, *234*, 112318.

[27] Abidin, Z. Z., Pudza, M. Y., Issa, M. A., Zentou, H., Harun, N. H., & Halim, N. A. A. (2023). Sustainable applications of carbon dots-based composites as photocatalyst for environmental pollutants remediation. In *Novel Materials for Environmental Remediation Applications* (pp. 555-577). Elsevier.

[28] Majeed, Y., Khan, M. U., Waseem, M., Zahid, U., Mahmood, F., Majeed, F., ... & Raza, A. (2023). Renewable energy as an alternative source for energy management in agriculture. *Energy Reports*, *10*, 344-359.

[29] Yatish, K. V., Omkaresh, B. R., Kattimani, V. R., Lalithamba, H. S., Sakar, M., & Balakrishna, R. G. (2023). Solar energy-assisted reactor for the sustainable biodiesel production from Butea monosperma oil: Optimization, kinetic, thermodynamic and assessment studies. *Energy*, *263*, 125768.

[30] Intisar, A., Ramzan, A., Hafeez, S., Hussain, N., Irfan, M., Shakeel, N., ... & Jesionowski, T. (2023). Adsorptive and photocatalytic degradation potential of porous polymeric materials for removal of pesticides, pharmaceuticals, and dyes-based emerging contaminants from water. *Chemosphere*, 139203.

[31] Renita, A. A., Sathish, S., Kumar, P. S., Prabu, D., Manikandan, N., Iqbal, A. M., ... & Rangasamy, G. (2023). Emerging aspects of metal ions-doped zinc oxide photocatalysts in degradation of organic dyes and pharmaceutical pollutants–A review. *Journal of Environmental Management*, *344*, 118614.

[32] Alahmadi, N. (2022). Recent progress in photocatalytic removal of environmental pollution hazards in water using nanostructured materials. *Separations*, *9*(10), 264.

[33] Guo, W., Guo, T., Zhang, Y., Yin, L., & Dai, Y. (2023). Progress on simultaneous photocatalytic degradation of pollutants and production of clean energy: A review. *Chemosphere*, 139486.

[34] Bui, T. S., Nguyen, H. T., Hoang, T. T., Rahman, G., Van Le, Q., & Nguyen, D. L. T. (2021). Solar-driven conversion of carbon dioxide over nanostructured metal-based catalysts in alternative approaches: fundamental mechanisms and recent progress. *Environmental Research*, *202*, 111781.

[35] Fang, J., Wang, D., Xu, H., Sun, F., Fan, Y., Chen, R., & Liu, Q. (2024). Unleashing solar energy's full potential: Synergetic thermo-photo catalysis for enhanced hydrogen production with metal-free carbon nitrides. *Energy Conversion and Management*, *300*, 117995.

[36] Xie, B., Lovell, E., Tan, T. H., Jantarang, S., Yu, M., Scott, J., & Amal, R. (2021). Emerging material engineering strategies for amplifying photothermal heterogeneous CO2 catalysis. *Journal of Energy Chemistry*, *59*, 108-125.

[37] Thanigaivel, S., Priya, A. K., Gnanasekaran, L., Hoang, T. K., Rajendran, S., & Soto-Moscoso, M. (2022). Sustainable applicability and environmental impact of wastewater treatment by emerging nanobiotechnological approach: Future strategy for efficient removal of contaminants and water purification. *Sustainable Energy Technologies and Assessments*, *53*, 102484.

[38] Mishra, R. K., Mentha, S. S., Misra, Y., & Dwivedi, N. (2023). Emerging pollutants of severe environmental concern in water and wastewater: A comprehensive review on current developments and future research. *Water-Energy Nexus*.

[39] Kaur, R., Bhardwaj, S. K., Chandna, S., Kim, K. H., & Bhaumik, J. (2021). Lignin-based metal oxide nanocomposites for UV protection applications: A review. *Journal of Cleaner Production*, *317*, 128300.

[40] Ahmed, S. F., Mofijur, M., Nuzhat, S., Chowdhury, A. T., Rafa, N., Uddin, M. A., ... & Show, P. L. (2021). Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater. *Journal of hazardous materials*, *416*, 125912.

[41] Nagasundari, S. M., Muthu, K., Kaviyarasu, K., Al Farraj, D. A., & Alkufeidy, R. M. (2021). Current trends of Silver doped Zinc oxide nanowires photocatalytic degradation for energy and environmental application. *Surfaces and Interfaces*, *23*, 100931.

[42] Ali, J., Bibi, S., Jatoi, W. B., Tuzen, M., Jakhrani, M. A., Feng, X., & Saleh, T. A. (2023). Green synthesized zinc oxide nanostructures and their applications in dye-sensitized solar cells and photocatalysis: A review. *Materials Today Communications*, 106840.

[43] Shubha, J. P., Kavalli, K., Adil, S. F., Assal, M. E., Hatshan, M. R., & Dubasi, N. (2022). Facile green synthesis of semiconductive ZnO nanoparticles for photocatalytic degradation of dyes from the textile industry: A kinetic approach. *Journal of king saud university-science*, *34*(5), 102047.

[44] Backer, S. N., Oussadou, S. E., Almanassra, I. W., Mousa, M. K., Atieh, M. A., & Shanableh, A. (2023). Effect of energy band alignments in carbon doped ZnO/TiO2 hybrid heterojunction photocatalyst on the photodegradation of ofloxacin. *Results in Engineering*, *20*, 101432.

[45] Rani, M., & Shanker, U. (2024). Highly efficient sunlight-driven photo-adsorptive degradation of organic pollutants by green synthesized Z-scheme heterojunction CeO 2@ ZnO nanocomposite. *Environmental Science: Nano*.

[46] Villegas-Fuentes, A., Rosillo-de la Torre, A., Vilchis-Nestor, A. R., & Luque, P. A. (2023). Improvement of the optical, photocatalytic and antibacterial properties of ZnO semiconductor nanoparticles using different pepper aqueous extracts. *Chemosphere*, *339*, 139577.

[47] Shen, J. H., Chiang, T. H., Tsai, C. K., Jiang, Z. W., & Horng, J. J. (2022). Mechanistic insights into hydroxyl radical formation of Cu-doped ZnO/g-C3N4 composite photocatalysis for enhanced degradation of ciprofloxacin under visible light: Efficiency, kinetics, products identification and toxicity evaluation. *Journal of Environmental Chemical Engineering*, *10*(2), 107352.

[48] Renita, A. A., Sathish, S., Kumar, P. S., Prabu, D., Manikandan, N., Iqbal, A. M., ... & Rangasamy, G. (2023). Emerging aspects of metal ions-doped zinc oxide photocatalysts in degradation of organic dyes and pharmaceutical pollutants–A review. *Journal of Environmental Management*, *344*, 118614.

[49] Hayati, F., Moradi, S., Saei, S. F., Madani, Z., Giannakis, S., Isari, A. A., & Kakavandi, B. (2022). A novel, Z-scheme ZnO@ AC@ FeO photocatalyst, suitable for the intensification of photo-mediated peroxymonosulfate activation: performance, reactivity and bisphenol A degradation pathways. *Journal of Environmental Management*, *321*, 115851.

[50] Al-Hasani, H., Al-Sabahi, J., Al-Ghafri, B., Al-Hajri, R., & Al-Abri, M. (2022). Effect of water quality in photocatalytic degradation of phenol using zinc oxide nanorods under visible light irradiation. *Journal of Water Process Engineering*, *49*, 103121.

[51] Khan, Z. U. H., Gul, N. S., Sabahat, S., Sun, J., Tahir, K., Shah, N. S., ... & Wu, J. (2023). Removal of organic pollutants through hydroxyl radical-based advanced oxidation processes. *Ecotoxicology and Environmental Safety*, *267*, 115564.

[52] Ricardo, I. A., Alberto, E. A., Júnior, A. H. S., Macuvele, D. L. P., Padoin, N., Soares, C., ... & Trovo, A. G. (2021). A critical review on microplastics, interaction with organic and inorganic pollutants, impacts and effectiveness of advanced oxidation processes applied for their removal from aqueous matrices. *Chemical Engineering Journal*, *424*, 130282.

[53] Mohammadi, S. A., Najafi, H., Zolgharnian, S., Sharifian, S., & Asasian-Kolur, N. (2022). Biological oxidation methods for the removal of organic and inorganic contaminants from wastewater: A comprehensive review. *Science of The Total Environment*, *843*, 157026.

[54] Liu, G., Zhao, T., Fei, H., Li, F., Guo, W., Yao, Z., & Feng, Z. (2023). A review of various self-cleaning surfaces, durability and functional applications on building exteriors. *Construction and Building Materials*, *409*, 134084.

[55] Lawrynowicz, A., Palo, E., Nizamov, R., & Miettunen, K. (2024). Self-cleaning and UV-blocking cotton–Fabricating effective ZnO structures for photocatalysis. *Journal of Photochemistry and Photobiology A: Chemistry*, *450*, 115420.

[56] Wang, T., Lu, Z., Wang, X., Zhang, Z., Zhang, Q., Yan, B., & Wang, Y. (2021). A compound of ZnO/PDMS with photocatalytic, self-cleaning and antibacterial properties prepared via two-step method. *Applied Surface Science*, *550*, 149286.

[57] Ali, J., Bibi, S., Jatoi, W. B., Tuzen, M., Jakhrani, M. A., Feng, X., & Saleh, T. A. (2023). Green synthesized zinc oxide nanostructures and their applications in dye-sensitized solar cells and photocatalysis: A review. *Materials Today Communications*, 106840.

[58] Panchal, P., Sharma, R., Reddy, A. S., Nehra, K., Sharma, A., & Nehra, S. P. (2023). Eco-friendly synthesis of Ag-doped ZnO/MgO as a potential photocatalyst for antimicrobial and dye degradation applications. *Coordination Chemistry Reviews*, *493*, 215283.

[59] Abdullah, F. H., Bakar, N. A., & Bakar, M. A. (2022). Current advancements on the fabrication, modification, and industrial application of zinc oxide as photocatalyst in the removal of organic and inorganic contaminants in aquatic systems. *Journal of hazardous materials*, *424*, 127416.

[60] Gonbadi, M., Sabbaghi, S., Rasouli, J., Rasouli, K., Saboori, R., & Narimani, M. (2023). Green synthesis of ZnO nanoparticles for spent caustic recovery: Adsorbent characterization and process optimization using I-optimal method. *Inorganic Chemistry Communications*, *158*, 111460.

[61] Ahmed, S. F., Mofijur, M., Nuzhat, S., Chowdhury, A. T., Rafa, N., Uddin, M. A., ... & Show, P. L. (2021). Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater. *Journal of hazardous materials*, *416*, 125912.

[62] Chen, Z., Liu, Y., Yu, W., He, Q., Ni, M., Yang, S., ... & Tan, P. (2021). Cost evaluation and sensitivity analysis of the alkaline zinc-iron flow battery system for large-scale energy storage applications. *Journal of Energy Storage*, *44*, 103327.

