ARTICLE
JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلــة جـــامعة بـــــابـل للعلـــــوم الهندسية
Vol. 33, No.3. \ 2025 ISSN: 2616 - 9916

"Eco-Friendly Photocatalytic Degradation of Organic Pollutants Using Nano-Semiconductors Derived from Onion Peel Extract: A Comprehensive Review"

Nabaa A. Al-Wahab [1, a] **Rasha A. Al-Husseiny[2, b]**

[1,2] *Water resources management Engineering Departmant, College of Engineering, Al Qasim Green University,51013, Babylon, Iraq*

[a)] Corresponding Author email: nabaaabedalwahab@wrec.uoqasim.edu.iq

[b)]Author Email: rasha83@wrec.uoqasim.edu.iq

Received:	14/4/2025	Accepted:	13/5/2025	Published:	29/6/2025

Abstract:

This review examines the photocatalytic degradation of organic pollutants using nano-semiconductor photocatalysts, particularly those derived from onion peel extract, as a sustainable solution for wastewater treatment. It highlights the high catalytic activity, cost-effectiveness, and solar energy utilization of these materials. Recent advancements in magnetic nano-semiconductors offer improved separation and reusability, addressing key limitations. Modified photocatalysts such as TiO_2 and ZnO it synthesized via sol-gel, microwave, and ultrasonication, methods, show strong potential for greywater treatment. The integration of photocatalysis with oxidants like Fe^{3+} enhances mineralization efficiency. Operational parameters including pH, pollutant concentration, and catalyst loading are also discussed for process optimization. This review identifies promising directions for scalable and efficient photocatalytic wastewater treatment.

Keywords**:** Nanotechnology, Green synthesis, Onion Peel, Nanoparticles, Organic Pollutants.

1. Introduction

Water scarcity has become one of the most pressing global challenges, affecting over two billion people worldwide with limited access to clean water, as highlighted by UNICEF and the World Health Organization (WHO) [1]. This crisis is exacerbated by factors such as rapid population growth, industrial expansion, economic development, prolonged droughts, and pervasive water pollution. In light of these challenges, sustainable and efficient solutions are critical to meeting the increasing demand for clean water. Among the most promising solutions is the reuse of greywater, which refers to domestic wastewater excluding toilet effluents. Greywater recycling offers a viable alternative to reduce reliance on surface and groundwater, optimizing water use in both urban and agricultural sectors [2]. However, greywater contains organic pollutants, surfactants, and other contaminants that require efficient treatment to ensure environmental safety and public health. Photocatalytic degradation, an advanced oxidation process (AOP), has emerged as a promising technology for treating wastewater, particularly for removing persistent organic pollutants. This process employs semiconductor-based photocatalysts, such as titanium dioxide (TiO_2) and zinc oxide (ZnO), to degrade harmful organic molecules into innocuous byproducts under the influence of light. When exposed to UV or solar light, these photocatalysts generate highly reactive hydroxyl radicals, which mineralize

Vol. 33, No.3. \ 2025 ISSN: 2616 - 9916

pollutants into water, carbon dioxide, and mineral acids, offering a sustainable, cost-effective, and environmentally friendly method for wastewater treatment. However, despite its advantages, the application of semiconductor photocatalysts faces significant challenges, including the recovery and reuse of fine particles and the reduced efficiency of immobilized systems [3]. To overcome these limitations, recent advancements have focused on the development of magnetic nano-semiconductor photocatalysts, which combine high catalytic activity with magnetic separation properties, enabling their repeated use in cyclic processes [4]. Furthermore, modifications to photocatalyst properties through techniques such as sol-gel, microwave, and ultrasonication methods, have enhanced their efficiency and applicability. These innovations are paving the way for scalable and sustainable solutions to tackle organic pollution in greywater and other wastewater streams. This review delves into the synthesis, mechanisms, and applications of nano-semiconductor photocatalysts, with a focus on their potential to address existing challenges and advance wastewater treatment technologies for broader industrial and environmental use [5].

2. Photocatalysis principles

Photocatalysis, a process inspired by natural photosynthesis, involves light-driven chemical reactions that are thermodynamically non-spontaneous, distinguishing it from conventional catalysis, where reactions typically occur spontaneously. The use of light as a reactant to facilitate non-spontaneous reactions expands the scope of photocatalysis, making it applicable to a variety of processes, including the oxidation of pollutants with high activation energies [6]. Light activation in these systems enhances reaction rates, aligning with the core principles of catalysis. Similarly, photoelectrochemical systems, which apply external potentials, follow similar photocatalytic mechanisms, encompassing both photosynthetic processes and traditional catalytic reactions [7]. The seminal work of Fujishima and Honda (1972) demonstrated the feasibility of photocatalysis in a photoelectrochemical cell designed for water splitting, producing hydrogen and oxygen gases from water using titanium dioxide (TiO_2) as the semiconductor electrode and platinum as the counter electrode under light irradiation , This setup demonstrates a key principle of solar-to-chemical energy conversion, where solar energy is used to split water into hydrogen and oxygen—a reaction central to green hydrogen production and clean energy technologies. (Figure 1).

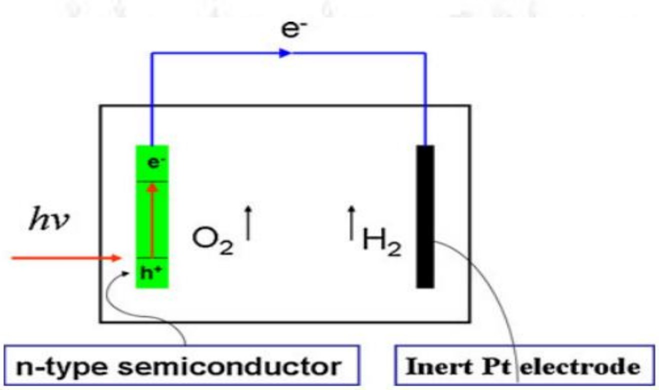

Fig. 1 Photoelectrochemical Cell Mechanisms: Electron and Hole Dynamics in Hydrogen and Oxygen Gas Generation [8].

