Proceeding – CAMIC

Cirebon Annual Multidisciplinary International Conference (CAMIC 2024)

Current Review on the Exploring Potential of TiO_2 Catalysts for Efficient Microplastic Removal from Aqueous Solutions

[1st] Mohammad Luqman Ismail
Universiti Kuala Lumpur Branch Campus Malaysian Institute of Chemical and Bioengineering Technology, Lot 1988 Vendor City, 78000 Alor Gajah, Melaka, Malaysia
luqman.ismail0407@gmail.com

[2nd] Norzahir Sapawe
Universiti Kuala Lumpur Branch Campus Malaysian Institute of Chemical and Bioengineering Technology, Lot 1988 Vendor City, 78000 Alor Gajah, Melaka, Malaysia.
norzahir@unikl.edu.my

[3rd] Muhammad Farhan Hanafi
Universiti Kuala Lumpur Branch Campus Malaysian Institute of Chemical and Bioengineering Technology, Lot 1988 Vendor City, 78000 Alor Gajah, Melaka, Malaysia
farhanhanafi@unikl.edu.my

[4th] Hairul Amani Abdul Hamid
Fakulti Sains Gunaan, Universiti Teknologi MARA, 40450 Shah Alam, Selangor Darul Ehsan, Malaysia
h.amani@uitm.edu.my

[5th] Siti Munirah Sidik
Faculty of Science and Mathematics, Universiti Pendidikan Sultan Idris, 35900 Tanjung Malim Perak, Malaysia
smunirah@fsmt.upsi.edu.my

Abstract*— This review explores the potential of titanium dioxide (TiO_2) catalyst for the removal of microplastics from aqueous solution, highlighting their photocatalytic properties, advantages, and challenges. TiO_2, as a widely studied and cost-effective photocatalyst, offers unique benefits for addressing the growing concern of microplastic pollution in water. The article examines various TiO_2-based materials, including pure TiO_2, doped TiO_2, and composite materials, and their effectiveness in degrading or removing microplastics through photocatalytic processes. Key factors such as light intensity, catalyst dosage, pH, and reaction time that influence the photocatalytic efficiency of TiO_2 catalyst are discussed. The review also explores the mechanisms of photocatalytic degradation, including the generation of reactive oxygen species (ROS) and the role of TiO_2 in breaking down microplastic polymers. Furthermore, challenges such as catalyst stability, reusability, and the need for optimization are addressed. The article concludes by proposing future research directions for enhancing the performance of TiO_2 catalyst and their potential application in large-scale water treatment for microplastic removal.

Keywords— ***photocatalytic reaction; microplastic polymers; nanoparticles; reactive radicals; potential catalyst***

I. INTRODUCTION

The accumulation of microplastics in aquatic environments has emerged as a critical global environmental issue, presenting significant risks to biodiversity, ecosystem stability, and human health [1,2]. Defined as plastic particles smaller than 5 mm, microplastics originate from the fragmentation of larger plastic materials due to environmental degradation processes, such as UV radiation, mechanical forces, and microbial activity [3]. These particles persist in the environment due to their chemical stability and resistance to degradation, creating a complex challenge for effective remediation [4]. Their ubiquity in water bodies, including oceans, rivers, and lakes, has raised widespread concern, particularly as they serve as carriers for toxic chemicals and can bioaccumulate within aquatic food chains, ultimately impacting human health through seafood consumption [5,6].

Conventional water treatment methods, such as filtration, sedimentation, and coagulation-flocculation, have proven inadequate for addressing microplastic contamination [7,8]. These techniques are designed to remove larger particles and soluble pollutants but are ineffective for particles in the micro- and nanoscale range due to their small size, buoyancy, and

chemical resilience. Moreover, many of these methods lack the capability to completely degrade microplastics, merely separating them from the water matrix without addressing their persistence [9,10]. This limitation underscores the urgent need for innovative technologies capable of both removing and breaking down microplastics to mitigate their environmental impact effectively.

Photocatalysis has gained significant attention as a potential solution to microplastic pollution, particularly due to its ability to degrade persistent organic pollutants through advanced oxidation processes. Among the various photocatalysts studied, titanium dioxide (TiO_2) has emerged as a frontrunner owing to its exceptional chemical stability, affordability, and environmental compatibility [11,12]. When exposed to UV or visible light, TiO_2 absorbs photons to generate electron-hole pairs, which subsequently produce reactive oxygen species (ROS) such as hydroxyl radicals and superoxide anions. These ROS are highly reactive and capable of breaking down microplastic polymers into smaller, less harmful byproducts [13-15].

The photocatalytic activity of TiO_2 relies on its ability to absorb light energy with wavelengths in the UV range (typically below 385 nm) or, in some modified forms, visible light. Upon excitation, electrons in the valence band of TiO_2 transition to the conduction band, leaving behind holes in the valence band. The electrons and holes react with water and oxygen to generate ROS, which initiate oxidative cleavage of polymer chains within microplastics. This process reduces the molecular weight of the plastic polymers, ultimately transforming them into carbon dioxide, water, and other benign substances [13-15]. Understanding the specific pathways and kinetics of these reactions is crucial for optimizing the degradation process.