[63] Mathew, S., Madhushree, R., KR, S. D., Pinheiro, D., Manickam, S., Pang, C. H., & Sonawane, S. H. (2023). Synthesis, mechanisms, challenges, and future prospects of Ti3C2 MXene and its heterojunctions for photocatalytic dye degradation efficiency: A comprehensive review. *Materials Today Sustainability*, 100568.

[64] Pathak, D., Sharma, A., Sharma, D. P., & Kumar, V. (2023). A review on electrospun nanofibers for photocatalysis: Upcoming technology for energy and environmental remediation applications. *Applied Surface Science Advances*, *18*, 100471.

[65] Srivastava, R. R., Kumar Vishwakarma, P., Yadav, U., Rai, S., Umrao, S., Giri, R., ... & Srivastava, A. (2021). 2D SnS2 nanostructure-derived photocatalytic degradation of organic pollutants under visible light. *Frontiers in Nanotechnology*, *3*, 711368.

[66] Gaur, J., Kumar, S., Pal, M., Kaur, H., Batoo, K. M., & Momoh, J. O. (2023). Current trends: Zinc oxide nanoparticles preparation via chemical and green method for the photocatalytic degradation of various organic dyes. *Hybrid Advances*, 100128.

[67] Oladoye, P. O., Kadhom, M., Khan, I., Aziz, K. H. H., & Alli, Y. A. (2023). Advancements in adsorption and photodegradation technologies for rhodamine B dye wastewater treatment: Fundamentals, applications, and future directions. *Green Chemical Engineering*.

[68] Zhang, X., Kamali, M., Zhang, S., Yu, X., Appels, L., Cabooter, D., & Dewil, R. (2022). Photo-assisted (waste) water treatment technologies—A scientometric-based critical review. *Desalination*, *538*, 115905.

[69] Norbert, A., Shaji, S., & Philip, R. R. (2023). Electrochemically anodized solid and stable ZnO nanorods as an adsorbent/nanophotocatalyst: ROS mediated degradation of azo dyes congo red and methyl orange. *Journal of Cleaner Production*, *428*, 139466.

[70] Waghchaure, R. H., Adole, V. A., & Jagdale, B. S. (2022). Photocatalytic degradation of methylene blue, rhodamine B, methyl orange and Eriochrome black T dyes by modified ZnO nanocatalysts: A concise review. *Inorganic Chemistry Communications*, 109764.

[71] Nguyen, D. T. C., Le, H. T., Nguyen, T. T., Nguyen, T. T. T., Bach, L. G., Nguyen, T. D., & Van Tran, T. (2021). Multifunctional ZnO nanoparticles bio-fabricated from Canna indica L. flowers for seed germination, adsorption, and photocatalytic degradation of organic dyes. *Journal of Hazardous Materials*, *420*, 126586.

[72] Ishfaq, M., Hassan, W., Sabir, M., Somaily, H. H., Hachim, S. K., Kadhim, Z. J., ... & Aadil, M. (2022). Wet-chemical synthesis of ZnO/CdO/CeO2 heterostructure: a novel material for environmental remediation application. *Ceramics International*, *48*(23), 34590-34601.

[73] Massima Mouele, E. S., Tijani, J. O., Badmus, K. O., Pereao, O., Babajide, O., Zhang, C., ... & Petrik, L. F. (2021). Removal of pharmaceutical residues from water and wastewater using dielectric barrier discharge methods—A review. *International Journal of Environmental Research and Public Health*, *18*(4), 1683.
[74] Tijani, J. O. (2021). Removal of Pharmaceutical Residues from Water and Wastewater Using Dielectric Barrier Discharge Methods—A Review.

[75] Gnanasekaran, L., Priya, A. K., Ghfar, A. A., Sekar, K., Santhamoorthy, M., Arthi, M., & Soto-Moscoso, M. (2022). The influence of heterostructured TiO2/ZnO nanomaterials for the removal of azo dye pollutant. *Chemosphere*, *308*, 136161.

[76] Dihom, H. R., Al-Shaibani, M. M., Mohamed, R. M. S. R., Al-Gheethi, A. A., Sharma, A., & Khamidun, M. H. B. (2022). Photocatalytic degradation of disperse azo dyes in textile wastewater using green zinc oxide nanoparticles synthesized in plant extract: A critical review. *Journal of Water Process Engineering*, *47*, 102705.

[77] Karimi, F., Zare, N., Jahanshahi, R., Arabpoor, Z., Ayati, A., Krivoshapkin, P., ... & Karimi-Maleh, H. (2023). Natural waste-derived nano photocatalysts for azo dye degradation. *Environmental Research*, 117202.

[78] Wazir, W., Ahmad, Z., Zulfiqar, S., Cochran, E. W., Mubarik, S., Kousar, T., ... & Aadil, M. (2023). Synergistic effects of noble metal doping and nanoengineering on boosting the azo dye mineralization activity of nickel oxide. *Ceramics International*, *49*(23), 38026-38035.

[79] Song, B., Yang, H., Wang, W., Yang, Y., Qin, M., Li, F., & Zhou, C. (2023). Disinfection byproducts formed from oxidation of pesticide micropollutants in water: Precursor sources, reaction kinetics, formation, influencing factors, and toxicity. *Chemical Engineering Journal*, 146310.

[80] Ao, J., Bu, L., Wu, Y., Zhu, S., & Zhou, S. (2023). Insights into the fate and properties of organic halamines during ultraviolet irradiation: Implications for drinking water safety. *Science of The Total Environment*, *904*, 165994.

[81] Rai, P. K. (2022). Novel adsorbents in remediation of hazardous environmental pollutants: Progress, selectivity, and sustainability prospects. *Cleaner Materials*, *3*, 100054.

[82] Othmani, A., Kadier, A., Singh, R., Igwegbe, C. A., Bouzid, M., Aquatar, M. O., ... & Sher, F. (2022). A comprehensive review on green perspectives of electrocoagulation integrated with advanced processes for effective pollutants removal from water environment. *Environmental Research*, *215*, 114294.
[83] Changotra, R., Rajput, H., Liu, B., & Murray, G. (2024). Occurrence, fate, and potential impacts of wood preservatives in the environment: Challenges and environmentally friendly solutions. *Chemosphere*, 141291.

[84] Oladoye, P. O., Kadhom, M., Khan, I., Aziz, K. H. H., & Alli, Y. A. (2023). Advancements in adsorption and photodegradation technologies for rhodamine B dye wastewater treatment: Fundamentals, applications, and future directions. *Green Chemical Engineering*.

[85] Iyyappan, J., Gaddala, B., Gnanasekaran, R., Gopinath, M., Yuvaraj, D., & Kumar, V. (2023). Critical review on wastewater treatment using photo catalytic advanced oxidation process: Role of photocatalytic materials, reactor design and kinetics. *Case Studies in Chemical and Environmental Engineering*, 100599.

[86] Perera, A. A. P. R., Madhushani, K. A. U., Kumar, A., & Gupta, R. K. (2023). Metal-organic frameworks for wastewater treatment: Recent developments, challenges, and future prospects. *Chemosphere*, 139713.

[87] Zhang, X., Kamali, M., Zhang, S., Yu, X., Appels, L., Cabooter, D., & Dewil, R. (2022). Photo-assisted (waste) water treatment technologies—A scientometric-based critical review. *Desalination*, *538*, 115905.

[88] Waghchaure, R. H., Adole, V. A., & Jagdale, B. S. (2022). Photocatalytic degradation of methylene blue, rhodamine B, methyl orange and Eriochrome black T dyes by modified ZnO nanocatalysts: A concise review. *Inorganic Chemistry Communications*, 109764.

[89] Yaman, M., Renkli̇tepe, C., Kaplan, G., Sakalli, Y., Seferoğlu, N., Şahi̇n, E., & Seferoğlu, Z. (2024). D-π-A azo dyes bearing thiazole-diphenylamine units: Synthesis, photophysical and molecular structure properties, and use for dyeing of polyester fabrics. *Dyes and Pigments*, *222*, 111840.

[90] Khanum, R., RA, S. A., Rangaswamy, H. R., Kumar, S. S., Kumar, A. P., & Jagadisha, A. S. (2023). Recent Review on Synthesis, Spectral Studies, Versatile Applications of Azo Dyes and its Metal Complexes. *Results in Chemistry*, 100890.

[91] Mansour, A., Souheyla, C., Youcef, M., Nourdine, B., Amel, D., Roufieda, G. A., ... & Abdelkader, C. (2022). Experimental and theoretical spectroscopic characterization, Hirshfield surface analysis, TD-DFT calculation, and nonlinear optical properties of (E)-1-[(2, 4, 6tribromophenyl) diazenyl]-naphthalen-2-ol azo dye. *Journal of Molecular Structure*, *1261*, 132887.

[92] Jorge, A. M., Athira, K. K., Alves, M. B., Gardas, R. L., & Pereira, J. F. (2023). Textile dyes effluents: A current scenario and the use of aqueous biphasic systems for the recovery of dyes. *Journal of Water Process Engineering*, *55*, 104125.

[93] Hemashenpagam, N., & Selvajeyanthi, S. (2023). Textile Dyes and Their Effect on Human Beings. In *Nanohybrid Materials for Treatment of Textiles Dyes* (pp. 41-60). Singapore: Springer Nature Singapore.

[94] Nachiyar, C. V., Rakshi, A. D., Sandhya, S., Jebasta, N. B. D., & Nellore, J. (2023). Developments in treatment technologies of dye-containing effluent: A review. *Case Studies in Chemical and Environmental Engineering*, 100339.

[95] Nachiyar, C. V., Rakshi, A. D., Sandhya, S., Jebasta, N. B. D., & Nellore, J. (2023). Developments in treatment technologies of dye-containing effluent: A review. *Case Studies in Chemical and Environmental Engineering*, 100339.

[96] Shabir, M., Yasin, M., Hussain, M., Shafiq, I., Akhter, P., Nizami, A. S., ... & Park, Y. K. (2022). A review on recent advances in the treatment of dye-polluted wastewater. *Journal of Industrial and Engineering Chemistry*, *112*, 1-19.

[97] Zafar, S., Bukhari, D. A., & Rehman, A. (2022). Azo dyes degradation by microorganisms-An efficient and sustainable approach. *Saudi Journal of Biological Sciences*, 103437.

[98] Chen, Y., Chen, W. J., Huang, Y., Li, J., Zhong, J., Zhang, W., ... & Chen, S. (2022). Insights into the microbial degradation and resistance mechanisms of glyphosate. *Environmental Research*, *215*, 114153.

[99] Miao, F., Yue, X., Cheng, C., Chen, X., Ren, W., & Zhang, H. (2022). Insights into the mechanism of carbocatalysis for peracetic acid activation: Kinetic discernment and active site identification. *Water Research*, *227*, 119346.