This landmark discovery provided a fundamental understanding of photocatalysis, where light-generated electron-hole pairs drive oxidation and reduction reactions. According to band theory, when photons with energy greater than the semiconductor's bandgap are absorbed, electrons are excited from the valence band (VB) to the conduction band (CB), generating reactive species that drive catalytic processes [9]. Photogenerated holes are responsible for oxidizing water or organic pollutants, while the electrons reduce oxygen to form reactive radicals. Among these radicals, hydroxyl radicals (OH•) exhibit a high oxidative potential, facilitating the near-complete mineralization of organic pollutants. These principles form the basis for photocatalytic processes, which have gained prominence as an environmentally sustainable and cost-effective technology for pollutant degradation [10]. This approach aligns with the broader goals of wastewater treatment and resource recovery, offering a viable pathway for addressing organic pollution. The continuous development of photocatalytic materials and systems is propelling the application of these technologies in tackling global environmental challenges [11]. In photoelectrochemical systems, when the external circuit is shortened, the platinum electrode is brought into direct contact with the n-type semiconductor, resulting in the reduction of platinum to the nanoscale. This creates a nanostructured photoelectrochemical cell, this simplified schematic (Fig. 2) represents a nanoscale photocatalytic system comprising a titania (TiO_2) semiconductor particle coupled with a platinum (Pt) nanoparticle counter electrode. In this system, titania (TiO_2) serves as the main photocatalyst, absorbing ultraviolet light to generate electron-hole pairs. The Pt nanoparticle acts as a co-catalyst or electron sink, improving the separation of photogenerated charges and enhancing the reduction reactions, such as hydrogen evolution. The close contact between the semiconductor and the noble metal nanoparticle facilitates faster electron transfer, which minimizes charge recombination and increases overall photocatalytic efficiency. (Figure 2).

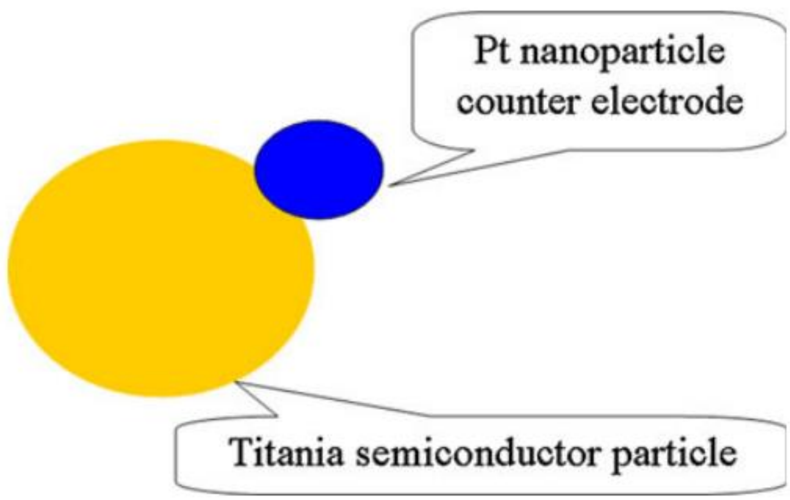

Fig. 2 Semiconductor Photocatalysts in Aqueous Suspension: A Nanoscale Photoelectrochemical System [12].

Within this structure, oxidation reactions occur at the surface of the n-type semiconductor, while reduction reactions take place on the inert platinum particle, which serves as the counter electrode. The fundamental mechanisms can be understood using band theory, which describes the electronic structure of semiconductors [13]. For instance, in TiO_2, the valence band (VB) consists primarily of O 2p orbitals, while the conduction band (CB) is dominated by Ti 3d orbitals. When photons with energy exceeding the bandgap are absorbed by TiO_2, electrons are excited from the VB to the CB, generating electron-hole pairs that facilitate catalytic reactions. The electrons reduce oxygen molecules to form superoxide radicals ($O_2^{\bullet -}$), while the photogenerated holes oxidize water or organic pollutants on the semiconductor surface (as in Figure 3).

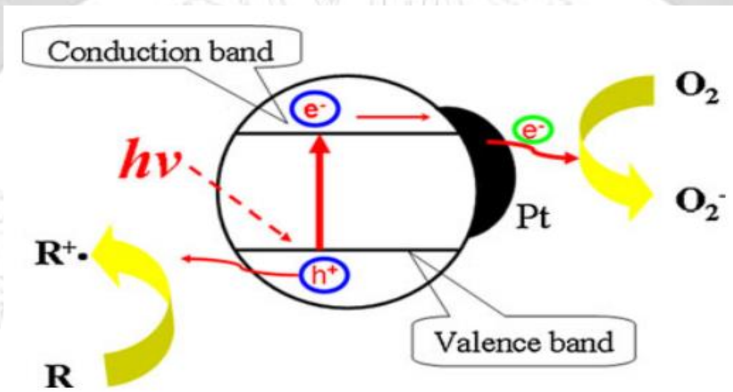

Fig. 3 Photocatalytic Mechanism of Semiconductors: Electron Dynamics and Reaction Pathways [13].

These processes result in the generation of highly reactive hydroxyl radicals (OH•), which have a high redox potential (2.8 V vs. NHE) and are capable of effectively decomposing a wide range of organic pollutants. This photophysical process can be summarized through as in Table 1:

Table 1. Key Photocatalytic Reactions Involved in Semiconductor-Based Organic Pollutant Degradation

Equation	**Reaction**	**Description**	**Reference**
Equation 1	$TiO_2 + hv \rightarrow h^+ + e^-$	Photon energy (hv) excites the TiO_2 semiconductor, generating electron-hole pairs (h^+ and e^-).	[14]
Equation 2	$O_2 + e^- \rightarrow O_2^{\bullet -} \rightarrow H^+ + HO_2^{\bullet} \rightarrow H_2O_2 + O_2$	Photogenerated electrons react with molecular oxygen (O_2) to form superoxide radicals ($O_2^{\bullet -}$), leading to hydrogen peroxide (H_2O_2).	[15]
Equation 3	$H_2O_2 \rightarrow hv \rightarrow 2OH^{\bullet}$	Under light irradiation, hydrogen peroxide decomposes into hydroxyl radicals (OH•).	[16]

Equation 4	$H_2O + h^+ \rightarrow OH\bullet + H^+$	Photogenerated holes oxidize water adsorbed on the TiO_2 surface, producing hydroxyl radicals ($OH\bullet$).	[16]
Equation 5	Organic compounds + $h^+ \rightarrow$ reactive intermediates	Photogenerated holes oxidize organic compounds into reactive intermediates.	[17]
Equation 6	Organic compounds + $OH\bullet \rightarrow$ reactive intermediates	Hydroxyl radicals ($OH\bullet$) oxidize organic compounds into reactive intermediates.	[18]

These reactions underscore the pivotal role of electron-hole pair generation and the subsequent oxidation and reduction processes in photocatalytic degradation. While semiconductor nanoparticles exhibit high catalytic activity due to their large surface area, their practical reuse remains challenging due to the instability of photogenerated charge carriers [19]. The enhancement of photocatalyst stability and charge carrier isolation is crucial for improving the long-term effectiveness of photocatalytic systems in wastewater treatment applications [20].