Recent research has focused on enhancing the photocatalytic efficiency of TiO_2 through various modifications. Doping with metals (e.g., Fe, Cu, Ag) and non-metals (e.g., N, S, C) has been shown to extend the light absorption range of TiO_2 into the visible spectrum, thereby improving its efficiency under natural sunlight [16]. Similarly, composite formulations combining TiO_2 with other materials, such as graphene oxide or carbon nanotubes, enhance its charge separation efficiency and surface area. These advancements have significantly increased the degradation rates of microplastics under both laboratory and field conditions, demonstrating the potential for practical applications [17].

While TiO_2-based photocatalysis shows great promise, it is essential to compare its performance with other emerging technologies for microplastic removal, such as advanced oxidation processes (AOPs), biological degradation, and magnetic separation techniques. AOPs, such as Fenton reactions and ozonation, also rely on ROS generation but often require additional chemical inputs, making them less sustainable than photocatalysis [18,19]. Biological methods, including enzymatic degradation, are limited by their slower reaction rates and substrate specificity [19]. TiO_2 photocatalysis, in contrast, offers a balance of high efficiency, scalability, and environmental compatibility, making it a competitive option for large-scale deployment [20,21].

Despite its potential, several challenges hinder the widespread adoption of TiO_2-based photocatalysis for microplastic degradation. The need for UV or visible light sources and the potential recombination of electron-hole pairs reduce its overall efficiency. Additionally, the recovery and reuse of TiO_2 photocatalysts in water treatment systems require further refinement to minimize operational costs and environmental impact. Addressing these challenges involves developing cost-effective reactor designs, integrating TiO_2 with renewable light sources, and enhancing catalyst durability to ensure long-term performance in real-world applications.

The application of TiO_2 photocatalysis for microplastic degradation represents a promising avenue for mitigating aquatic plastic pollution. Continued advancements in catalyst design, coupled with innovations in reactor engineering and light harvesting, can enhance the efficiency and practicality of this technology. Future research should prioritize understanding the environmental fate of degradation byproducts, optimizing reaction conditions for diverse water matrices, and evaluating the economic feasibility of large-scale systems. By addressing these gaps, TiO_2-based photocatalysis could become a cornerstone technology in combating the pervasive issue of microplastic pollution, contributing to the restoration and sustainability of aquatic ecosystems.

II. METHOD

To prepare the TiO_2 catalyst using the impregnation method, dimethylformamide (DMF) is utilized as the solvent due to its inert reactivity and excellent capability to disperse particles uniformly. Sonication is employed to ensure thorough mixing and proper dispersion of the TiO_2 particles [22-26].

The process begins by accurately weighing the required amount of TiO_2 powder using a calibrated analytical balance. The weighed TiO_2 powder is then transferred into a clean and dry glass beaker. An appropriate volume of DMF is added to the TiO_2 powder, with the amount of solvent carefully calculated to create a suspension that is well-dispersed but not excessively diluted. The mixture is gently stirred using a magnetic stirrer or a mechanical stirrer to ensure initial integration of the powder and solvent [22-26].

To further ensure uniform dispersion and prevent the formation of particle agglomerates, the mixture is subjected to sonication. The beaker containing the suspension is placed in an ultrasonic bath or treated with a probe sonicator for 15 minutes. The sonication process facilitates the breakdown of any clumps, ensuring the TiO_2 particles are evenly distributed within the DMF. This step is crucial for creating a homogeneous suspension and maximizing the performance of the final catalyst.

Following sonication, the mixture is heated gently to a temperature range of 60–80°C. The heating process allows for the gradual evaporation of excess DMF. During this stage, continuous stirring is maintained to prevent localized drying or uneven distribution of the remaining TiO_2. The process is continued until the mixture thickens and forms a paste-like

consistency, indicating that most of the solvent has been removed [22-26].

The resulting thickened mixture is then transferred into a shallow, heat-resistant dish and placed in an oven preheated to 100–120°C. The material is allowed to dry completely in the oven for 24 hours to ensure that all residual DMF and any remaining moisture are removed. This thorough drying process prepares the material for the subsequent calcination step.

After drying, the TiO_2 powder is transferred into a ceramic or quartz crucible that is suitable for high-temperature operations. The crucible is placed in a muffle furnace, and the temperature is gradually increased at a controlled rate of 5°C per minute until the target temperature of 550°C is reached. The material is then held at this temperature for 3 hours in a normal air atmosphere. This calcination process eliminates any residual organic material, enhances the crystalline structure, and develops the chemical properties essential for catalytic activity. Once calcination is complete, the furnace is allowed to cool naturally to room temperature before removing the sample to avoid thermal shock [22-26].

To confirm the quality and performance of the prepared TiO_2 catalyst, optional characterization techniques can be applied. X-ray diffraction (XRD) can be used to analyze the crystalline phases, while scanning electron microscopy (SEM) combined with energy-dispersive X-ray spectroscopy (EDS) can provide insights into the surface morphology and elemental distribution. Brunauer-Emmett-Teller (BET) analysis can be conducted to determine the specific surface area and pore volume, and UV-Vis diffuse reflectance spectroscopy (UV-Vis DRS) can be utilized to evaluate the optical properties and bandgap of the material [22-26].