[100] Ren, L., Zong, B., Zhao, R., Sun, Y., Meng, F., & Wang, R. (2022). Insights into the mechanism underlying remediation of Cr (VI) contaminated aquifer using nanoscale zero-valent iron@ reduced graphene oxide. *Environmental Research*, *214*, 113973.

[101] Subhiksha, V., Alatar, A. A., Okla, M. K., Alaraidh, I. A., Mohebaldin, A., Aufy, M., ... & Khan, S. S. (2022). Double Z-Scheme ZnCo2O4/MnO2/FeS2 photocatalyst with enhanced photodegradation of organic compound: Insights into mechanisms, kinetics, pathway and toxicity studies. *Chemosphere*, *303*, 135177.

[102] Chebbi, A., Franzetti, A., Formicola, F., Ambaye, T. G., Gomez, F. H., Murena, B., ... & Vaccari, M. (2022). Insights into rhamnolipid-based soil remediation technologies by safe microorganisms: A critical review. *Journal of Cleaner Production*, 133088.

[103] Zafar, S., Bukhari, D. A., & Rehman, A. (2022). Azo dyes degradation by microorganisms-An efficient and sustainable approach. *Saudi Journal of Biological Sciences*, 103437.

[104] Sudarshan, S., Harikrishnan, S., RathiBhuvaneswari, G., Alamelu, V., Aanand, S., Rajasekar, A., & Govarthanan, M. (2023). Impact of textile dyes on human health and bioremediation of textile industry effluent using microorganisms: current status and future prospects. *Journal of Applied Microbiology*, *134*(2), lxac064.

[105] Hemashenpagam, N., & Selvajeyanthi, S. (2023). Textile Dyes and Their Effect on Human Beings. In *Nanohybrid Materials for Treatment of Textiles Dyes* (pp. 41-60). Singapore: Springer Nature Singapore.

[106] Josephy, P. D., & Allen-Vercoe, E. (2023). Reductive metabolism of azo dyes and drugs: Toxicological implications. *Food and Chemical Toxicology*, 113932.

[107] Zafar, S., Bukhari, D. A., & Rehman, A. (2022). Azo dyes degradation by microorganisms-An efficient and sustainable approach. *Saudi Journal of Biological Sciences*, 103437.

[108] Wu, Y., Arwa, A. H., Farhan, Z. A., Alkhalifah, T., Alturise, F., & Ali, H. E. (2022). Enhanced artificial intelligence for electrochemical sensors in monitoring and removing of azo dyes and food colorant substances. *Food and Chemical Toxicology*, *169*, 113398.

[109] Monisha, B., Sridharan, R., Kumar, P. S., Rangasamy, G., Krishnaswamy, V. G., & Subhashree, S. (2023). Sensing of azo toxic dyes using nanomaterials and its health effects-A review. *Chemosphere*, *313*, 137614.

[110] Keshava, C., Nicolai, S., Vulimiri, S. V., Cruz, F. A., Ghoreishi, N., Knueppel, S., ... & Pirow, R. (2023). Application of systematic evidence mapping to identify available data on the potential human health hazards of selected market-relevant azo dyes. *Environment International*, *176*, 107952.

[111] Hashemi, S. H., & Kaykhaii, M. (2022). Azo dyes: sources, occurrence, toxicity, sampling, analysis, and their removal methods. In *Emerging freshwater pollutants* (pp. 267-287). Elsevier.

[112] Fonacier, L., Frankel, D., & Mawhirt, S. (2022). Contact allergens for the allergist. *Annals of Allergy, Asthma & Immunology*, *128*(6), 629-644.

[113] Singh, K., Byun, C., & Bux, F. (2022). Ecological restoration of degraded ecosystems in India: Science and practices. *Ecological Engineering*, *182*, 106708.

[114] Ismanto, A., Hadibarata, T., Kristanti, R. A., Maslukah, L., Safinatunnajah, N., & Kusumastuti, W. (2022). Endocrine disrupting chemicals (EDCs) in environmental matrices: Occurrence, fate, health impact, physio-chemical and bioremediation technology. *Environmental Pollution*, *302*, 119061.

[115] Khan, W. U., Ahmed, S., Dhoble, Y., & Madhav, S. (2023). A critical review of hazardous waste generation from textile industries and associated ecological impacts. *Journal of the Indian Chemical Society*, *100*(1), 100829.

[116] Dutta, S., Adhikary, S., Bhattacharya, S., Roy, D., Chatterjee, S., Chakraborty, A., ... & Rajak, P. (2024). Contamination of textile dyes in aquatic environment: Adverse impacts on aquatic ecosystem and human health, and its management using bioremediation. *Journal of Environmental Management*, *353*, 120103.

[117] Vasconcelos, M. W., Goncalves, S., de Oliveira, E. C., Rubert, S., & de Castilhos Ghisi, N. (2022). Textile effluent toxicity trend: A scientometric review. *Journal of Cleaner Production*, 132756.

[118] Wibowo, Y. G., Syahnur, M. T., Al-Azizah, P. S., Gintha, D. A., & Lululangi, B. R. G. (2023). Phytoremediation of high concentration of ionic dyes using aquatic plant (Lemna minor): A potential eco-friendly solution for wastewater treatment. *Environmental Nanotechnology, Monitoring & Management*, *20*, 100849.

[119] Rai, P. K. (2022). Novel adsorbents in remediation of hazardous environmental pollutants: Progress, selectivity, and sustainability prospects. *Cleaner Materials*, *3*, 100054.

[120] Narwal, N., Katyal, D., Kataria, N., Rose, P. K., Warkar, S. G., Pugazhendhi, A., ... & Khoo, K. S. (2023). Emerging micropollutants in aquatic ecosystems and nanotechnology-based removal alternatives: a review. *Chemosphere*, 139945.

[121] Alahmadi, N. (2022). Recent progress in photocatalytic removal of environmental pollution hazards in water using nanostructured materials. *Separations*, *9*(10), 264.

[122] Thamarai, P., Kamalesh, R., Saravanan, A., Swaminaathan, P., & Deivayanai, V. C. (2024). Emerging trends and promising prospects in nanotechnology for improved remediation of wastewater contaminants: Present and future outlooks. *Environmental Nanotechnology, Monitoring & Management*, 100913.

[123] Priyadharshini, S. D., Manikandan, S., Kiruthiga, R., Rednam, U., Babu, P. S., Subbaiya, R., ... & Govarthanan, M. (2022). Graphene oxide-based nanomaterials for the treatment of pollutants in the aquatic environment: recent trends and perspectives–a review. *Environmental Pollution*, *306*, 119377.

[124] Babuponnusami, A., Sinha, S., Ashokan, H., Paul, M. V., Hariharan, S. P., Arun, J., ... & Pugazhendhi, A. (2023). Advanced oxidation process (AOP) combined biological process for wastewater treatment: A review on advancements, feasibility and practicability of combined techniques. *Environmental research*, 116944.

[125] Prasad, M. N. V. (2024). Bioremediation, bioeconomy, circular economy, and circular bioeconomy—Strategies for sustainability. In *Bioremediation and Bioeconomy* (pp. 3-32). Elsevier.

[126] Mohan, C., Robinson, J., Vodwal, L., & Kumari, N. (2024). Sustainable Development Goals for addressing environmental challenges. In *Green Chemistry Approaches to Environmental Sustainability* (pp. 357-374). Elsevier.

[127] Joseph, T. M., Al-Hazmi, H. E., Śniatała, B., Esmaeili, A., & Habibzadeh, S. (2023). Nanoparticles and nanofiltration for wastewater treatment: From polluted to fresh water. *Environmental Research*, 117114.
[128] Sultana, R., Dwivedi, A., & Moktadir, M. A. (2023). Investigating the role of consumers, producers, and policymakers: A case of leather supply chain towards sustainable chemistry. *Current Opinion in Green and Sustainable Chemistry*, *39*, 100724.

[129] Castillo-Suárez, L. A., Sierra-Sánchez, A. G., Linares-Hernández, I., Martínez-Miranda, V., & Teutli-Sequeira, E. A. (2023). A critical review of textile industry wastewater: green technologies for the removal of indigo dyes. *International Journal of Environmental Science and Technology*, 1-38.

[130] Hossain, L., Sarker, S. K., & Khan, M. S. (2018). Evaluation of present and future wastewater impacts of textile dyeing industries in Bangladesh. *Environmental Development*, *26*, 23-33.

[131] Maiti, S., Maity, S., Pandit, P., Maulik, S. R., & Singha, K. (2022). Sustainability analysis for knitting process and products. In *Advanced Knitting Technology* (pp. 657-671). Woodhead Publishing.

[132] Chen, X., Cheng, X., Zhang, T., Chen, H. W., & Wang, Y. (2024). Decarbonization practices in the textile supply chain: Towards an integrated conceptual framework. *Journal of Cleaner Production*, *435*, 140452.

[133] Jensen, F., & Whitfield, L. (2022). Leveraging participation in apparel global supply chains through green industrialization strategies: Implications for low-income countries. *Ecological Economics*, *194*, 107331.

[135] Del Rio, D. D. F., Sovacool, B. K., Griffiths, S., Bazilian, M., Kim, J., Foley, A. M., & Rooney, D. (2022). Decarbonizing the pulp and paper industry: A critical and systematic review of sociotechnical developments and policy options. *Renewable and Sustainable Energy Reviews*, *167*, 112706.

[136] Farhana, K., Kadirgama, K., Mahamude, A. S. F., & Mica, M. T. (2022). Energy consumption, environmental impact, and implementation of renewable energy resources in global textile industries: an overview towards circularity and sustainability. *Materials Circular Economy*, *4*(1), 15.

[137] Debnath, B., Siraj, M. T., Rashid, K. H. O., Bari, A. M., Karmaker, C. L., & Al Aziz, R. (2023). Analyzing the critical success factors to implement green supply chain management in the apparel manufacturing industry: Implications for sustainable development goals in the emerging economies. *Sustainable Manufacturing and Service Economics*, *2*, 100013.

[138] Kumar, L., Nadeem, F., Sloan, M., Restle-Steinert, J., Deitch, M. J., Ali Naqvi, S., ... & Sassanelli, C. (2022). Fostering green finance for sustainable development: A focus on textile and leather small medium enterprises in Pakistan. *Sustainability*, *14*(19), 11908.

[139] Thanigaivel, S., Priya, A. K., Gnanasekaran, L., Hoang, T. K., Rajendran, S., & Soto-Moscoso, M. (2022). Sustainable applicability and environmental impact of wastewater treatment by emerging nanobiotechnological approach: Future strategy for efficient removal of contaminants and water purification. *Sustainable Energy Technologies and Assessments*, *53*, 102484.

[140] Othmani, A., Kadier, A., Singh, R., Igwegbe, C. A., Bouzid, M., Aquatar, M. O., ... & Sher, F. (2022). A comprehensive review on green perspectives of electrocoagulation integrated with advanced processes for effective pollutants removal from water environment. *Environmental Research*, *215*, 114294.