2.1 Photocatalytic Activities

The photocatalytic activities of multi-component systems, such as those derived from onion peel extract, are enhanced by incorporating an insulating interlayer between the core and shell components. Similar to findings with Fe3O4, γ-Fe2O3, and MFe2O4 magnetic cores, introducing an insulator mitigates photogenerated electron–hole recombination, which is a key limitation in direct core/shell configurations. This structural optimization is essential for improving photocatalytic efficiency [21]. In the direct contact core/shell systems, the heterojunction structures, influenced by bandgap differences, contribute to reduced photocatalytic activity. For instance, the narrower bandgaps of Fe3O4 (0.10 eV), γ-Fe2O3 (2.30 eV), and NiFe2O4 (2.19 eV) result in unfavorable conduction band (CB) and valence band (VB) alignment compared to TiO2, which has a wider bandgap of 3.20 eV (Table 2). The electron transfer from TiO2’s CB to the lower CBs of magnetic materials and hole transfer to their higher VBs lead to inefficient charge separation and reduced activity.In contrast, when onion peel extract-derived catalysts are integrated with an insulating interlayer, such as silica or carbon-based materials, these challenges are alleviated[22]. The interlayer prevents direct electrical contact, enabling efficient charge separation and improving the stability of the photocatalytic system (Table 3). This approach highlights the potential of onion peel extract as a sustainable precursor for high-activity photocatalysts, with further research needed to explore optimal material combinations and configurations for enhanced degradation of organic pollutants [23].

Table 2. Components of Core/Insulator/Shell Magnetic Photocatalysts Derived from Onion Peel Extract for Organic Pollutant Degradation

Magnet Core	Insulator	Photocatalyst Shell	References
γ-Fe2O3	SiO2	TiO2	[24]
γ-Fe2O3	PPS-/PDD+	TiO2	[25]
Fe3O4	SiO2	TiO2	[26]
Fe3O4	SiO2	AgBr	[27]
Fe3O4	Poly(methyl methacrylate)	TiO2	[27]
Zn0.35Ni0.65Fe2O4 BaFe2O4	SiO2 SiO2	TiO2 TiO2	[28]
Black sand	SiO2	TiO2	[29]
ZnFe2O4	Al2O3	TiO2	[30]

- PPS^{-}: Poly (sodium 4-styrene sulfonate) polyanion.
- PDD^{+}: Poly (diallyldimethylammonium) cation.

Table 3. Positions of CB and VB for Fe_3O_4, γ-Fe_2O_3, and TiO_2 at pH 7.0 and Their Bandgaps

Material	ECB (V vs. NHE)	ECV (V vs. NHE)	Bandgap (eV)	Notes	References
Fe_3O_4	0.17	0.27	0.1	Measured at pH 3.5	[31]
γ-Fe_2O_3	0.10	2.40	2.3	Measured at pH 3.4	[32]
TiO_2	-0.50	2.70	3.2	Measured at pH 3.7	[32]

Onion peel extract has gained significant attention as an effective and sustainable material for the degradation of organic pollutants in wastewater treatment. The extract contains various bioactive compounds, such as flavonoids, phenolic acids, and antioxidants, which possess photocatalytic properties. Studies have shown that onion peel extract can enhance the degradation of organic contaminants through advanced oxidation processes (AOPs). The natural compounds in onion peel extract promote the generation of hydroxyl radicals (•OH) and superoxide anions ($O2^{\bullet-}$), which contribute to the breakdown of organic pollutants [33]. These compounds also support the adsorption and catalysis of organic materials, accelerating the degradation process.

Recent studies suggest that the extract's ability to act as a green photocatalyst offers a promising alternative to traditional methods, such as titanium dioxide (TiO_2)-based photocatalysts, which require significant energy input for activation. The utilization of onion peel extract in photocatalysis is not only cost-effective, but also environmentally friendly, as it can be sourced from agricultural waste [34]. Moreover, its activity has been shown to be comparable to or even surpass conventional photocatalytic materials in some cases. The decomposition of organic materials through onion peel extract-based photocatalysis is therefore a promising method for wastewater treatment, offering both efficiency and sustainability [35].

ARTICLE
JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلـة جـــامعة بـــــابـل للعلـــــوم الهندسية
Vol. 33, No.3. \ 2025 ISSN: 2616 - 9916

2.2 Onion Peel Extract for Degradation of Organic Material

Onion peel extract has gained significant attention as a sustainable and eco-friendly alternative for the degradation of organic pollutants in wastewater. The extract contains bioactive compounds such as flavonoids, tannins, and phenolic acids, which exhibit remarkable antioxidant and catalytic properties [36]. These compounds enhance the breakdown of complex organic materials into simpler, less harmful substances, leveraging natural photochemical reactions. One of the primary advantages of using onion peel extract is its ability to act as a green catalyst, promoting fast degradation rates of organic pollutants while avoiding the environmental drawbacks associated with conventional chemical photocatalysts. Additionally, its natural abundance and low cost make it an attractive resource for large-scale applications [37]. However, like many natural catalysts, onion peel extract presents challenges in recovery and reuse due to its solubility and dispersion in aqueous media. To address these limitations, onion peel extract is often immobilized onto solid supports such as silica, cellulose, or biochar, which facilitate its recovery while maintaining catalytic efficiency. Despite these advancements, immobilization may reduce the active surface area and limit the transfer of pollutants, thereby lowering degradation efficiency [38]. Innovations in material engineering, such as the integration of onion peel extract with mesoporous carriers or nanostructured scaffolds, are being explored to enhance the extract's catalytic activity and ensure its effective utilization in wastewater treatment. The ongoing research on onion peel extract highlights its potential as a green and effective solution for organic pollutant degradation, aligning with global efforts toward sustainable and environmentally friendly water purification technologies [39].