Finally, the prepared TiO_2 catalyst is stored in an airtight container or a desiccator to protect it from environmental contaminants and moisture. Proper storage ensures the long-term stability and effectiveness of the catalyst for its intended applications. This comprehensive procedure, with careful attention to sonication, controlled drying, and calcination, ensures the preparation of a high-quality TiO_2 catalyst suitable for diverse industrial and environmental uses.

III. RESULTS AND DISCUSSION

COMPARISON OF MICROPLASTIC DEGRADATION METHODS

1. Photocatalysis Beyond TiO_2

In recent years, photocatalysis has gained attention as an effective method for environmental remediation, particularly in the degradation of microplastics [27]. While titanium dioxide (TiO_2) remains the most widely studied and used photocatalyst due to its high efficiency and stability, alternative materials like zinc oxide (ZnO) and graphitic carbon nitride (g-C_3N_4) have also shown significant potential in photocatalytic applications [28]. These materials offer unique advantages in terms of their light absorption properties and photocatalytic efficiency, making them valuable candidates for various environmental applications [27,28].

Zinc oxide (ZnO) is particularly promising due to its strong photocatalytic activity under UV light. It has a wide bandgap that allows it to generate a high number of reactive oxygen species (ROS), which are essential for breaking down pollutants such as microplastics. ZnO's photocatalytic performance is highly effective under UV illumination, but its practical use is limited by its poor stability in acidic and basic environments. In such conditions, ZnO can undergo dissolution or structural degradation, reducing its long-term catalytic efficiency. This lack of stability in varying pH conditions presents a significant drawback for its application in real-world environments, where water chemistry often fluctuates [29].

Graphitic carbon nitride (g-C_3N_4) offers another alternative photocatalyst, particularly due to its ability to absorb visible light effectively. The narrow bandgap of g-C_3N_4 allows it to utilize solar energy more efficiently compared to TiO_2, which primarily absorbs UV light. This makes g-C_3N_4 a more sustainable option for photocatalytic degradation under natural sunlight [30]. However, despite its advantage in visible light absorption, g-C_3N_4 suffers from a high recombination rate of photogenerated electron-hole pairs, which reduces its overall photocatalytic efficiency. The rapid recombination of these charge carriers limits the formation of reactive species [30], thereby hindering the material's ability to effectively degrade contaminants such as microplastics.

To address these issues, various strategies have been proposed to enhance the photocatalytic performance of ZnO and g-C_3N_4 [28]. For ZnO, improving its stability can be achieved through surface modifications, such as coating or doping with other materials that prevent dissolution and enhance its robustness in acidic or basic environments [31]. For g-C_3N_4, efforts have focused on reducing the electron-hole recombination rate by incorporating co-catalysts, doping with metals or non-metals, and developing hybrid composites. These modifications can help improve charge separation, increase the material's efficiency, and expand its practical application in environmental cleanup [30].

Both ZnO and g-C_3N_4 have shown great promise as photocatalysts for microplastic degradation, but their challenges must be addressed for them to be more widely applicable in real-world scenarios. ZnO’s instability in varying pH conditions and g-C_3N_4’s high recombination rate are significant hurdles that must be overcome. By exploring innovative approaches to modify these materials, it is possible to enhance their photocatalytic properties and make them more effective for environmental remediation. The successful development of these materials could lead to more sustainable and efficient photocatalytic technologies for tackling pollution and improving water quality worldwide.

2. Biological Treatment

Biological treatment, specifically biodegradation, has emerged as a promising approach for the breakdown of microplastics. This process utilizes microorganisms to degrade plastic polymers into harmless byproducts such as carbon dioxide (CO_2) and water (H_2O) [32]. Among the microorganisms identified for this purpose, Ideonella sakaiensis has garnered significant attention due to its ability to degrade polyethylene terephthalate (PET) polymers. This bacterium produces enzymes that break down the PET structure, making it an exciting candidate for combating plastic pollution [32].

However, despite the potential of biological treatment, there are several limitations that hinder its practical application. One of the primary challenges is the relatively slow degradation rate of microplastics. Microorganisms, including I. sakaiensis, typically require extended periods to degrade plastic materials, which are not ideal for large-scale environmental remediation. Additionally, the degradation rate can vary depending on environmental factors such as temperature, pH, and the presence of other substances, further complicating the process [32].

Another significant limitation is the narrow range of polymers that can be biodegraded by microorganisms like I. sakaiensis. While I. sakaiensis has shown promise in degrading PET, its ability to degrade other types of plastic, such as polyethylene (PE) or polypropylene (PP), is limited. These plastics, which are among the most commonly found in the environment, are not readily degraded by I. sakaiensis or other known microorganisms. As a result, biological treatment using I. sakaiensis is only applicable to specific types of plastic, which limits its utility in addressing the broader issue of microplastic pollution [32].

Furthermore, the effectiveness of biological treatment is constrained by the environmental conditions required for microbial activity. Factors such as temperature, moisture, and nutrient availability can significantly affect the ability of microorganisms to degrade microplastics. In natural environments, the conditions necessary for optimal microbial degradation are not always present, which can further slow down or inhibit the process [32].