[141] Babuponnusami, A., Sinha, S., Ashokan, H., Paul, M. V., Hariharan, S. P., Arun, J., ... & Pugazhendhi, A. (2023). Advanced oxidation process (AOP) combined biological process for wastewater treatment: A review on advancements, feasibility and practicability of combined techniques. *Environmental research*, 116944.

[142] Mishra, V., Mudgal, N., Rawat, D., Poria, P., Mukherjee, P., Sharma, U., ... & Sharma, R. S. (2023). Integrating microalgae into textile wastewater treatment processes: Advancements and opportunities. *Journal of Water Process Engineering*, *55*, 104128.

[143] Singh, A., Pal, D. B., Mohammad, A., Alhazmi, A., Haque, S., Yoon, T., ... & Gupta, V. K. (2022). Biological remediation technologies for dyes and heavy metals in wastewater treatment: New insight. *Bioresource Technology*, *343*, 126154.

[144] Urbina-Suarez, N. A., Angel-Ospina, A. C., Lopez-Barrera, G. L., Barajas-Solano, A. F., & Machuca-Martínez, F. (2024). S-curve and landscape maps for the analysis of trends on industrial textile wastewater treatment. *Environmental Advances*, 100491.

[145] Moreira, N., de Santa-Eulalia, L. A., Aït-Kadi, D., Wood–Harper, T., & Wang, Y. (2015). A conceptual framework to develop green textiles in the aeronautic completion industry: a case study in a large manufacturing company. *Journal of Cleaner Production*, *105*, 371-388.

[146] Birniwa, A. H., Habibu, S., Abdullahi, S. S. A., Mohammad, R. E. A., Hussaini, A., Magaji, H., ... & Jagaba, A. H. (2023). Membrane technologies for heavy metals removal from water and wastewater: A mini review. *Case Studies in Chemical and Environmental Engineering*, 100538.

[147] Joseph, T. M., Al-Hazmi, H. E., Śniatała, B., Esmaeili, A., & Habibzadeh, S. (2023). Nanoparticles and nanofiltration for wastewater treatment: From polluted to fresh water. *Environmental Research*, 117114.

[148] Bui, T. D., Nguyen, T. T. V., Wu, K. J., Lim, M. K., & Tseng, M. L. (2024). Green manufacturing performance improvement under uncertainties: An interrelationship hierarchical model. *International Journal of Production Economics*, *268*, 109117.

[149] Salvador López, H. (2023). *Creating a more sustainable supplu chain for the clothing industry* (Master's thesis, Universitat Politècnica de Catalunya).

[150] Ali, J., Bibi, S., Jatoi, W. B., Tuzen, M., Jakhrani, M. A., Feng, X., & Saleh, T. A. (2023). Green synthesized zinc oxide nanostructures and their applications in dye-sensitized solar cells and photocatalysis: A review. *Materials Today Communications*, 106840.

[151] Teja, A. S., Srivastava, A., Satrughna, J. A. K., Tiwari, M. K., Kanwade, A., Yadav, S. C., & Shirage, P. M. (2023). Optimal processing methodology for futuristic natural dye-sensitized solar cells and novel applications. *Dyes and Pigments*, *210*, 110997.

[152] Abdellah, I. M., Zaky, O. S., & Eletmany, M. R. (2023). Visible light photoredox catalysis for the synthesis of new chromophores as co-sensitizers with benchmark N719 for highly efficient DSSCs. *Optical Materials*, *145*, 114454.

[153] Bhardwaj, K., & Singh, A. K. (2023). Bio-waste and natural resource mediated eco-friendly synthesis of zinc oxide nanoparticles and their photocatalytic application against dyes contaminated water. *Chemical Engineering Journal Advances*, *16*, 100536.

[154] Alahdal, F. A., Qashqoosh, M. T., Manea, Y. K., Salem, M. A., Khan, A. M., & Naqvi, S. (2022). Eco-friendly synthesis of zinc oxide nanoparticles as nanosensor, nanocatalyst and antioxidant agent using leaf extract of P. austroarabica. *OpenNano*, *8*, 100067.

[155] Ali, J., Bibi, S., Jatoi, W. B., Tuzen, M., Jakhrani, M. A., Feng, X., & Saleh, T. A. (2023). Green synthesized zinc oxide nanostructures and their applications in dye-sensitized solar cells and photocatalysis: A review. *Materials Today Communications*, 106840.

[156] Mustafa, S. M., Barzinjy, A. A., & Hamad, A. H. (2023). An environmentally friendly green synthesis of Co2+ and Mn2+ ion doped ZnO nanoparticles to improve solar cell efficiency. *Journal of Environmental Chemical Engineering*, *11*(2), 109514.

[157] Aadil, M., Hassan, W., Somaily, H. H., Ejaz, S. R., Abass, R. R., Jasem, H., ... & Alsafari, I. A. (2022). Synergistic effect of doping and nanotechnology to fabricate highly efficient photocatalyst for environmental remediation. *Journal of Alloys and Compounds*, *920*, 165876.

[158] Noureen, L., Wang, Q., Humayun, M., Shah, W. A., Xu, Q., & Wang, X. (2023). Recent advances in structural engineering of photocatalysts for environmental remediation. *Environmental Research*, *219*, 115084.

[159] Shubha, J. P., Kavalli, K., Adil, S. F., Assal, M. E., Hatshan, M. R., & Dubasi, N. (2022). Facile green synthesis of semiconductive ZnO nanoparticles for photocatalytic degradation of dyes from the textile industry: A kinetic approach. *Journal of king saud university-science*, *34*(5), 102047.

[160] Giannakoudakis, D. A., Qayyum, A., Barczak, M., Colmenares-Quintero, R. F., Borowski, P., Triantafyllidis, K., & Colmenares, J. C. (2023). Mechanistic and kinetic studies of benzyl alcohol photocatalytic oxidation by nanostructured titanium (hydro) oxides: Do we know the entire story?. *Applied Catalysis B: Environmental*, *320*, 121939.

[161] Xie, H., Li, N., Chen, X., Jiang, J., & Zhao, X. (2020). Surface oxygen vacancies promoted photodegradation of benzene on TiO2 film. *Applied Surface Science*, *511*, 145597.

[162] Rajkumar, R., Rajam, J. A., Karpagavinayagam, P., Kavitha, M., & Vedhi, C. (2024). Future sustainability and sensitivity of nanostructured material–based electrochemical biosensors over other technologies. In *Novel Nanostructured Materials for Electrochemical Bio-Sensing Applications* (pp. 575-595). Elsevier.

[163] Ismael, M., Sharma, A., & Kumar, N. (2024). An extensive catalytic potential of sustainable TiO2-based materials fabricated via flame spray pyrolysis: A comprehensive review. *Sustainable Materials and Technologies*, e00826.

[164] Bhandari, S., Roy, A., Mallick, T. K., & Sundaram, S. (2022). Morphology modulated brookite TiO2 and BaSnO3 as alternative electron transport materials for enhanced performance of carbon perovskite solar cells. *Chemical Engineering Journal*, *446*, 137378.

[165] Rajkumar, S., Venkatraman, M. R., Balraju, P., Suguna, K., & Pugazhendhi, A. (2022). Performance of simple green synthesized Ag incorporated TiO2 nanoparticles based photoanodes by doctor-blade coating as working electrodes for dye sensitized solar cells. *Progress in Organic Coatings*, *164*, 106697.

[166] Xie, Z., Xie, L., Qi, F., Liu, H., Meng, L., Wang, J., ... & Lu, C. Z. (2023). Efficient photocatalytic hydrogen production by space separation of photo-generated charges from S-scheme ZnIn2S4/ZnO heterojunction. *Journal of Colloid and Interface Science*, *650*, 784-797.

[167] Yang, M., Wang, Z., Yao, L., & Shi, L. (2023). Construction of 2D/2D Ti3C2/Bi12O17Cl2: Effective charge separation and improved photocatalytic activity. *Materials Research Bulletin*, *159*, 112110.

[168] Jiao, Y., Li, Y., Wang, J., He, Z., & Li, Z. (2022). Edge electron-rich carbon nitride via π-acceptor frame with high-efficient charge separation for photocatalytic hydrogen evolution and environmental remediation. *Journal of Colloid and Interface Science*, *626*, 889-898.

[169] Kuo, H. H., Vo, T. G., & Hsu, Y. J. (2023). From Sunlight to Valuable Molecules: A Journey through Photocatalytic and Photoelectrochemical Glycerol Oxidation towards Valuable Chemical Products. *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, 100649.

[170] Mukherjee, J., Lodh, B. K., Sharma, R., Mahata, N., Shah, M. P., Mandal, S., ... & Bhunia, B. (2023). Advanced oxidation process for the treatment of industrial wastewater: A review on strategies, mechanisms, bottlenecks and prospects. *Chemosphere*, 140473.

[171] Yuvaraja, S., Khandelwal, V., Tang, X., & Li, X. (2023). Wide bandgap semiconductor-based integrated circuits. *Chip*, 100072.

[172] Singh, P. K., Kaur, G. A., Shandilya, M., Rana, P., Rai, R., Mishra, Y. K., ... & Tiwari, A. (2023). Trends in Piezoelectric Nanomaterials towards Green Energy Scavenging Nanodevices. *Materials Today Sustainability*, 100583.

[173] Ali, J., Bibi, S., Jatoi, W. B., Tuzen, M., Jakhrani, M. A., Feng, X., & Saleh, T. A. (2023). Green synthesized zinc oxide nanostructures and their applications in dye-sensitized solar cells and photocatalysis: A review. *Materials Today Communications*, 106840.

[174] Rehman, M. F. U., Zahra, M., Shoukat, W., Reshak, A. H., Ali, D., Raza, A., ... & Ramli, M. M. (2023). Surface modified ZnO nano structures: Electrochemical studies for energy applications and removal of emerging organic pollutant dye by photo induced hetero-catalysis. *Inorganic Chemistry Communications*, *157*, 111276.

[175] Wang, J., Yang, Y., & Xia, Y. (2022). Mesoporous MXene/ZnO nanorod hybrids of high surface area for UV-activated NO2 gas sensing in ppb-level. *Sensors and Actuators B: Chemical*, *353*, 131087.

[176] Gowthaman, N. S. K., Chen, J. W., Dee, C. F., Chai, S. P., & Chang, W. S. (2022). Nanostructural dimension and oxygen vacancy synergistically induced photoactivity across high surface area monodispersed AuNPs/ZnO nanorods heterojunction. *Journal of Alloys and Compounds*, *920*, 165836.

[177] Habibi-Yangjeh, A., Pirhashemi, M., & Ghosh, S. (2020). ZnO/ZnBi2O4 nanocomposites with pn heterojunction as durable visible-light-activated photocatalysts for efficient removal of organic pollutants. *Journal of Alloys and Compounds*, *826*, 154229.

[178] Zhang, J. X., & Zhao, Z. Y. (2023). A comprehensive review on the preparation and applications of delafossite CuAlO2 optoelectronic functional materials. *Materials Science in Semiconductor Processing*, *167*, 107819.