2.3 Structural Model of Onion Peel

The structural model for using onion peel extract in organic pollutant degradation is based on its rich composition of phenolic compounds, flavonoids, and tannins, which possess strong antioxidant and catalytic properties [40]. These bioactive compounds initiate oxidative and photochemical reactions that break down complex organic molecules into less harmful substances. Functional groups like hydroxyl and carboxyl within the extract interact with pollutants, triggering redox reactions—particularly under solar irradiation due to the extract’s natural light-absorbing capability [41]. This process is illustrated in Fig. 4. However, the free form of onion peel extract presents challenges in recovery and reuse due to its solubility and dispersion in water. To address this, immobilization on solid supports such as biochar, silica, or cellulose has been developed, enhancing structural stability, catalytic longevity, and facilitating separation post-treatment [42]. These hybrid systems maintain high degradation efficiency while improving reusability. Ongoing research focuses on optimizing operational conditions to minimize the recombination of reactive intermediates and improve pollutant–catalyst interactions [43, 44]. Overall, onion peel extract represents a sustainable, low-cost catalyst for wastewater treatment, aligning with the goals of eco-friendly environmental remediation. (Figure. 4) shows a microscopic view of onion peel cells, highlighting their internal structure and basic components commonly studied in cell biology. The image identifies the cell wall, which provides structural support and shape to the plant cell, and the cytoplasm, where various metabolic activities occur. The nucleus—visible as a dark, rounded structure—is responsible for genetic control and cell regulation. The vacuole, a large central sac, is crucial for maintaining turgor pressure, storing nutrients, and isolating harmful substances. Onion peel is a widely used plant material when

Vol. 33, No.3. \ 2025 ISSN: 2616 - 9916

microscopy due to its clear visibility of these organelles and its high phenolic and flavonoid content, which is central to its utility in photocatalytic applications (Fig.4) [45].

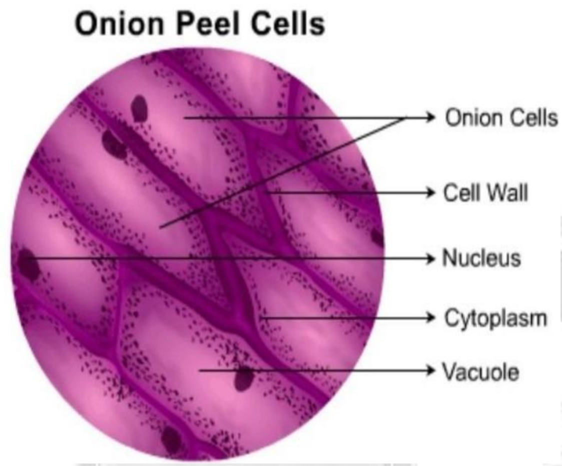

Fig 4 .The structure of the onion cell [46].

2.4 Advancements in Onion Peel Extract-Based Catalytic Systems for Organic Material Degradation

The limitations of direct catalytic systems, such as reduced activity and stability due to the recombination of reactive species, have driven innovations in the structural design of catalysts derived from onion peel extract [46]. Researchers have explored multi-layered composite systems to address these challenges, drawing inspiration from advancements in magnetic photocatalysts. For instance, the incorporation of an interlayer material between the active catalytic sites and the support structure has proven effective in mitigating activity loss and enhancing long-term stability. Building on these principles, onion peel extract-based systems are being developed using multi-component architectures [47]. In these systems, bioactive compounds from onion peels act as the catalytic core. A secondary interlayer typically composed of silica or biochar—functions as an insulating medium to prevent undesirable interactions, while a stabilizing outer layer improves the catalyst's durability and reusability. These configurations parallel models such as the γ-$Fe_2O_3/SiO_2/TiO_2$ system in magnetic photocatalysis, where each layer serves a specific purpose in optimizing performance [46]. This three-component approach ensures the efficient degradation of organic materials by reducing electron-hole recombination and protecting catalytic sites from deactivation. Recent studies have demonstrated the feasibility of such systems for environmental remediation, positioning onion peel extracts as a sustainable, biodegradable, and efficient alternative to synthetic photocatalysts (Table 4). Future research will refine these models to improve pollutant degradation rates, simplify recovery processes, and reduce costs, aligning with the principles of green chemistry and the circular economy [46]. To achieve practical applicability, there is a pressing need for broader comparative studies that evaluate different photocatalytic systems under standardized conditions. Additionally, more emphasis should be placed on addressing real-world implementation challenges, such as scalability, economic feasibility, and long-term operational stability. A more rigorous engagement with in-depth studies published in high-impact international journals is also essential to ensure that future developments are grounded in scientifically validated methodologies and contribute meaningfully to advancing commercial and industrial applications. [46].

Table 4. Contributions to the Development of Onion Peel Extract-Based Catalytic Systems

Study Focus	Contributions from Previous Studies	Contributions from Current Research	References
Reactivity and Stability	Explored challenges in direct catalytic systems, such as the recombination of reactive species, leading to reduced stability.	Introduced multi-component architectures to address electron-hole recombination and improve the durability of catalysts.	[47]
Structural Design	Investigated basic layered configurations inspired by magnetic photocatalysts.	Developed advanced three-layer systems integrating silica or biochar interlayers for enhanced performance and longevity.	[47]
Application Feasibility	Demonstrated the basic potential of onion peel extract in catalytic degradation.	Expanded feasibility for environmental remediation, showcasing improved pollutant degradation rates and reusability.	[48]
Sustainability and Green Chemistry	Recognized the sustainability of using onion peel extracts but lacked comprehensive system designs.	Enhanced integration with circular economy principles, optimizing catalyst recovery and minimizing synthetic material usage.	[48]
Future Directions	Highlighted the need for improved material stability and cost-effectiveness.	Focused on refining models to increase efficiency, reduce costs, and simplify recovery processes for practical applications.	[48]

2.5 Onion Peel Extract-Based Catalysts with Carbon-Enhanced Synergy

The application of interlayer materials in composite catalytic systems has revolutionized the field of photocatalysis, and these principles can be extended to catalysts derived from onion peel extract. Studies on multi-component systems, such as silica-insulated magnetic photocatalysts, have demonstrated how interlayers effectively prevent direct charge transfer between active sites and core materials, thereby improving stability and catalytic efficiency [49].