Despite these challenges, biological treatment remains an area of active research and development. Efforts to improve the degradation rate and broaden the scope of applicable polymers are ongoing, with some researchers exploring genetic modification or enzyme optimization to enhance microbial degradation capabilities. By overcoming the current limitations, biological treatment could play a critical role in the sustainable management of microplastic pollution, offering an eco-friendlier alternative to conventional methods such as incineration or landfill disposal [32].

3. Chemical Oxidation

Chemical oxidation has emerged as a promising approach for the degradation of microplastics, utilizing oxidative agents such as ozone or Fenton's reagent to break down plastic polymers. This method is effective in reducing the size of microplastics and decreasing their toxicity, offering a potential solution to the growing issue of plastic pollution [33]. Ozone, for example, is a strong oxidizing agent that can attack the chemical bonds in plastics, leading to their degradation into smaller, less harmful fragments [34]. Similarly, Fenton's reagent, a mixture of hydrogen peroxide and iron salts, generates hydroxyl radicals that can also break down various plastic polymers [35].

Despite the effectiveness of chemical oxidation, several significant challenges hinder its widespread implementation. One of the primary concerns is the high energy requirement of the process. Both ozone and Fenton's reagent require substantial amounts of energy to generate the reactive species needed for oxidation, making the process energy-intensive and potentially costly. This high energy demand raises questions about the overall sustainability and practicality of chemical oxidation for large-scale microplastic remediation, particularly when compared to other treatment methods [33,34].

Another issue with chemical oxidation is the potential formation of secondary pollutants during the degradation process [35]. The breakdown of microplastics through oxidative agents may result in the production of byproducts that are themselves harmful to the environment. For example, ozone treatment can generate intermediate products, such as aldehydes and carboxylic acids, which may have toxic effects if released into ecosystems [34]. Similarly, Fenton's reagent can lead to the formation of reactive oxygen species (ROS) that, while effective in degrading plastics, can also pose a risk to aquatic organisms if not carefully controlled [36]. These secondary pollutants complicate the environmental impact assessment of chemical oxidation as a treatment method [37].

In addition to the energy and byproduct concerns, the efficiency of chemical oxidation can be influenced by the type and composition of the plastic being treated. Different polymers respond differently to oxidative agents, and some materials may require more aggressive treatments or longer exposure times to achieve effective degradation [38]. The heterogeneous nature of microplastic pollution, with various types of plastics mixed in the environment, further complicates the application of chemical oxidation as a one-size-fits-all solution.

Despite these challenges, chemical oxidation remains an important tool in the fight against microplastic pollution. Ongoing research is focused on optimizing the process to improve its energy efficiency, reduce the formation of harmful byproducts, and enhance its applicability to a wider range of plastic types. Advances in technology and the development of more targeted oxidation methods could make chemical oxidation a viable and sustainable option for addressing microplastic pollution on a larger scale, complementing other treatment strategies such as biological and physical approaches.

4. Mechanical Fragmentation

Mechanical fragmentation is one of the physical approaches used to break down microplastics into smaller particles, facilitating their management and potential subsequent treatment. Common techniques such as milling and ultrasonication are employed to reduce the size of plastic fragments, thereby increasing the surface area for further processing [39]. Milling uses mechanical forces to grind larger plastic pieces into smaller, more manageable particles [40], while ultrasonication applies high-frequency sound waves to generate intense pressure waves that cause microplastics to fragment [39]. These methods can help in laboratory-scale studies and certain industrial applications where size reduction is necessary before further treatment processes.

While mechanical fragmentation is effective at reducing the size of microplastic particles, it does not address the underlying issue of microplastic accumulation in the environment. The fragments produced through milling or ultrasonication remain in the environment as microplastics, posing a continued threat

to ecosystems. This is a significant limitation of mechanical methods, as the fragmented plastics, though smaller, are still present in aquatic and terrestrial habitats, potentially causing harm to wildlife and contaminating ecosystems [41]. Unlike chemical or biological processes, which can degrade plastics into non-toxic byproducts, mechanical fragmentation merely alters the physical form of the plastic without eliminating its environmental persistence.

Furthermore, the effectiveness of mechanical fragmentation can be limited by the nature of the microplastics being treated. Different types of plastics exhibit varying levels of hardness, flexibility, and resistance to mechanical forces. For instance, more rigid plastics such as polystyrene may fragment more easily, while flexible plastics like polyethylene can be more challenging to break down. Additionally, the high-energy consumption of these mechanical processes can be a concern, especially when used on large volumes of microplastics. The need for specialized equipment and energy inputs further complicates the scalability and efficiency of mechanical fragmentation as a stand-alone solution.

In addition to the fragmentation of microplastics, mechanical processes like ultrasonication can also lead to the generation of secondary microplastic particles [39,41]. For example, during ultrasonic treatment, the energy can break the plastic into even smaller particles, potentially increasing the total number of microplastic particles in the environment. This phenomenon complicates the overall effectiveness of mechanical fragmentation in tackling the microplastic pollution problem, as it may contribute to a larger accumulation of microplastic debris rather than its complete removal [39,41].