[179] Li, Y., Zhang, X., Huang, H., Kershaw, S. V., & Rogach, A. L. (2020). Advances in metal halide perovskite nanocrystals: Synthetic strategies, growth mechanisms, and optoelectronic applications. *Materials Today*, *32*, 204-221.

[180] Li, Z., Mi, B., Ma, X., Liu, P., Ma, F., Zhang, K., ... & Li, W. (2023). Review of thin-film resistor sensors: Exploring materials, classification, and preparation techniques. *Chemical Engineering Journal*, 147029.

[181] Sohail, M., Anwar, U., Taha, T. A., Qazi, H. I. A., Al-Sehemi, A. G., Ullah, S., ... & Hayat, A. (2022). Nanostructured materials based on g-C3N4 for enhanced photocatalytic activity and potentials application: A review. *Arabian Journal of Chemistry*, *15*(9), 104070.

[182] Anucha, C. B., Altin, I., Bacaksiz, E., & Stathopoulos, V. N. (2022). Titanium dioxide (TiO_2)-based photocatalyst materials activity enhancement for contaminants of emerging concern (CECs) degradation: In the light of modification strategies. *Chemical Engineering Journal Advances*, *10*, 100262.

[183] Rasouli, K., Rasouli, J., Mohtaram, M. S., Sabbaghi, S., Kamyab, H., Moradi, H., & Chelliapan, S. (2023). Biomass-derived activated carbon nanocomposites for cleaner production: a review on aspects of photocatalytic pollutant degradation. *Journal of Cleaner Production*, 138181.

[184] Zedan, M., Zedan, A. F., Amin, R. M., & Li, X. (2022). Visible-light active metal nanoparticles@ carbon nitride for enhanced removal of water organic pollutants. *Journal of Environmental Chemical Engineering*, *10*(3), 107780.

[185] Bilal, M., Rizwan, K., Rahdar, A., Badran, M. F., & Iqbal, H. M. (2022). Graphene-based porous nanohybrid architectures for adsorptive and photocatalytic abatement of volatile organic compounds. *Environmental Pollution*, *309*, 119805.

[186] Xia, G., Lam, Y., Fan, S., Bian, X., Qi, P., Qiao, Z., ... & Xin, J. H. (2024). Recent advances in cotton fabric-based photocatalytic composites for the degradation of organic contaminants. *Carbohydrate Polymers*, 121872.

[187] Anucha, C. B., Altin, I., Bacaksiz, E., & Stathopoulos, V. N. (2022). Titanium dioxide (TiO_2)-based photocatalyst materials activity enhancement for contaminants of emerging concern (CECs) degradation: In the light of modification strategies. *Chemical Engineering Journal Advances*, *10*, 100262.

[188] Gnanasekaran, L., Priya, A. K., Ghfar, A. A., Sekar, K., Santhamoorthy, M., Arthi, M., & Soto-Moscoso, M. (2022). The influence of heterostructured TiO2/ZnO nanomaterials for the removal of azo dye pollutant. *Chemosphere*, *308*, 136161.

[189] Ahmad, A., Ali, M., Al-Sehemi, A. G., Al-Ghamdi, A. A., Park, J. W., Algarni, H., & Anwer, H. (2023). Carbon-integrated semiconductor photocatalysts for removal of volatile organic compounds in indoor environments. *Chemical Engineering Journal*, *452*, 139436.

[190] Jabbar, Z. H., Graimed, B. H., Ammar, S. H., Sabit, D. A., Najim, A. A., Radeef, A. Y., & Taher, A. G. (2024). The latest progress in the design and application of semiconductor photocatalysis systems for degradation of environmental pollutants in wastewater: Mechanism insight and theoretical calculations. *Materials Science in Semiconductor Processing*, *173*, 108153.
[191] Askari, N., Jamalzadeh, M., Askari, A., Liu, N., Samali, B., Sillanpaa, M., ... & Dewil, R. (2024). Unveiling the photocatalytic marvels: Recent advances in solar heterojunctions for environmental remediation and energy harvesting. *Journal of Environmental Sciences*.

[192] Mohtaram, S., Mohtaram, M. S., Sabbaghi, S., You, X., Wu, W., & Golsanami, N. (2024). Enhancement strategies in CO2 conversion and management of biochar supported photocatalyst for effective generation of renewable and sustainable solar energy. *Energy Conversion and Management*, 117987.

[193] Khan, H., & Shah, M. U. H. (2023). Modification Strategies of TiO2 Based Photocatalysts for Enhanced Visible Light Activity and Energy Storage Ability: A Review. *Journal of Environmental Chemical Engineering*, 111532.

[194] Rani, M., Yadav, J., Shanker, U., & Sillanpää, M. (2023). Green synthesized zinc derived nanocomposites with enhanced photocatalytic activity: An updated review on structural modification, scientific assessment and environmental applications. *Inorganic Chemistry Communications*, *147*, 110246.
[195] Bhardwaj, K., & Singh, A. K. (2023). Bio-waste and natural resource mediated eco-friendly synthesis of zinc oxide nanoparticles and their photocatalytic application against dyes contaminated water. *Chemical Engineering Journal Advances*, *16*, 100536.

[196] Noureen, L., Wang, Q., Humayun, M., Shah, W. A., Xu, Q., & Wang, X. (2023). Recent advances in structural engineering of photocatalysts for environmental remediation. *Environmental Research*, *219*, 115084.

[197] Shoeb, M., Ahmad, S., Mashkoor, F., Khan, M. N., Hasan, I., Singh, B. R., & Jeong, C. (2024). Investigating the size-dependent structural, optical, dielectric, and photocatalytic properties of benign-synthesized ZnO nanoparticles. *Journal of Physics and Chemistry of Solids*, *184*, 111707.

[198] Hannachi, E., Slimani, Y., Nawaz, M., Trabelsi, Z., Yasin, G., Bilal, M., ... & Thakur, P. (2022). Synthesis, characterization, and evaluation of the photocatalytic properties of zinc oxide co-doped with lanthanides elements. *Journal of Physics and Chemistry of Solids*, *170*, 110910.

[199] Asjadi, F., & Yaghoobi, M. (2022). Characterization and dye removal capacity of green hydrothermal synthesized ZnO nanoparticles. *Ceramics International*, *48*(18), 27027-27038.

[200] Shubha, J. P., Kavalli, K., Adil, S. F., Assal, M. E., Hatshan, M. R., & Dubasi, N. (2022). Facile green synthesis of semiconductive ZnO nanoparticles for photocatalytic degradation of dyes from the textile industry: A kinetic approach. *Journal of king saud university-science*, *34*(5), 102047.

[201] Yusuff, A. S., Obende, B. A., & Egbosiuba, T. C. (2024). Photocatalytic decolorization of textile effluent over ZnO nanoparticles immobilized on eucalyptus bark biochar: Parametric optimization, kinetic and economic analyses. *Water Resources and Industry*, 100245.

[202] Zhang, Y., Qiu, J., Zhu, B., Fedin, M. V., Cheng, B., Yu, J., & Zhang, L. (2022). ZnO/COF S-scheme heterojunction for improved photocatalytic H2O2 production performance. *Chemical Engineering Journal*, *444*, 136584.

[203] Liu, H., Li, Y., Ma, L., Liu, J., & He, D. (2022). Photo-thermal conversion of CO2 and biomass-based glycerol into glycerol carbonate over Co3O4-ZnO pn heterojunction catalysts. *Fuel*, *315*, 123294.

[204] Raza, A., Altaf, S., Ali, S., Ikram, M., & Li, G. (2022). Recent advances in carbonaceous sustainable nanomaterials for wastewater treatments. *Sustainable Materials and Technologies*, *32*, e00406.

[205] Sharma, P., Bano, A., Singh, S. P., Atkinson, J. D., Lam, S. S., Iqbal, H. M., & Tong, Y. W. (2022). Nanomaterials as highly efficient photocatalysts used for bioenergy and biohydrogen production from waste toward a sustainable environment. *Fuel*, *329*, 125408.

[206] Ajmal, Z., ul Haq, M., Naciri, Y., Djellabi, R., Hassan, N., Zaman, S., ... & Qadeer, A. (2022). Recent advancement in conjugated polymers based photocatalytic technology for air pollutants abatement: Cases of CO2, NOx, and VOCs. *Chemosphere*, *308*, 136358.

[207] Hameed, T. A., Mohamed, F., Abd-El-Messieh, S. L., & Ward, A. A. (2023). Methylammonium lead iodide/poly (methyl methacrylate) nanocomposite films for photocatalytic applications. *Materials Chemistry and Physics*, *293*, 126811.

[208] Fellah, M., Hezil, N., Hamadi, F., Iqbal, A., Samad, M. A., Alburaikan, A., ... & Obrosov, A. (2024). Effect of Fe content on physical, tribological and photocatalytical properties of Ti-6Al-xFe alloys for biomedical applications. *Tribology International*, *191*, 109146.

[209] Wu, Y. H., Wu, T., & Lin, Y. W. (2019). Photoelectrocatalytic degradation of methylene blue on cadmium sulfide–sensitized titanium dioxide film. *Materials Research Bulletin*, *118*, 110500.

[210] Yavuz, C., & Ela, S. E. (2023). Fabrication of g-C3N4-reinforced CdS nanosphere-decorated TiO2 nanotablet composite material for photocatalytic hydrogen production and dye-sensitized solar cell application. *Journal of Alloys and Compounds*, *936*, 168209.

[211] Yu, Z., Qian, L., Zhong, T., Ran, Q., Huang, J., Hou, Y., ... & Zhang, H. (2020). Enhanced visible light photocatalytic activity of CdS through controllable self-assembly compositing with ZIF-67. *Molecular Catalysis*, *485*, 110797.

[212] Hameed, T. A., Mohamed, F., Abd-El-Messieh, S. L., & Ward, A. A. (2023). Methylammonium lead iodide/poly (methyl methacrylate) nanocomposite films for photocatalytic applications. *Materials Chemistry and Physics*, *293*, 126811.

[213] Fellah, M., Hezil, N., Hamadi, F., Iqbal, A., Samad, M. A., Alburaikan, A., ... & Obrosov, A. (2024). Effect of Fe content on physical, tribological and photocatalytical properties of Ti-6Al-xFe alloys for biomedical applications. *Tribology International*, *191*, 109146.

[214] Alaskar, A., Mahmood, M. S., Zaid, O., Althoey, F., & Arbili, M. M. (2023). Systematic review on geopolymer composites modified with nanomaterials and thin films: Enhancing performance and sustainability in construction. *Construction and Building Materials*, *409*, 133888.

[215] Drabczyk, A., Kudłacik-Kramarczyk, S., Korniejenko, K., Figiela, B., & Furtos, G. (2023). Review of Geopolymer Nanocomposites: Novel Materials for Sustainable Development. *Materials*, *16*(9), 3478.