Inspired by these advancements, onion peel extract-based systems can integrate a bioactive core, an inert insulating interlayer, and a carbon-enhanced catalytic shell. The inclusion of carbonaceous materials, such as activated carbon or biochar derived from biomass, enhances photocatalytic activity by preconcentrating organic pollutants and facilitating electron–hole separation. This synergistic interaction significantly increases degradation efficiency, as evidenced by carbon-enhanced systems like titania-coated magnetic activated carbon and porous carbon [50].

Carbon components in onion peel extract-based catalysts also act as electron reservoirs, improving charge transfer dynamics and enabling more efficient breakdown of organic contaminants.

Moreover, the high surface area of porous carbon facilitates pollutant adsorption, accelerating degradation rates. These systems leverage the inherent bioactivity of onion peel compounds and the stability imparted by interlayers, offering a sustainable and efficient approach for treating organic pollutants. Future research should focus on optimizing the structural configuration and exploring alternative carbon materials to further enhance catalytic performance [51].

2.6 Impact of Size Dispersion on Photocatalytic Efficiency

Size dispersion, referring to the distribution of particle sizes within a sample of photocatalysts or nanomaterials, plays a critical role in determining their physicochemical properties and photocatalytic performance. In nanostructured materials, particularly those used for environmental applications such as pollutant degradation, uniform particle size is often desirable because it ensures consistent surface area, optical properties, and charge carrier dynamics. High size dispersion—where particles vary significantly in size—can lead to heterogeneity in active site availability and inconsistent light absorption across the material. Smaller particles generally provide a higher surface-to-volume ratio, enhancing the adsorption of pollutants and facilitating faster redox reactions. However, excessively small nanoparticles may suffer from agglomeration, reducing their effective surface area and impeding photocatalytic efficiency. Conversely, larger particles often exhibit slower electron-hole separation kinetics, reducing reactivity. Moreover, broad size dispersion can influence the bandgap energy distribution, leading to variable photo-response behavior across the catalyst surface. In systems where photogenerated charge carriers play a central role, such inconsistency can significantly reduce overall catalytic performance[51]. Controlled synthesis methods such as sol-gel, hydrothermal, or microwave-assisted techniques are often employed to minimize size dispersion, ensuring uniformity and maximizing photocatalytic efficiency. Thus, understanding and managing size dispersion is essential for optimizing the reactivity, stability, and scalability of photocatalyst systems [51].

3. Preparation and cyclic applications

The preparation of onion peel extract-based photocatalysts for the degradation of organic pollutants involves a systematic approach that integrates green chemistry principles with materials engineering. Initially, onion peels are washed, dried, and ground before undergoing extraction to isolate bioactive compounds such as flavonoids, tannins, and phenolic acids—key agents responsible for redox activity [52]. Solvent extraction (commonly using ethanol or methanol) and aqueous extraction methods are employed to maximize the yield of these compounds while preserving their structural integrity and photocatalytic potential. These bioactives function as natural antioxidants and electron donors, capable of generating reactive oxygen species (ROS) under light exposure, thereby promoting the degradation of organic pollutants through oxidative pathways. Following extraction, the active compounds are incorporated into solid support matrices such as activated carbon, silica, or biochar, which provide a high surface area, structural stability, and enhanced adsorption of target pollutants [53].

The integration of the extract with these carriers not only increases the availability of catalytic sites but also improves charge carrier separation by minimizing electron-hole recombination, a critical factor in enhancing photocatalytic efficiency. In advanced configurations, these composites are further modified by the deposition or doping of semiconductor materials like TiO_2 or ZnO.

These additions enable the photocatalysts to operate effectively under UV or even visible light, expanding their practical applicability in solar-driven wastewater treatment systems. After synthesis, the photocatalysts undergo rigorous characterization and performance testing, including techniques such as UV–Vis spectroscopy, XRD, SEM, and BET surface area analysis, to evaluate their optical, structural, and surface properties. Their photocatalytic performance is then assessed in aqueous systems containing model organic pollutants such as dyes (e.g., methylene blue or rhodamine B), pharmaceuticals, or pesticides [54]. These studies consistently demonstrate high degradation rates, attributable to the

JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلــة جـــامعة بـــــابـل للعلـــــوم الهندسية
Vol. 33, No.3. \ 2025 ISSN: 2616 - 9916

synergistic effects of the bioactive compounds and the engineered support structure. Furthermore, onion peel extract-based photocatalysts exhibit notable reusability, often maintaining their efficiency over multiple cycles of use. Recovery is facilitated through simple filtration when immobilized on non-soluble carriers or via magnetic separation when magnetic nanoparticles are incorporated into the system, further improving operational convenience and sustainability [55]. This approach aligns with the principles of circular economy and environmental sustainability by valorizing agricultural waste into high-value materials. It offers a low-cost, eco-friendly alternative to conventional synthetic photocatalysts, with strong potential for large-scale application in wastewater treatment and environmental remediation [56] Although no studies to date have directly applied onion peel extract-based photocatalysts for the removal of specific pollutants in real wastewater systems, the effectiveness of onion peel extract in catalytic and oxidative processes has been demonstrated through various indirect investigations. These include studies showing its high content of phenolic compounds, flavonoids, and tannins—known for their redox potential and ability to generate reactive oxygen species (ROS) under light exposure. Additionally, onion peel extract has shown proven efficacy as a reducing and stabilizing agent in the green synthesis of metal and metal oxide nanoparticles, where its functional groups facilitate electron transfer and enhance nanoparticle formation and stability. These properties closely parallel the mechanisms required in photocatalysis [57], suggesting strong potential for pollutant degradation applications. Therefore, while direct pollutant removal using this extract remains underexplored, its bioactive profile and performance in analogous systems support its continued investigation as a sustainable photocatalytic material [58].