Overall, while mechanical fragmentation provides an essential means of reducing the size of microplastics, it does not provide a comprehensive solution to the environmental issue of microplastic pollution. The persistent presence of these smaller particles in the environment and the potential for secondary fragmentation are significant challenges. As a result, mechanical fragmentation is often considered a complementary technique to other methods, such as chemical, biological, or advanced physical treatments, which may offer more effective routes for the complete removal or degradation of microplastics from ecosystems.

5. Thermal Degradation

Thermal degradation processes, such as pyrolysis, offer a promising approach to the treatment of microplastics by converting them into gases, oils, and char through the application of high heat [42,43]. Pyrolysis, in particular, is a chemical decomposition process that occurs in the absence of oxygen, where heat breaks down plastics into simpler components, often producing valuable byproducts like bio-oil or syngas [42,43]. This method is effective in reducing the volume of microplastics and can potentially recover energy from plastic waste, making it a candidate for large-scale plastic waste management and microplastic remediation.

However, while thermal degradation methods such as pyrolysis can effectively reduce the size and volume of microplastics, they come with several significant drawbacks. One of the most prominent challenges is the high energy input required to reach the temperatures necessary for pyrolysis, which often exceeds 400°C [44]. This energy-intensive process raises concerns about its sustainability, as the carbon footprint associated with heating plastic waste to such high temperatures may offset the environmental benefits of the waste reduction. The energy consumption required for thermal degradation is one of the key factors limiting the widespread adoption of these methods for microplastic management [44].

Additionally, thermal degradation methods pose environmental and health risks due to the potential formation of toxic emissions during the process. While pyrolysis is designed to operate in the absence of oxygen, incomplete decomposition or improper conditions can lead to the release of harmful compounds such as dioxins, furans, and volatile organic compounds (VOCs), which can be hazardous to both the environment and human health [44]. These toxic byproducts are a major concern when considering the application of thermal degradation at an industrial scale, as they could exacerbate environmental pollution rather than alleviating it.

Another challenge with thermal degradation is the variability in the composition of microplastics. Different types of plastics have varying thermal properties and chemical structures, which can affect their decomposition rates and the nature of the byproducts produced. For example, thermoplastics like polyethylene and polypropylene may degrade differently compared to thermosetting plastics or bioplastics, leading to inconsistencies in the quality and composition of the resulting gases, oils, and char [45,46]. This variability complicates the optimization of the pyrolysis process and may result in the production of unwanted or harmful byproducts, depending on the types of plastics being treated.

Despite these challenges, thermal degradation remains a viable option for managing microplastics, particularly when combined with advanced technologies to minimize emissions and improve energy efficiency [42-47]. Ongoing research aims to develop more energy-efficient pyrolysis systems, enhance the purification of byproducts, and implement cleaner technologies to reduce the environmental impact of toxic emissions. By addressing these issues, thermal degradation could serve as an important tool for microplastic disposal, especially in combination with other methods that focus on complete degradation or recycling of plastic materials [47].

In conclusion, this current review provides a comprehensive analysis of the potential of TiO_2 catalysts in comparison with other catalytic materials and treatment methods for the efficient removal of microplastics from aqueous solutions. The review highlights the advantages and limitations of TiO_2-based photocatalysis, including its high photocatalytic efficiency, reusability, and potential for large-scale application. Furthermore, a comparative evaluation of alternative catalysts and emerging removal techniques is presented to offer insights into their respective effectiveness, mechanisms, and feasibility for real-world implementation.

To facilitate better understanding and provide a concise yet informative summary, the key findings of this review have been systematically generalized and summarized in Table I and Figure I, offering a structured representation of the discussed catalysts and methodologies. These visual and tabular

representations aim to assist researchers and practitioners in identifying the most suitable approaches for microplastic removal, contributing to the advancement of sustainable water treatment solutions.

TABLE I. METHOD COMPARISON ON MICROPLASTICS DEGRADATION

Method	Effectiveness	Strengths	Weaknesses
Photocatalysts	Moderate	Visible light-active (g-C_3N_4)	Stability issues, high recombination rate
Biological Treatment	Low	Eco-friendly	Slow, polymer-specific
Chemical Oxidation	High	Fast degradation	Energy-intensive, secondary pollutants
Mechanical Fragmentation	Moderate	Simple technology	Produces micro-fragments
Thermal Degradation	High	Converts plastics into valuable products	Energy-intensive, potential