[216] Butt, A. N., & Dimitrijević, B. (2022). Multidisciplinary and transdisciplinary collaboration in nature-based design of sustainable architecture and urbanism. *Sustainability*, *14*(16), 10339.

[217] Le, A. T., Le, T. D. H., Cheong, K. Y., & Pung, S. Y. (2022). Immobilization of zinc oxide-based photocatalysts for organic pollutant degradation: A review. *Journal of Environmental Chemical Engineering*, *10*(5), 108505.

[218] An, H., Dat, N. M., Hai, N. D., Cong, C. Q., Nam, N. T. H., Thi, D. N. M., ... & Hieu, N. H. (2023). Photocatalytic degradation of organic dyes using zinc oxide-decorated graphitic carbon nitride composite under visible light. *Diamond and Related Materials*, *131*, 109583.

[219] Al-Zahrani, S. A., Khedr, A. M., Alturki, A. M., & El-Yazeed, W. S. A. (2024). Integration of 2D graphene oxide/zinc oxide nanohybrid for enhancement adsorption and photodegradation of organic pollutants. *Journal of Molecular Liquids*, *395*, 123956.

[220] Peechmani, P., Makhtar, S. N. N. M., Mansur, S., Othman, M. H. D., Kamaludin, R., Puteh, M. H., ... & Ismail, A. F. (2024). Uncovering the potential of yttrium doped zinc oxide nanoparticles as an efficient catalyst for photodegradation of recalcitrant pollutant and a contributor antibacterial property. *Journal of Water Process Engineering*, *58*, 104706.

[221] Bharathi, K., Sathiyamoorthy, K., Bakiyaraj, G., Archana, J., & Navaneethan, M. (2023). 2D V2O5 nanoflakes on 2D p-gC3N4 nanosheets of heterostructure photocatalysts with the enhanced photocatalytic activity of organic pollutants under direct sunlight. *Surfaces and Interfaces*, *41*, 103219.

[222] Bilal, M., Rizwan, K., Rahdar, A., Badran, M. F., & Iqbal, H. M. (2022). Graphene-based porous nanohybrid architectures for adsorptive and photocatalytic abatement of volatile organic compounds. *Environmental Pollution*, *309*, 119805.

[223] Dong, S., Gong, Y., Zeng, Z., Chen, S., Ye, J., Wang, Z., & Dionysiou, D. D. (2023). Dissolved organic matter promotes photocatalytic degradation of refractory organic pollutants in water by forming hydrogen bonding with photocatalyst. *Water Research*, *242*, 120297.

[224] Liu, C., Mao, S., Wang, H., Wu, Y., Wang, F., Xia, M., & Chen, Q. (2022). Peroxymonosulfate-assisted for facilitating photocatalytic degradation performance of 2D/2D WO3/BiOBr S-scheme heterojunction. *Chemical Engineering Journal*, *430*, 132806.

[225] Ahmadi, Y., & Kim, K. H. (2024). Modification strategies for visible-light photocatalysts and their performance-enhancing effects on photocatalytic degradation of volatile organic compounds. *Renewable and Sustainable Energy Reviews*, *189*, 113948.

[226] Ahmad, I., Zou, Y., Yan, J., Liu, Y., Shukrullah, S., Naz, M. Y., ... & Khalid, N. R. (2023). Semiconductor photocatalysts: A critical review highlighting the various strategies to boost the photocatalytic performances for diverse applications. *Advances in Colloid and Interface Science*, *311*, 102830.

[227] Aadil, M., Hassan, W., Somaily, H. H., Ejaz, S. R., Abass, R. R., Jasem, H., ... & Alsafari, I. A. (2022). Synergistic effect of doping and nanotechnology to fabricate highly efficient photocatalyst for environmental remediation. *Journal of Alloys and Compounds*, *920*, 165876.

[228] Noureen, L., Wang, Q., Humayun, M., Shah, W. A., Xu, Q., & Wang, X. (2023). Recent advances in structural engineering of photocatalysts for environmental remediation. *Environmental Research*, *219*, 115084.

[229] Umejuru, E. C., Mashifana, T., Kandjou, V., Amani-Beni, M., Sadeghifar, H., Fayazi, M., ... & Sithole, N. T. (2023). Application of zeolite based nanocomposites for wastewater remediation: Evaluating newer and environmentally benign approaches. *Environmental research*, *231*, 116073.

[230] Askari, N., Jamalzadeh, M., Askari, A., Liu, N., Samali, B., Sillanpaa, M., ... & Dewil, R. (2024). Unveiling the photocatalytic marvels: Recent advances in solar heterojunctions for environmental remediation and energy harvesting. *Journal of Environmental Sciences*.

[231] Srinet, G., Sharma, S., Kumar, M., & Anshul, A. (2021). Structural and optical properties of Mg modified ZnO nanoparticles: An x-ray peak broadening analysis. *Physica E: Low-dimensional Systems and Nanostructures*, *125*, 114381.

[232] Rad, S. S., Sani, A. M., & Mohseni, S. (2019). Biosynthesis, characterization and antimicrobial activities of zinc oxide nanoparticles from leaf extract of Mentha pulegium (L.). *Microbial pathogenesis*, *131*, 239-245.

[233] Fischer, D., Zagorac, D., & Schön, J. C. (2023). Fundamental insight into the formation of the zinc oxide crystal structure. *Thin Solid Films*, *782*, 140017.

[234] Samar, S., Kumar, A., & Kumar, P. (2024). Green synthesis of ZnO nano-crystals using Chenopodium album L. Leaf extract, their characterizations and antibacterial activities. *Materials Science and Engineering: B*, *299*, 117005.

[235] Byzynski, G., Melo, C., Volanti, D. P., Ferrer, M. M., Gouveia, A. F., Ribeiro, C., ... & Longo, E. (2017). The interplay between morphology and photocatalytic activity in ZnO and N-doped ZnO crystals. *Materials & Design*, *120*, 363-375.

[236] Yang, T., Oliver, S., Chen, Y., Boyer, C., & Chandrawati, R. (2019). Tuning crystallization and morphology of zinc oxide with polyvinylpyrrolidone: Formation mechanisms and antimicrobial activity. *Journal of colloid and interface science*, *546*, 43-52.

[237] Harish, V., Ansari, M. M., Tewari, D., Yadav, A. B., Sharma, N., Bawarig, S., ... & Barhoum, A. (2023). Cutting-edge advances in tailoring size, shape, and functionality of nanoparticles and nanostructures: A review. *Journal of the Taiwan Institute of Chemical Engineers*, *149*, 105010.

[238] Sharma, D. K., Shukla, S., Sharma, K. K., & Kumar, V. (2022). A review on ZnO: Fundamental properties and applications. *Materials Today: Proceedings*, *49*, 3028-3035.

[239] Baghini, Z. K., Mostafaei, A., & Abbasnejad, M. (2022). Y2CF2 and Lu2CF2 MXenes under applied strain: Electronic, optical, and photocatalytic properties. *Journal of Alloys and Compounds*, *922*, 166198.

[240] Tareq, S., Almayyali, A. O. M., & Jappor, H. R. (2022). Prediction of two-dimensional AlBrSe monolayer as a highly efficient photocatalytic for water splitting. *Surfaces and Interfaces*, *31*, 102020.

[241] Vinayagam, V., Palani, K. N., Ganesh, S., Rajesh, S., Akula, V. V., Avoodaiappan, R., ... & Pugazhendhi, A. (2023). Recent developments on advanced oxidation processes for degradation of pollutants from wastewater with focus on antibiotics and organic dyes. *Environmental Research*, 117500.

[242] Shabir, M., Yasin, M., Hussain, M., Shafiq, I., Akhter, P., Nizami, A. S., ... & Park, Y. K. (2022). A review on recent advances in the treatment of dye-polluted wastewater. *Journal of Industrial and Engineering Chemistry*, *112*, 1-19.
[243] Lee, D. E., Kim, M. K., Danish, M., & Jo, W. K. (2023). State-of-the-art review on photocatalysis for efficient wastewater treatment: Attractive approach in photocatalyst design and parameters affecting the photocatalytic degradation. *Catalysis Communications*, 106764.

[244] Shabir, M., Yasin, M., Hussain, M., Shafiq, I., Akhter, P., Nizami, A. S., ... & Park, Y. K. (2022). A review on recent advances in the treatment of dye-polluted wastewater. *Journal of Industrial and Engineering Chemistry*, *112*, 1-19.

[245] Oladoye, P. O., Bamigboye, M. O., Ogunbiyi, O. D., & Akano, M. T. (2022). Toxicity and decontamination strategies of Congo red dye. *Groundwater for Sustainable Development*, *19*, 100844.

[246] Jorge, A. M., Athira, K. K., Alves, M. B., Gardas, R. L., & Pereira, J. F. (2023). Textile dyes effluents: A current scenario and the use of aqueous biphasic systems for the recovery of dyes. *Journal of Water Process Engineering*, *55*, 104125.

[247] Samarasinghe, L. V., Muthukumaran, S., & Baskaran, K. (2023). Recent advances in visible light-activated photocatalysts for degradation of dyes: A comprehensive review. *Chemosphere*, 140818.
[248] Robinson, T., McMullan, G., Marchant, R., & Nigam, P. (2001). Remediation of dyes in textile effluent: a critical review on current treatment technologies with a proposed alternative. *Bioresource technology*, *77*(3), 247-255.

[249] Singh, A. L., Chaudhary, S., Kumar, S., Kumar, A., Singh, A., & Yadav, A. (2022). Biodegradation of Reactive Yellow-145 azo dye using bacterial consortium: A deterministic analysis based on degradable Metabolite, phytotoxicity and genotoxicity study. *Chemosphere*, *300*, 134504.

[250] Priyadharsini, P., SundarRajan, P., Pavithra, K. G., Naveen, S., SanjayKumar, S., Gnanaprakash, D., ... & Pugazhendhi, A. (2023). Nanohybrid photocatalysts in dye (Colorants) wastewater treatment: Recent trends in simultaneous dye degradation, hydrogen production, storage and transport feasibility. *Journal of Cleaner Production*, 139180.

[251] Sudarshan, S., Harikrishnan, S., RathiBhuvaneswari, G., Alamelu, V., Aanand, S., Rajasekar, A., & Govarthanan, M. (2023). Impact of textile dyes on human health and bioremediation of textile industry effluent using microorganisms: current status and future prospects. *Journal of Applied Microbiology*, *134*(2), lxac064.

[252] Kumar, N., Pandey, A., & Sharma, Y. C. (2023). A review on sustainable mesoporous activated carbon as adsorbent for efficient removal of hazardous dyes from industrial wastewater. *Journal of Water Process Engineering*, *54*, 104054.

[253] Roy, S., Darabdhara, J., & Ahmaruzzaman, M. (2023). Recent advances of Copper-BTC metal-organic frameworks for efficient degradation of organic dye-polluted wastewater: Synthesis, Mechanistic Insights and Future Outlook. *Journal of Hazardous Materials Letters*, 100094.