4. Conclusion

In this article, the photocatalytic principles have been thoroughly explored, emphasizing the role of natural materials like onion peel extract for the degradation of organic pollutants. By utilizing the bioactive compounds in onion peel extract, such as flavonoids and phenolic acids, this approach enhances photocatalytic activity for wastewater treatment. The integration of onion peel extract into suitable supports, such as activated carbon or silica, improves both photocatalytic efficiency and pollutant adsorption. The potential synergy between the extract and support materials results in enhanced degradation efficiency. Furthermore, the size, dispersion, and stability of the photocatalysts are crucial factors for ensuring their long-term effectiveness. The ability of these natural photocatalysts to be cyclically reused, with simple recovery methods, offers significant environmental and economic benefits. Future work could focus on optimizing the stability of these photocatalysts and exploring their application under visible light, further expanding their potential for sustainable wastewater treatment.

References

[1] M. Ahmed and S. L. Kareem, “Comprehensive Review of Arundo donax and Lemna gibba for Phytoremediation Efficacy in Sustainable Wastewater Treatment,” *Environ. Claims J.*, pp. 1–27, 2025.

[2] M. Ahmed and S. L. Kareem, “Evaluating the role of hydraulic retention time (HRT) in pollutant removal efficiency using Arundo donax in vertical subsurface flow constructed wetlands,” *Bioremediation J.*, pp. 1–15, 2024.

[3] M. Ahmed and S. L. Kareem, “Evaluation of the effectiveness of phytoremediation technologies utilizing Lemna minor in constructed wetlands for wastewater treatment,” *Biomass Convers. Biorefin.*, pp. 1–13, 2024.

Vol. 33, No.3. \ 2025 ISSN: 2616 - 9916

[4] M. Ahmed, "Comparative Analysis of Vertical and Horizontal Subsurface Flow Constructed Wetlands for Eutrophication Mitigation," *Al-Bahir J. Eng. Pure Sci.*, vol. 6, no. 2, p. 2, 2025.

[5] Roy *et al*., "Antibacterial and dye degradation activity of green synthesized iron nanoparticles," *J. Nanomater.*, vol. 2022, pp. 1–6, 2022.

[6] Bekele *et al*., "Green versus chemical precipitation methods of preparing zinc oxide nanoparticles and investigation of antimicrobial properties," *J. Nanomater.*, vol. 2021, pp. 1–10, 2021.

[7] Siripireddy and B. K. Mandal, "Facile green synthesis of zinc oxide nanoparticles by *Eucalyptus globulus* and their photocatalytic and antioxidant activity," *Adv. Powder Technol.*, vol. 28, no. 3, pp. 785–797, 2017.

[8] F. Chang and C. Y. Man, "Titania-coated magnetic composites as photocatalysts for phthalate photodegradation," *Ind. Eng. Chem. Res.*, vol. 50, pp. 11620–11627, 2011; F. Chen and C. Zhao, "Preparation and photocatalytic properties of a novel kind of loaded photocatalyst of $TiO_2/SiO_2/\gamma\text{-}Fe_2O_3$," *Chem. Mater.*, vol. 15, pp. 3326–3331, 2003.

[9] Suresh *et al*., "*Artocarpus gomezianus* aided green synthesis of ZnO nanoparticles: Luminescence, photocatalytic and antioxidant properties," *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, vol. 141, pp. 128–134, 2015.

[10] Derakhshani, A. Naghizadeh, and S. Mortazavi-Derazkola, "Biosynthesis of $MnFe_2O_4@TiO_2$ magnetic nanocomposite using oleaster tree bark for efficient photocatalytic degradation of humic acid in aqueous solutions," *Environ. Sci. Pollut. Res.*, vol. 30, no. 2, pp. 3862–3871, 2023.

[11] E. M. Widyasari *et al*., "Physicochemical characteristic of 99mTc-DTPA-deoxy-D-glucose radiopharmaceutical," in *AIP Conf. Proc.*, AIP Publishing, 2022.

[12] E. S. Elmolla and M. Chaudhuri, "Photocatalytic degradation of amoxicillin, ampicillin and cloxacillin antibiotics in aqueous solution using UV/TiO_2 and $UV/H_2O_2/TiO_2$ photocatalysis," *Desalination*, vol. 252, no. 1–3, pp. 46–52, 2010.

[13] Al Qarni, N. A. Alomair, and H. H. Mohamed, "Environment-friendly nanoporous titanium dioxide with enhanced photocatalytic activity," *Catalysts*, vol. 9, no. 10, p. 799, 2019.

[14] F. Chen, Y. Xie, J. Zhao, and G. Lu, "Photocatalytic degradation of dyes on a magnetically separated photocatalyst under visible and UV irradiation," *Catal. Lett.*, vol. 58, pp. 245–247, 2001.

[15] F. Moosavi *et al*., "Photocatalytic Destruction of Amoxicillin in a Pilot Sunlight Reactor With Supported Titania Nano-Photocatalyst," in *Chemical Engineering Transactions*, 2019. [Online]. Available: https://doi.org/10.3303/CET1973030

[16] Parthasarathy, M. Saroja, M. Venkatachalam, S. Shankar, and V. K. Evanjelene, "Green synthesis of zinc oxide nanoparticles—review paper," *World J. Pharm. Pharm. Sci.*, vol. 5, no. 4, pp. 922–931, 2016.

[17] Agarwal, S. V. Kumar, and S. Rajeshkumar, "A review on green synthesis of zinc oxide nanoparticles–An eco-friendly approach," *Resource-Efficient Technologies*, vol. 3, no. 4, pp. 406–413, 2017.

[18] H. Çolak and E. Karaköse, "Green synthesis and characterization of nanostructured ZnO thin films using *Citrus aurantifolia* (lemon) peel extract by spin-coating method," *J. Alloys Compd.*, vol. 690, pp. 658–662, 2017.

[19] H. Jan *et al*., "Plant-based synthesis of zinc oxide nanoparticles (ZnO-NPs) using aqueous leaf extract of *Aquilegia pubiflora*: Their antiproliferative activity against HepG2 cells inducing reactive oxygen species and other in vitro properties," *Oxid. Med. Cell. Longev.*, vol. 2021, Art. no. 6699410, 2021.