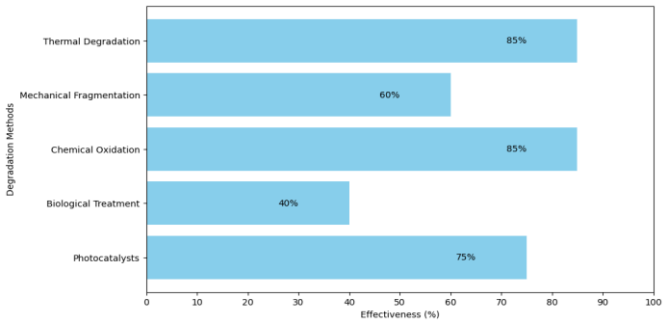

FIGURE I. EFFECTIVENESS OF VARIOUS METHODS FOR MICROPLASTIC DEGRADATION

IV. CONCLUSIONS

Among the numerous methods explored for microplastic degradation, TiO_2-based photocatalysis stands out as a highly promising approach due to its efficiency, cost-effectiveness, and environmental compatibility. Titanium dioxide (TiO_2) is a widely studied photocatalyst known for its ability to harness ultraviolet (UV) light to break down organic pollutants, including microplastics. Its relatively low cost, non-toxic nature, and high stability under UV light make it an attractive option for addressing microplastic pollution in various environments. TiO_2-based photocatalysis offers a sustainable, green solution to microplastic degradation by converting harmful plastics into less toxic substances, such as smaller fragments or mineralized byproducts like carbon dioxide and water.

However, despite its many advantages, TiO_2-based photocatalysis faces several challenges that hinder its widespread application for microplastic degradation. One of the main limitations is its strong dependence on UV light for activation. Since UV light represents only a small portion of the solar spectrum, TiO_2's photocatalytic activity under natural sunlight is limited, reducing its effectiveness in outdoor applications. Additionally, the need for UV light sources can increase energy consumption and operational costs, making the process less viable for large-scale, real-world use. This challenge necessitates the development of TiO_2 modifications that can extend its activity into the visible light spectrum, where sunlight is abundant, thus improving its practical applicability.

Another significant challenge is the reusability of TiO_2 catalysts. While TiO_2 is generally stable under UV light, its performance can degrade over multiple cycles due to factors like particle agglomeration, surface deactivation, or the adsorption of reaction byproducts. This affects the long-term efficacy of TiO_2-based photocatalysis and limits its practical use for continuous or large-scale microplastic degradation. To address this issue, strategies such as immobilizing TiO_2 on substrates, designing more robust composites, or enhancing the stability of the catalyst through surface modifications are being explored to improve its reusability and performance over extended periods.

In addition to reusability concerns, TiO_2-based photocatalysis faces challenges related to its limited efficiency in degrading certain types of microplastics, particularly under visible light conditions. Although TiO_2 is effective under UV light, it struggles to efficiently degrade microplastics when exposed to visible light. This limitation can be addressed through doping or the creation of TiO_2 composites with other materials that can shift the absorption spectrum of TiO_2 into the visible region. For example, doping TiO_2 with elements like nitrogen, sulfur, or carbon, or combining TiO_2 with materials such as graphene or carbon-based compounds, has been shown to enhance its photocatalytic performance under visible light, broadening its applicability.

To overcome these challenges and optimize TiO_2-based photocatalysis for microplastic degradation, researchers are investigating synergistic combinations with other degradation methods, such as chemical oxidation. For instance, combining TiO_2 photocatalysis with oxidative agents like ozone or Fenton's reagent could enhance the degradation efficiency of microplastics, leading to more complete breakdowns in less time. These hybrid approaches hold great promise for scaling up TiO_2-based photocatalytic processes and improving their overall effectiveness in real-world applications, offering a multifaceted solution to the growing problem of microplastic pollution.

REFERENCES

[1] Hasan, M., Bin, M. F., Ahmed, S., Maksud, A., Jubayer, A., and Rahman, A. (2024). Microplastics in Aquatic Ecosystems: Sources, Impacts, and Challenges for Biodiversity, Food Security, and Human Health-A Meta Analysis. Journal of Angiotherapy, 8(11), 1-12.

[2] Yu, R.S., and Singh, S. (2023). Microplastic pollution: threats and impacts on global marine ecosystems. Sustainability, 15(17), 13252.

[3] Golmohammadi, M., Musavi, S.F., Habibi, M., Maleki, R., Golgoli, M., Zargar, M., Dumée L.F., Baroutian, S., and Razmjou, A. (2023). Molecular mechanisms of microplastics degradation: A review. Separation and Purification Technology, 309, 122906.

[4] Song, Q., Zhang, Y., Ju, C., Zhao, T., Meng, Q., and Cong, J. (2024). Microbial strategies for effective microplastics biodegradation: insights and innovations in environmental remediation. Environmental Research, 263, 120046.

[5] Ali, N., Khan, M.H., Ali, M., Ahmad, S., Khan, A., Nabi, G., Ali, F., Bououdina, M., and Kyzas, G. Z. (2024). Insight into microplastics in

the aquatic ecosystem: Properties, sources, threats and mitigation strategies. Science of The Total Environment, 913, 169489.

[6] Pothiraj, C., Gokul, T. A., Kumar, K. R., Ramasubramanian, A., Palanichamy, A., Venkatachalam, K., Pastorino, P., Barcelò, D., Balaji, P., and Faggio, C. (2023). Vulnerability of microplastics on marine environment: A review. Ecological Indicators, 155, 111058.

[7] Elgarahy, A.M., Eloffy, M.G., Priya, A.K., Yogeshwaran, V., Elwakeel, K.Z., Yang, Z., and Lopez-Maldonado, E. A. (2024). A review on the synergistic efficacy of sonication-assisted water treatment process with special attention given to microplastics. Chemical Engineering Research and Design, 206, 524-552.