[254] Babuponnusami, A., Sinha, S., Ashokan, H., Paul, M. V., Hariharan, S. P., Arun, J., ... & Pugazhendhi, A. (2023). Advanced oxidation process (AOP) combined biological process for wastewater

treatment: A review on advancements, feasibility and practicability of combined techniques. *Environmental research*, 116944.

[255] Saravanan, A., Deivayanai, V. C., Kumar, P. S., Rangasamy, G., Hemavathy, R. V., Harshana, T., ... & Alagumalai, K. (2022). A detailed review on advanced oxidation process in treatment of wastewater: Mechanism, challenges and future outlook. *Chemosphere*, *308*, 136524.

[256] Vinayagam, V., Palani, K. N., Ganesh, S., Rajesh, S., Akula, V. V., Avoodaiappan, R., ... & Pugazhendhi, A. (2023). Recent developments on advanced oxidation processes for degradation of pollutants from wastewater with focus on antibiotics and organic dyes. *Environmental Research*, 117500.

[257] Castillo-Suárez, L. A., Sierra-Sánchez, A. G., Linares-Hernández, I., Martínez-Miranda, V., & Teutli-Sequeira, E. A. (2023). A critical review of textile industry wastewater: green technologies for the removal of indigo dyes. *International Journal of Environmental Science and Technology*, 1-38.

[258] Sudarshan, S., Harikrishnan, S., RathiBhuvaneswari, G., Alamelu, V., Aanand, S., Rajasekar, A., & Govarthanan, M. (2023). Impact of textile dyes on human health and bioremediation of textile industry effluent using microorganisms: current status and future prospects. *Journal of Applied Microbiology*, *134*(2), lxac064.

[259] Lara, L., Cabral, I., & Cunha, J. (2022). Ecological approaches to textile dyeing: a review. *Sustainability*, *14*(14), 8353.

[260] Karimi, F., Zare, N., Jahanshahi, R., Arabpoor, Z., Ayati, A., Krivoshapkin, P., ... & Karimi-Maleh, H. (2023). Natural waste-derived nano photocatalysts for azo dye degradation. *Environmental Research*, 117202.

[261] Hashim, A., Aadil, M., Choudhry, Q., Mubeen, S., Zainab, B., Somaily, H. H., ... & Mohamed, R. M. (2023). Boosting the antimicrobial and Azo dye mineralization activities of ZnO ceramics by enhancing the light-harvesting and charge transport properties. *Ceramics International*, *49*(20), 32377-32387.

[262] Venkatesh, N., & Sakthivel, P. (2022). Efficient degradation of azo dye pollutants on Zn doped SnO2 photocatalyst under sunlight irradiation: Performance, mechanism and toxicity evaluation. *Inorganic Chemistry Communications*, *139*, 109360.

[263] Zafar, S., Bukhari, D. A., & Rehman, A. (2022). Azo dyes degradation by microorganisms-An efficient and sustainable approach. *Saudi Journal of Biological Sciences*, 103437.

[264] Kumar, J. E., Mulai, T., Kharmawphlang, W., Sharan, R. N., & Sahoo, M. K. (2023). The efficiency of Fenton, Fenton/MW and UV/oxidant processes in the treatment of a mixture of higher concentrations of azo dyes. *Chemical Engineering Journal Advances*, 100515.

[265] Liu, X., & Wang, J. (2024). Decolorization and degradation of various dyes and dye-containing wastewater treatment by electron beam radiation technology: An overview. *Chemosphere*, 141255.

[266] Vishani, D. B., & Shrivastav, A. (2022). Enzymatic decolorization and degradation of azo dyes. *Development in Wastewater Treatment Research and Processes*, 419-432.

[267] Ahmadi, Y., & Kim, K. H. (2024). Modification strategies for visible-light photocatalysts and their performance-enhancing effects on photocatalytic degradation of volatile organic compounds. *Renewable and Sustainable Energy Reviews*, *189*, 113948.

[268] Tian, N., Giannakis, S., Akbarzadeh, L., Hasanvandian, F., Dehghanifard, E., & Kakavandi, B. (2023). Improved catalytic performance of ZnO via coupling with CoFe2O4 and carbon nanotubes: A new, photocatalysis-mediated peroxymonosulfate activation system, applied towards Cefixime degradation. *Journal of Environmental Management*, *329*, 117022.

[269] Dewanjee, S., Chakraborty, P., Bhattacharya, H., Chacko, L., Singh, B., Chaudhary, A., ... & Kandimalla, R. (2022). Altered glucose metabolism in Alzheimer's disease: Role of mitochondrial dysfunction and oxidative stress. *Free Radical Biology and Medicine*, *193*, 134-157.

[270] Rotariu, D., Babes, E. E., Tit, D. M., Moisi, M., Bustea, C., Stoicescu, M., ... & Bungau, S. G. (2022). Oxidative stress–Complex pathological issues concerning the hallmark of cardiovascular and metabolic disorders. *Biomedicine & Pharmacotherapy*, *152*, 113238.

[271] Basit, F., Bhat, J. A., Alyemeni, M. N., Shah, T., & Ahmad, P. (2023). Nitric oxide mitigates vanadium toxicity in soybean (Glycine max L.) by modulating reactive oxygen species (ROS) and antioxidant system. *Journal of Hazardous Materials*, *451*, 131085.

[272] Zhao, Q., Chen, S., Wang, G., Du, Y., Zhang, Z., Yu, G., ... & Du, J. (2022). Exogenous melatonin enhances soybean (Glycine max (L.) Merr.) seedling tolerance to saline-alkali stress by regulating antioxidant response and DNA damage repair. *Physiologia Plantarum*, *174*(4), e13731.

[273] Ribeiro, C. F., de Borba, M. C., Geller, A. C., Pontes, E. S., Kulcheski, F. R., de Freitas, M. B., & Stadnik, M. J. (2023). Enhanced oxidative enzymes activity and lipid peroxidation are associated with hypersensitive response and atypical lesions in resistant bean plants infected with Colletotrichum lindemuthianum. *Physiological and Molecular Plant Pathology*, *127*, 102099.

[274] Rehmani, M. S., Xian, B., Wei, S., He, J., Feng, Z., Huang, H., & Shu, K. (2023). Seedling establishment: The neglected trait in the seed longevity field. *Plant Physiology and Biochemistry*, 107765.

[275] Alsamadany, H., & Ahmed, Z. (2022). Assessing aging impact on growth potential of Vitamin E primed soybean seeds via biochemical profiling. *Saudi Journal of Biological Sciences*, *29*(5), 3717-3726.

[276] Boniecka, J., Kotowicz, K., Skrzypek, E., Dziurka, K., Rewers, M., Jedrzejczyk, I., ... & Dąbrowska, G. B. (2019). Potential biochemical, genetic and molecular markers of deterioration advancement in seeds of oilseed rape (Brassica napus L.). *Industrial Crops and Products*, *130*, 478-490.

[277] Sharma, S., Shree, B., Sharma, D., Kumar, S., Kumar, V., Sharma, R., & Saini, R. (2022). Vegetable microgreens: The gleam of next generation super foods, their genetic enhancement, health benefits and processing approaches. *Food Research International*, *155*, 111038.

[278] Kumar, M., Kapoor, S., Dhumal, S., Tkaczewska, J., Changan, S., Saurabh, V., ... & Bhuyan, D. J. (2022). Guava (Psidium guajava L.) seed: A low-volume, high-value byproduct for human health and the food industry. *Food Chemistry*, *386*, 132694.

[279] Manzoor, M. A., Xu, Y., Xu, J., Wang, Y., Sun, W., Liu, X., ... & Zhang, C. (2023). Nanotechnology-based approaches for promoting horticulture crop growth, antioxidant response and abiotic stresses tolerance: an overview. *Plant Stress*, 100337.

[280] Vitali, C., Peters, R. J., Janssen, H. G., Nielen, M. W., & Ruggeri, F. S. (2022). Microplastics and nanoplastics in food, water, and beverages, part II. Methods. *TrAC Trends in Analytical Chemistry*, *157*, 116819.

[281] Moldovan, R., Vereshchagina, E., Milenko, K., Iacob, B. C., Bodoki, A. E., Falamas, A., ... & Bodoki, E. (2022). Review on combining surface-enhanced Raman spectroscopy and electrochemistry for analytical applications. *Analytica Chimica Acta*, *1209*, 339250.

[282] Kamariotis, A., Chatzi, E., & Straub, D. (2022). Value of information from vibration-based structural health monitoring extracted via Bayesian model updating. *Mechanical Systems and Signal Processing*, *166*, 108465.

[283] Xu, Y. Y., Fan, X., Mo, W. L., Muhammad, T., Bai, X., Saikia, B. K., ... & Ma, F. Y. (2022). Advanced separation of soluble organic matter in a low-rank coal and evaluation using unsupervised analyses. *Fuel*, *328*, 125212.

[284] Ganorkar, S. B., & Vander Heyden, Y. (2022). Recent trends in pharmaceutical analysis to foster modern drug discovery by comparative in-silico profiling of drugs and related substances. *TrAC Trends in Analytical Chemistry*, 116747.

[285] Rasheed, S., Fatima, M., Rehman, K., Kamal, S., Hussain, I., & Akash, M. S. H. (2022). Bioanalytical techniques for prediction of metabolic activity of drug-metabolizing enzymes. In *Biochemistry of Drug Metabolizing Enzymes* (pp. 399-425). Academic Press.

[286] Ganorkar, S. B., & Vander Heyden, Y. (2022). Recent trends in pharmaceutical analysis to foster modern drug discovery by comparative in-silico profiling of drugs and related substances. *TrAC Trends in Analytical Chemistry*, 116747.

[287] Feng, L., Song, W., Oturan, N., Karbasi, M., van Hullebusch, E. D., Esposito, G., ... & Oturan, M. A. (2023). Electrochemical oxidation of Naproxen in aqueous matrices: Elucidating the intermediates' eco-toxicity, by assessing its degradation pathways via experimental and density functional theory (DFT) approaches. *Chemical Engineering Journal*, *451*, 138483.

[288] Marinho, B. A., Suhadolnik, L., Likozar, B., Huš, M., Marinko, Ž., & Čeh, M. (2022). Photocatalytic, electrocatalytic and photoelectrocatalytic degradation of pharmaceuticals in aqueous media: Analytical methods, mechanisms, simulations, catalysts and reactors. *Journal of Cleaner Production*, *343*, 131061.

[289] Sun, X., Zhuang, J., Ma, X., Tang, Y., Ali, M. M., Lu, Z., ... & Du, Z. (2022). Structure elucidation and risk assessment of degradation products in gamma irradiated rubber closures. *Polymer Degradation and Stability*, *204*, 110126.

[290] Yu, X., Jin, X., Wang, N., Zheng, Q., Yu, Y., Tang, J., ... & Zhu, L. (2022). UV activated sodium percarbonate to accelerate degradation of atrazine: mechanism, intermediates, and evaluation on residual toxicity by metabolomics. *Environment International*, *166*, 107377.