[20] H. Xu and L. Xu, "Preparation of ZnO Nanomaterials and Their Photocatalytic Degradation of Organic Pollutants," *J. Donghua Univ. Eng. Ed.*, vol. 37, pp. 271–279, 2020.

[21] Byrappa and M. Yoshimura, *Handbook of Hydrothermal Technology*. Norwich, NY: William Andrew, 2012.

[22] Elumalai and S. Velmurugan, "Green synthesis, characterization and antimicrobial activities of zinc oxide nanoparticles from the leaf extract of *Azadirachta indica* (L.)," *Appl. Surf. Sci.*, vol. 345, pp. 329–336, 2015.

[23] K. Bharadwaj *et al*., "Green synthesis of silver nanoparticles using Diospyros malabarica fruit extract and assessments of their antimicrobial, anticancer and catalytic reduction of 4-nitrophenol (4-NP)," *Nanomaterials*, vol. 11, no. 8, p. 1999, 2021.

[24] Ahmadi *et al*., "Enhanced photocatalytic degradation of tetracycline and real pharmaceutical wastewater using MWCNT/TiO2 nano-composite," *J. Environ. Manage.*, vol. 186, pp. 55–63, 2017.

[25] Gadewar *et al*., "Unlocking nature's potential: Green synthesis of ZnO nanoparticles and their multifaceted applications–A concise overview," *J. Saudi Chem. Soc.*, vol. 28, no. 1, p. 101774, 2024.

[26] M. Hajiali *et al*., "Application of $TiO_2/ZnFe_2O_4$/glycine nanocatalyst to the treatment of methyl orange dye from aqueous solution: Impacts of dissolved mineral salts on dye removal efficiency," *Scientia Iranica*, vol. 28, no. 3, pp. 1464–1477, 2021.

[27] M. Ramesh, M. Anbuvannan, and G. Viruthagiri, "Green synthesis of ZnO nanoparticles using *Solanum nigrum* leaf extract and their antibacterial activity," *Spectrochim. Acta A Mol. Biomol. Spectrosc.*, vol. 136, pp. 864–870, 2015.

[28] M. Y. Al-darwesh, S. S. Ibrahim, and M. A. Mohammed, "A review on plant extract mediated green synthesis of zinc oxide nanoparticles and their biomedical applications," *Results Chem.*, p. 101368, 2024.

[29] M. Yu *et al*., "Sub-coherent growth of ZnO nanorod arrays on three-dimensional graphene framework as one-bulk high-performance photocatalyst," *Appl. Surf. Sci.*, vol. 390, pp. 266–272, 2016.

[30] B. Chanu *et al*., "Engineered nanomaterial and their interactions with plant–soil system: a developmental journey and opposing facts," *Nanotechnol. Environ. Eng.*, vol. 6, pp. 1–15, 2021.

[31] N. Le-Minh *et al*., "Fate of antibiotics during municipal water recycling treatment processes," *Water Res.*, vol. 44, no. 15, pp. 4295–4323, 2010.

[32] Basnet, T. I. Chanu, D. Samanta, and S. Chatterjee, "A review on bio-synthesized zinc oxide nanoparticles using plant extracts as reductants and stabilizing agents," *J. Photochem. Photobiol. B: Biol.*, vol. 183, pp. 201–221, 2018.

[33] Mishra *et al*., "*Caralluma fimbriata* extract induced green synthesis, structural, optical and photocatalytic properties of ZnO nanostructure modified with Gd," *J. Alloys Compd.*, vol. 685, pp. 656–669, 2016.

[34] P. Nagore *et al*., "Structural properties and antimicrobial activities of *Polyalthia longifolia* leaf extract-mediated CuO nanoparticles," *BioNanoScience*, vol. 11, pp. 579–589, 2021.

[35] P. Ramesh *et al*., "Green synthesis and characterization of biocompatible zinc oxide nanoparticles and evaluation of its antibacterial potential," *Sens. Bio-Sens. Res.*, vol. 31, p. 100399, 2021.

[36] Andreozzi, V. Caprio, A. Insola, and R. Marotta, "Advanced oxidation processes (AOP) for water purification and recovery," *Catal. Today*, vol. 53, no. 1, pp. 51–59, 1999.

[37] D. H. A. Jalill, R. S. Nuaman, and A. N. Abd, "Biological synthesis of Titanium Dioxide nanoparticles by Curcuma longa plant extract and study its biological properties," *World Scientific News*, vol. 49, no. 2, pp. 204–222, 2016.

[38] R. Hamed, R. Z. Obeid, and R. Abu-Huwaij, "Plant mediated-green synthesis of zinc oxide nanoparticles: An insight into biomedical applications," *Nanotechnol. Rev.*, vol. 12, no. 1, p. 20230112, 2023.

[39] R. Verma, S. Pathak, A. K. Srivastava, S. Prawer, and S. Tomljenovic-Hanic, "ZnO nanomaterials: Green synthesis, toxicity evaluation and new insights in biomedical applications," *J. Alloys Compd.*, vol. 876, p. 160175, 2021.

[40] R. Yuvakkumar *et al*., "Novel green synthetic strategy to prepare ZnO nanocrystals using rambutan (*Nephelium lappaceum* L.) peel extract and its antibacterial applications," *Mater. Sci. Eng. C*, vol. 41, pp. 17–27, 2014.

[41] Ambika and M. Sundrarajan, "Green biosynthesis of ZnO nanoparticles using Vitex negundo L. extract: Spectroscopic investigation of interaction between ZnO nanoparticles and human serum albumin," *J. Photochem. Photobiol. B: Biol.*, vol. 149, pp. 143–148, 2015.

[42] S. Drummer, T. Madzimbamuto, and M. Chowdhury, "Green synthesis of transition-metal nanoparticles and their oxides: A review," *Materials*, vol. 14, no. 11, p. 2700, 2021.

[43] S. Gunalan, R. Sivaraj, and V. Rajendran, "Green synthesized ZnO nanoparticles against bacterial and fungal pathogens," *Prog. Nat. Sci.: Mater. Int.*, vol. 22, no. 6, pp. 693–700, 2012.

[44] S. H. Ammar, A. I. Elaibi, and I. S. Mohammed, “Core/shell Fe_3O_4@Al_2O_3-PMo magnetic nanocatalyst for photocatalytic degradation of organic pollutants in an internal loop airlift reactor,” *J. Water Process Eng.*, vol. 37, p. 101240, 2020.