[8] Ahmed, S.F., Islam, N., Tasannum, N., Mehjabin, A., Momtahin, A., Chowdhury, A.A., Almomani, F., and Mofijur, M. (2024). Microplastic removal and management strategies for wastewater treatment plants. Chemosphere, 347, 140648.

[9] Nasir, M.S., Tahir, I., Ali, A., Ayub, I., Nasir, A., Abbas, N., Sajjad, U., and Hamid, K. (2024). Innovative technologies for removal of microplastic: A review of recent advances. Heliyon, 10(4), e25883.

[10] Matavos-Aramyan, S. (2024). Addressing the microplastic crisis: A multifaceted approach to removal and regulation. Environmental Advances, 17, 100579.

[11] Hanafi, M. F., Hassan, N., and Sapawe, N. (2022). Performance Studies of TiO2 Catalyst for Phenol Degradation. Materials Science Forum, 1076, 215-220.

[12] Lu, L., Luo, T., Zhao, Y., and Cai, Z. (2020). Recent progress of microplastics in the environment: Occurrence, analysis, and remediation. Journal of Hazardous Materials, 383, 121682.

[13] Yang, Z., Li, Y., and Zhang, G. (2024). Degradation of microplastic in water by advanced oxidation processes. Chemosphere, 357, 141939.

[14] Kumar, R., Verma, A., Rakib, M.R.J., Gupta, P.K., Sharma, P., Garg, A., Girard, P., and Aminabhavi, T.M. (2023). Adsorptive behavior of micro (nano) plastics through biochar: Co-existence, consequences, and challenges in contaminated ecosystems. Science of the Total Environment, 856, 159097.

[15] Ding, L., Yu, X., Guo, X., Zhang, Y., Ouyang, Z., Liu, P., Zhang, C., Wang, T., Jia, H., and Zhu, L. (2022). The photodegradation processes and mechanisms of polyvinyl chloride and polyethylene terephthalate microplastic in aquatic environments: Important role of clay minerals. Water Research, 208, 117879.

[16] Abdi, N. (2024). A Review of Advances in TiO2 Photocatalysts: Exploring the Benefits of Metal and Nonmetal Doping. Recent Developments in Management and Industrial Engineering, 1-19.

[17] Peressut, A.B., Cristiani, C., Dotelli, G., Dotti, A., Latorrata, S., Bahamonde, A., Gasco, A., Hermosilla, D., and Balzarotti, R. (2023). Reduced graphene oxide/waste-derived TiO2 composite membranes: preliminary study of a new material for hybrid wastewater treatment. Nanomaterials, 13(6), 1043.

[18] Iyyappan, J., Gaddala, B., Gnanasekaran, R., Gopinath, M., Yuvaraj, D., and Kumar, V. (2024). 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, 9, 100599.

[19] Zoppas, F.M., Sacco, N., Soffietti, J., Devard, A., Akhter, F., and Marchesini, F.A. (2023). Catalytic approaches for the removal of microplastics from water: Recent advances and future opportunities. Chemical Engineering Journal Advances, 16, 100529.

[20] Abhishek, B., Jayarama, A., Rao, A. S., Nagarkar, S. S., Dutta, A., Duttagupta, S. P., Prabhu, S.S., and Pinto, R. (2024). Challenges in photocatalytic hydrogen evolution: Importance of photocatalysts and photocatalytic reactors. International Journal of Hydrogen Energy, 81, 1442-1466.

[21] Ruan, X., Li, S., Huang, C., Zheng, W., Cui, X., and Ravi, S.K. (2024). Catalyzing Artificial Photosynthesis with TiO2 Heterostructures and Hybrids: Emerging Trends in a Classical yet Contemporary Photocatalyst. Advanced Materials, 36(17), 2305285.

[22] Perego, C., Villa, P. (1997). Catalyts preparation methods. Catalysis Today, 34, 281-305.

[23] Mehrabadi, B. A. T., Eskandari, S., Khan, U.m White, R. D., Regalbuto, J. R. (2017). A review of preparation methods for supported metal catalysts. Advances in Catalysis, 61, 1-35.

[24] Hanafi, M. F., Sapawe, N. (2020). A review on the water problem associate with organic pollutants derived from phenol, methyl orange, and remazol brilliant blue dyes. Materials Today: Proceedings, 31, A141-A150.

[25] Sapawe, N., Jalil, A. A., Triwahyono, S., Shah, M. I. A., Jusoh, R., Saleh, N. F. M., Hameed, B. H., Karim, A. H. (2013). Cost-effective microwave rapid synthesis of zeolite NaA for removal of methylene blue. Chemical Engineering Journal, 229, 388-398.

[26] Sapawe, N., Jalil, A. A., Triwahyono, S. (2013). One-pot electro-synthesis of ZrO2–ZnO/HY nanocomposite for photocatalytic decolorization of various dye-contaminants. Chemical Engineering Journal, 225, 254-265.

[27] Adamu, H., Bello, U., IbrahimTafida, U., Garba, Z.N., Galadima, A., Lawan, M.M., Abba, S.I., and Qamar, M. (2024). Harnessing bio and (Photo) catalysts for microplastics degradation and remediation in soil environment. Journal of Environmental Management, 370, 122543.