[291] Gangola, S., Bhatt, P., Kumar, A. J., Bhandari, G., Joshi, S., Punetha, A., ... & Rene, E. R. (2022). Biotechnological tools to elucidate the mechanism of pesticide degradation in the environment. *Chemosphere*, *296*, 133916.

[292] Zhang, M., Zhou, B., Chen, Y., & Gong, H. (2022). Mechanism and safety analysis of acetylene decomposition explosion: A combined ReaxFF MD with DFT study. *Fuel*, *327*, 124996.

[293] Rani, M., Yadav, J., Shanker, U., & Sillanpää, M. (2023). Green synthesized zinc derived nanocomposites with enhanced photocatalytic activity: An updated review on structural modification, scientific assessment and environmental applications. *Inorganic Chemistry Communications*, *147*, 110246.

[294] Ahmad, I., Zou, Y., Yan, J., Liu, Y., Shukrullah, S., Naz, M. Y., ... & Khalid, N. R. (2023). Semiconductor photocatalysts: A critical review highlighting the various strategies to boost the photocatalytic performances for diverse applications. *Advances in Colloid and Interface Science*, *311*, 102830.

[295] Roy, H., Rahman, T. U., Khan, M. A. J. R., Al-Mamun, M. R., Islam, S. Z., Khaleque, M. A., ... & Awual, M. R. (2023). Toxic dye removal, remediation, and mechanism with doped SnO2-based nanocomposite photocatalysts: A critical review. *Journal of Water Process Engineering*, *54*, 104069.

[296] Aadil, M., Hassan, W., Somaily, H. H., Ejaz, S. R., Abass, R. R., Jasem, H., ... & Alsafari, I. A. (2022). Synergistic effect of doping and nanotechnology to fabricate highly efficient photocatalyst for environmental remediation. *Journal of Alloys and Compounds*, *920*, 165876.

[297] Abdullah, F. H., Bakar, N. A., & Bakar, M. A. (2022). Current advancements on the fabrication, modification, and industrial application of zinc oxide as photocatalyst in the removal of organic and inorganic contaminants in aquatic systems. *Journal of hazardous materials*, *424*, 127416.

[298] Pigosso, T., Melo, B. A. A., Evangelista, L. L., González, S. Y. G., & Binder, C. (2023). Rapid synthesis of in situ nitrogen-doped ZnO nanoparticles for visible-light-driven photocatalytic removal of emerging contaminants. *Materials Today Chemistry*, *33*, 101753.

[299] Abubshait, H. A., Saad, M., Iqbal, S., Abubshait, S. A., Bahadur, A., Raheel, M., ... & Somaily, H. H. (2023). Co-doped zinc oxide nanoparticles embedded in Polyvinylalcohol Hydrogel as solar light derived photocatalyst disinfection and removal of coloured pollutants. *Journal of Molecular Structure*, *1271*, 134100.

[300] Sun, Y., Zhang, W., Li, Q., Liu, H., & Wang, X. (2023). Preparations and applications of zinc oxide based photocatalytic materials. *Advanced Sensor and Energy Materials*, 100069.

[301] Bachhav, K., & Garde, A. S. (2023). Versatile synthesis of zinc oxide nanoparticles via chemical route: A review. *Materials Today: Proceedings*.

[302] Pham, Q. P., Le Nguyen, Q. N., Nguyen, N. H., Doan, U. T. T., Ung, T. D. T., Tran, V. C., ... & Pham, N. K. (2023). Calcination-dependent microstructural and optical characteristics of eco-friendly synthesized ZnO nanoparticles and their implementation in analog memristor application. *Ceramics International*, *49*(12), 20742-20755.

[303] Miranda-López, M. I., Contreras-Torres, F. F., Cavazos-Cavazos, D., Martínez-Ortiz, P. F., Pineda-Aguilar, N., Hernández, M. B., & Aguilar-Martínez, J. A. (2023). Crystal evolution of nano-sized CoCr2O4 synthesized by a modified sol–gel method. *Journal of Physics and Chemistry of Solids*, *178*, 111315.

[304] Ismael, M. (2023). Environmental remediation and sustainable energy generation via photocatalytic technology using rare earth metals modified g-C3N4: A review. *Journal of Alloys and Compounds*, *931*, 167469.

[305] Kumari, K., & Ahmaruzzaman, M. (2023). SnO2 quantum dots (QDs): Synthesis and potential applications in energy storage and environmental remediation. *Materials Research Bulletin*, 112446.

[306] Chaloeipote, G., Prathumwan, R., Subannajui, K., Wisitsoraat, A., & Wongchoosuk, C. (2021). 3D printed CuO semiconducting gas sensor for ammonia detection at room temperature. *Materials Science in Semiconductor Processing*, *123*, 105546.

[307] Abdullah, F. H., Bakar, N. A., & Bakar, M. A. (2022). Current advancements on the fabrication, modification, and industrial application of zinc oxide as photocatalyst in the removal of organic and inorganic contaminants in aquatic systems. *Journal of hazardous materials*, *424*, 127416.

[308] Ali, J., Bibi, S., Jatoi, W. B., Tuzen, M., Jakhrani, M. A., Feng, X., & Saleh, T. A. (2023). Green synthesized zinc oxide nanostructures and their applications in dye-sensitized solar cells and photocatalysis: A review. *Materials Today Communications*, 106840.

[309] Dat, N. M., Nam, N. T. H., Hai, N. D., An, H., Cong, C. Q., Dat, N. T., ... & Hieu, N. H. (2023). An overall assessment of the pathway procedures, analytical approaches, and potentially essential applications of zinc oxide nanostructured materials. *Inorganic Chemistry Communications*, 111430.

[310] Noureen, L., Wang, Q., Humayun, M., Shah, W. A., Xu, Q., & Wang, X. (2023). Recent advances in structural engineering of photocatalysts for environmental remediation. *Environmental Research*, *219*, 115084.

[311] Suhan, M. B. K., Al-Mamun, M. R., Farzana, N., Aishee, S. M., Islam, M. S., Marwani, H. M., ... & Awual, M. R. (2023). Sustainable pollutant removal and wastewater remediation using TiO2-based nanocomposites: A critical review. *Nano-Structures & Nano-Objects*, *36*, 101050.

[312] Rasheed, T. (2022). Magnetic nanomaterials: Greener and sustainable alternatives for the adsorption of hazardous environmental contaminants. *Journal of Cleaner Production*, *362*, 132338.

[313] Pathak, D., Sharma, A., Sharma, D. P., & Kumar, V. (2023). A review on electrospun nanofibers for photocatalysis: Upcoming technology for energy and environmental remediation applications. *Applied Surface Science Advances*, *18*, 100471.

[314] Omran, B. A., & Baek, K. H. (2022). Valorization of agro-industrial biowaste to green nanomaterials for wastewater treatment: Approaching green chemistry and circular economy principles. *Journal of Environmental Management*, *311*, 114806.

[315] Ncube, A., Mtetwa, S., Bukhari, M., Fiorentino, G., & Passaro, R. (2023). Circular Economy and Green Chemistry: The Need for Radical Innovative Approaches in the Design for New Products. *Energies*, *16*(4), 1752.

[316] Ambaye, T. G., Djellabi, R., Vaccari, M., Prasad, S., Aminabhavi, T., & Rtimi, S. (2023). Emerging technologies and sustainable strategies for municipal solid waste valorization: Challenges of circular economy implementation. *Journal of Cleaner Production*, 138708.

[317] Srivastava, A., Dutta, S., Ahuja, S., & Sharma, R. K. (2021). Green chemistry: key to reducing waste and improving water quality. *Handbook of Water Purity and Quality*, 359-407.

[318] Thanigaivel, S., Priya, A. K., Gnanasekaran, L., Hoang, T. K., Rajendran, S., & Soto-Moscoso, M. (2022). Sustainable applicability and environmental impact of wastewater treatment by emerging nanobiotechnological approach: Future strategy for efficient removal of contaminants and water purification. *Sustainable Energy Technologies and Assessments*, *53*, 102484.

[319] Bilal, M., Rizwan, K., Rahdar, A., Badran, M. F., & Iqbal, H. M. (2022). Graphene-based porous nanohybrid architectures for adsorptive and photocatalytic abatement of volatile organic compounds. *Environmental Pollution*, *309*, 119805.

[320] Sharmila, V. G., Tyagi, V. K., Varjani, S., & Banu, J. R. (2023). A review on the lignocellulosic derived biochar-based catalyst in wastewater remediation: Advanced treatment technologies and machine learning tools. *Bioresource Technology*, 129587.

[321] Ali, H., Masar, M., Yasir, M., Machovsky, M., Monteiro, O. C., & Kuritka, I. (2023). Current trends in environmental and energy photocatalysis and ISO standardization. *Journal of Environmental Chemical Engineering*, 111541.

[322] Sabri, M. A., Al Jitan, S., Bahamon, D., Vega, L. F., & Palmisano, G. (2021). Current and future perspectives on catalytic-based integrated carbon capture and utilization. *Science of the Total Environment*, *790*, 148081.

[323] Ma, N., Zhao, W., Wang, W., Li, X., & Zhou, H. (2023). Large scale of green hydrogen storage: Opportunities and challenges. *International Journal of Hydrogen Energy*.

[324] Al-Hazmi, H. E., Łuczak, J., Habibzadeh, S., Hasanin, M., Mohammadi, A., Esmaeili, A., ... & Saeb, M. R. (2023). Polysaccharide nanocomposites in water treatment: A review. *Chemosphere*, 140578.

[325] Smith, T. S., Baranowski, M., & Schmid, B. (2021). Intentional degrowth and its unintended consequences: Uneven journeys towards post-growth transformations. *Ecological Economics*, *190*, 107215.

[326] D'amato, D., & Korhonen, J. (2021). Integrating the green economy, circular economy and bioeconomy in a strategic sustainability framework. *Ecological Economics*, *188*, 107143.

[327] Bibri, S. E. (2021). Data-driven smart sustainable cities of the future: An evidence synthesis approach to a comprehensive state-of-the-art literature review. *Sustainable Futures*, *3*, 100047.

[328] Rai, P. K. (2022). Novel adsorbents in remediation of hazardous environmental pollutants: Progress, selectivity, and sustainability prospects. *Cleaner Materials*, *3*, 100054.

[329] Silva, A. L. P., Prata, J. C., Duarte, A. C., Barcelò, D., & Rocha-Santos, T. (2021). An urgent call to think globally and act locally on landfill disposable plastics under and after covid-19 pandemic: Pollution prevention and technological (Bio) remediation solutions. *Chemical Engineering Journal*, *426*, 131201.

[330] Sahu, S., Kaur, A., Singh, G., & Arya, S. K. (2023). Harnessing the potential of microalgae-bacteria interaction for eco-friendly wastewater treatment: A review on new strategies involving machine learning and artificial intelligence. *Journal of Environmental Management*, *346*, 119004.