[45] S. Harouni, N. Bouanimba, and N. Boulares, “Synthesis of ZnO Nanostructures Using Sublimation-Condensation and Sol-Gel Methods: Evaluation of the Photocatalytic Degradation Activity of Industrial Dye,” *Acta Phys. Pol. A*, vol. 136, no. 3, 2019.

[46] S. K. Chaudhuri and L. Malodia, “Biosynthesis of zinc oxide nanoparticles using leaf extract of Calotropis gigantea: characterization and its evaluation on tree seedling growth in nursery stage,” *Appl. Nanosci.*, vol. 7, no. 8, pp. 501–512, 2017.

[47] S. Modi *et al*., “Onion Peel Waste Mediated-Green Synthesis of Zinc Oxide Nanoparticles and Their Phytotoxicity on Mung Bean and Wheat Plant Growth,” *Materials*, vol. 15, no. 7, 2022. [Online]. Available: https://doi.org/10.3390/ma15072393

[48] S. Modi and M. H. Fulekar, “Green synthesis of zinc oxide nanoparticles using garlic skin extract and its characterization,” *J. Nanostruct.*, vol. 10, pp. 20–27, 2020.

[49] S. P. Hinge and A. B. Pandit, “Solar-assisted synthesis of ZnO nanoparticles using lime juice: a green approach,” *Adv. Nat. Sci.: Nanosci. Nanotechnol.*, vol. 8, no. 4, p. 045006, 2017.

[50] S. Raina, A. Roy, and N. Bharadvaja, “Degradation of dyes using biologically synthesized silver and copper nanoparticles,” *Environ. Nanotechnol. Monit. Manage.*, vol. 13, p. 100278, 2020.

[51] S. Rasalingam, R. Peng, and R. T. Koodali, “Removal of hazardous pollutants from wastewaters: applications of TiO_2–SiO_2 mixed oxide materials,” *J. Nanomater.*, vol. 2014, p. 10, 2014.

[52] S. Y. Chae, M. K. Park, S. K. Lee, T. Y. Kim, S. K. Kim, and W. I. Lee, “Preparation of size-controlled TiO_2 nanoparticles and derivation of optically transparent photocatalytic films,” presented at [publication details not fully specified], 2003.

[53] B. Rashed, *Photocatalytic Degradation of Ciprofloxacin From Aqueous Solution Using Prepared Green Synthesis TiO_2*, n.d.

[54] Chikan and E. J. McLaurin, “Rapid nanoparticle synthesis by magnetic and microwave heating,” *Nanomaterials*, vol. 6, no. 5, p. 85, 2016.

[55] Y. A. M. Esa and N. Sapawe, “A short review on zinc metal nanoparticles synthesize by green chemistry via natural plant extracts,” *Mater. Today: Proc.*, vol. 31, pp. 386–393, 2020.

[56] Y. Chen, L. Chen, and N. Shang, “Photocatalytic degradation of dimethyl phthalate in an aqueous solution with Pt-doped TiO_2-coated magnetic PMMA microspheres,” *Chemosphere*, vol. 44, pp. 1159–1168, 2001.

[57] Z. H. Jabbar, A. A. Okab *et al*., “Photocatalytic destruction of Congo red dye in wastewater using a novel Ag_2WO_4/Bi_2S_3 nanocomposite decorated g-C_3N_4 nanosheet as

Vol. 33, No.3. \ 2025 ISSN: 2616 - 9916

ternary S-scheme heterojunction: Improving the charge transfer efficiency,” *Diamond Relat. Mater.*, vol. 133, p. 109711, 2023.

[58] Z. H. Jabbar, B. H. Graimed *et al*., “Synthesis of geopolymer for the removal of hazardous waste: a review,” *J. Photochem. Photobiol. A: Chem.*, vol. 441, p. 114734, 2023. [Online]. Available: https://doi.org/10.1016/j.jphotochem.2023.114734

ARTICLE
JOURNAL`S UNIVERSITY OF BABYLON FOR ENGINEERING SCIENCES (JUBES)
مـــجلـة جـــامعة بـــــابـل للعلــــوم الهندسية
Vol. 33, No.3. \ 2025 ISSN: 2616 - 9916

التحلل التحفيزي الضوئي الصديق للبيئة للملوثات العضوية باستخدام أنصاف النواقل النانوية المستخلصة من قشور البصل: مراجعة شاملة

نبأ عبد الجبار الوهاب رشا عبد الأمير الحسيني

قسم هندسة إدارة الموارد المائية، كلية الهندسة، جامعة القاسم الخضراء

nabaaabedalwahab@wrec.uoqasim.edu.iq rasha83@wrec.uoqasim.edu.iq

الخلاصة :-

تتناول هذه المراجعة التحلل التحفيزي الضوئي للملوثات العضوية باستخدام أنصاف النواقل النانوية، لا سيما تلك المستخلصة من قشور البصل، كحل مستدام لمعالجة مياه الصرف. وتسلط الضوء على النشاط التحفيزي العالي، والكفاءة من حيث التكلفة، والاستفادة من الطاقة الشمسية لهذه المواد. تقدم التطورات الحديثة في أنصاف النواقل النانوية المغناطيسية تحسينات في عملية الفصل وقابلية إعادة الاستخدام، مما يعالج قيودًا رئيسية. تظهر المحفزات الضوئية المعدلة مثل TiO_2 و ZnOالتي تم تصنيعها باستخدام طرق السول–جيل، والميكروويف، والتصويتن فوق الصوتي، إمكانات قوية في معالجة المياه الرمادية. كما يعزز دمج التحفيز الضوئي مع المؤكسدات مثل Fe^{3+} من كفاءة التمعدن. وتناقش أيضًا المعلمات التشغيلية بما في ذلك الرقم الهيدروجيني، وتركيز الملوث، وكمية التحميل بالمحفز من أجل تحسين العملية. وتحدد هذه المراجعة اتجاهات واعدة نحو معالجة فعالة وقابلة للتوسيع لمياه الصرف الصحي بالتحفيز الضوئي.

الكلمات الدالة:– تقنية النانو، التخليق الأخضر، قشور البصل، الجسيمات النانوية، الملوثات العضوية.