[28] Sharma, J.S.J. (2025). Design and Optimization of a Sustainable Water Purification System Using Photocatalytic Nanomaterials. In Shodh Prakashan (Eds.), Journal of Engineering & Scientific Research, 1(1), 27-46.

[29] Rana, S., Gupta, T., and Singh, P. (2022). Photocatalytic degradation of plastics using ZnO nanomaterials. Environmental Nanotechnology, 7(4), 2076.

[30] Bhanderi, D., Lakhani, P., and Modi, C.K. (2024). Graphitic carbon nitride (gC3N 4) as an emerging photocatalyst for sustainable environmental applications: a comprehensive review. RSC Sustainability, 2, 265-287.

[31] Navidpour, A.H., Hosseinzadeh, A., Zhou, J.L., and Huang, Z. (2023). Progress in the application of surface engineering methods in immobilizing TiO2 and ZnO coatings for environmental photocatalysis. Catalysis Reviews, 65(3), 822-873.

[32] Hasan, M., Hasan, M.R., and Rashid, T.U. (2024). Bioremediation of Microplastics by Microorganisms: Trends, Challenges, and Perspectives. In Ameen F., Bhat, S.A., and Kumar, V. (Eds.) Microbial Bioremediation and Multiomics Technologies for Sustainable Development: Recent Trends, 13, 49-79.

[33] Xing, R., Sun, H., Du, X., Lin, H., Qin, S., Chen, Z., and Zhou, S. (2023). Enhanced degradation of microplastics during sludge composting via microbially-driven Fenton reaction. Journal of Hazardous Materials, 449, 131031.

[34] Hawkins, W. L. (1984). Polymer degradation. In Polymer degradation and stabilization (pp. 3-34). Berlin, Heidelberg: Springer Berlin Heidelberg.

[35] Huang, C. P., Dong, C., and Tang, Z. (1993). Advanced chemical oxidation: its present role and potential future in hazardous waste treatment. Waste management, 13(5-7), 361-377.

[36] Hu, K., Zhou, P., Yang, Y., Hall, T., Nie, G., Yao, Y., and Wang, S. (2021). Degradation of microplastics by a thermal Fenton reaction. ACS ES&T Engineering, 2(1), 110-120.

[37] Wang, J., and Wang, S. (2021). Toxicity changes of wastewater during various advanced oxidation processes treatment: An overview. Journal of Cleaner Production, 315, 128202.

[38] Rani, M., Ducoli, S., Depero, L.E., Prica, M., Tubić, A., Ademovic, Z., and Federici, S. (2023). A complete guide to extraction methods of microplastics from complex environmental matrices. Molecules, 28(15), 5710.

[39] Hwangbo, S., Kim, I. Y., Ko, K., Park, K., Hong, J., Kang, G., and Lee, T.G. (2024). Preparation of fragmented polyethylene nanoplastics using a focused ultrasonic system and assessment of their cytotoxic effects on human cells. Environmental Pollution, 362, 125009.

[40] Bhagia, S., Gallego, N.C., Hiremath, N., Harper, D.P., Lowden, R.A., Lowden, R.R., and Ragauskas, A.J. (2021). Fine grinding of thermoplastics by high speed friction grinding assisted by guar gum. Journal of Applied Polymer Science, 138(32), 50797.

[41] Richard, C. M., Dejoie, E., Wiegand, C., Gouesbet, G., Colinet, H., Balzani, P., and Renault, D. (2024). Plastic pollution in terrestrial ecosystems: current knowledge on impacts of micro and nano fragments on invertebrates. Journal of Hazardous Materials, 135299.

[42] Nawaz, A., Haddad, H., Shah, M. A., Uddin, S., Hossain, M.M., and Razzak, S.A. (2024). Fueling sustainability: Co-pyrolysis of microalgae biomass and waste plastics for renewable energy and waste mitigation. Biomass and Bioenergy, 187, 107303.

[43] Rathi, B.S., Kumar, P.S., and Rangasamy, G. (2023). A sustainable approach on thermal and catalytic conversion of waste plastics into fuels. Fuel, 339, 126977.

[44] Hasan, M.M., Haque, R., Jahirul, M.I., and Rasul, M.G. (2025). Pyrolysis of plastic waste for sustainable energy Recovery: Technological advancements and environmental impacts. Energy Conversion and Management, 326, 119511.

[45] Jiao, H., Ali, S. S., Alsharbaty, M. H. M., Elsamahy, T., Abdelkarim, E., Schagerl, M., and Sun, J. (2024). A critical review on plastic waste life cycle assessment and management: Challenges, research gaps, and future perspectives. Ecotoxicology and Environmental Safety, 271, 115942.

[46] Kibria, M. G., Masuk, N. I., Safayet, R., Nguyen, H. Q., and Mourshed, M. (2023). Plastic waste: challenges and opportunities to mitigate pollution and effective management. International Journal of Environmental Research, 17(1), 20.

[47] Lee, S., Kim, D., and Choi, H. (2022). Pyrolysis of microplastics for environmental applications. Environmental Science: Nano, 9(3), 758–768.