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A Comprehensive Review on Role of Magnesium Spinel Ferrite in Photo-catalysis

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ABSTRACT:

This review explores the effectiveness of magnesium ferrite-based materials as photocatalysts for breaking down organic pollutants, such as antibiotics and synthetic dyes, in wastewater. It focuses on how various synthesis approaches, doping techniques, and composite formations influence their degradation performance. Due to its narrow band gap and magnetic nature, magnesium ferrite is capable of utilizing a wider range of light while also allowing for easy recovery after treatment. The review also sheds light on the underlying photocatalytic mechanisms, presenting magnesium ferrite as a promising candidate for developing affordable and reusable catalysts. Overall, this concise summary highlights recent progress and underscores the significant potential of magnesium ferrite in addressing the environmental challenges posed by organic wastewater contaminants.

1. Introduction

The textile industry is widely recognized as one of the leading contributors to environmental pollution, particularly due to the high volume of wastewater it generates during various processing stages. This sector is known for its excessive use of water and over 8000 different chemicals, making it a major source of both surface and groundwater contamination [1,2]. On average, textile operations produce approximately 200–350 m^3 of wastewater per tonn of finished product, with a chemical oxygen demand (COD) output of around 100 kg per tonn [3,4]. The effluents from these industries commonly contain both organic and inorganic pollutants, with synthetic dyes and antibiotics being among the most persistent and hazardous contaminants.

Synthetic dyes, including azo, vat, disperse, reactive, and sulphur dyes, are frequently used in textile processing and are known for their complex chemical structures that resist natural degradation [5]. These dyes severely impact aquatic ecosystems by reducing sunlight penetration and subsequently lowering dissolved oxygen levels in water bodies [6]. In addition to environmental effects, they pose significant risks to human health. For instance, some azo dye derivatives are carcinogenic and have been associated with bladder cancer, along with causing skin and eye irritation [7–9].

Antibiotics represent another category of organic pollutants increasingly found in industrial wastewater. Substances such as sulfamethoxazole, ciprofloxacin, and tetracycline are commonly detected in aquatic systems [10,11]. The overuse and improper disposal of antibiotics have led to the emergence of antibiotic-resistant bacteria in the environment, a growing concern for both current and future generations [12].

In response to these threats, several water treatment technologies have been developed, including adsorption, membrane separation, catalytic degradation, ionizing radiation, and magnetically assisted processes [13]. However, many of these methods are either inefficient in degrading persistent organic pollutants or are cost-prohibitive for large-scale applications. Among the emerging solutions, photocatalysis has attracted significant attention due to its eco-friendly nature and ability to utilize sunlight for degrading pollutants [14–16]. This method typically employs semiconductor-based photocatalysts that are relatively inexpensive, easy to produce, and simple to recover from treated water systems [17,18].

Traditional photocatalysts such as titanium dioxide (TiO_2), Tungsten Trioxide (WO_3) and zinc oxide (ZnO) have demonstrated good photocatalytic activity under UV light, but their wide band gaps limit visible light

absorption, thus restricting their efficiency under solar irradiation [17, 56-61]. To overcome these limitations, researchers have shifted focus toward spinel ferrites (general formula AB_2O_4), which exhibit narrower band gaps and excellent magnetic and chemical properties [19–21].

One such promising material is magnesium ferrite ($MgFe_2O_4$)**,** a soft magnetic n-type semiconductor with a suitable band gap for visible light absorption. It offers high thermal and chemical stability, good electron–hole separation, and high saturation magnetization, making it easier to recover from treated solutions using an external magnetic field [22–25]. These properties not only enhance its efficiency but also make it ideal for reuse under varying environmental conditions.

Various synthesis routes—such as sol-gel, co-precipitation, and microwave sintering—have been developed for producing magnesium ferrite, each affecting the size, morphology, and surface characteristics of the material, and thus its photocatalytic performance [26]. This review aims to provide a comprehensive overview of the recent progress in the field of magnesium ferrite-based photocatalysts for the degradation of harmful dyes and antibiotics. It also explores the impact of synthesis methods, structural features, and dopants on its photocatalytic activity and outlines future directions for its application in sustainable wastewater treatment.

2. Literature Review

2.1 Magnesium Ferrite: Structure and Photocatalytic Properties

Magnesium ferrite ($MgFe_2O_4$) is a type of spinel ferrite with a cubic crystal structure, where Mg^{2+} and Fe^{3+} ions occupy the interstitial positions in a mixed distribution. The general spinel formula AB_2O_4 describes its configuration, in which 'A' and 'B' sites represent tetrahedral and octahedral coordination sites, respectively. The unit cell of a spinel structure contains 64 tetrahedral and 32 octahedral positions, among which only 8 and 16 are typically occupied [27]. Spinels are classified into three types based on their cation distribution: normal, inverse, and mixed. In a normal spinel, divalent cations occupy the tetrahedral (A) sites while trivalent cations are located in the octahedral (B) sites. In inverse spinels, trivalent cations take the A-sites, and both divalent and remaining trivalent cations share the B-sites. In the case of mixed spinels—such as magnesium ferrite—the cations are randomly distributed among A and B sites [28-29].

Magnesium ferrite is considered a soft magnetic material, characterized by moderate coercivity, high electrical resistivity, and magnetic reusability [30]. As a ternary semiconductor, it is capable of absorbing a wide range of the visible light spectrum due to its relatively narrow bandgap, typically ranging from 1.5 to 3.0 eV [31]. Upon illumination, $MgFe_2O_4$ generates electron–hole pairs, which participate in surface redox reactions with organic contaminants, ultimately degrading them. These properties render it a highly suitable material for photocatalytic applications, particularly in wastewater treatment.

One of the significant advantages of using magnesium ferrite is its magnetic nature, which enables easy separation and recovery of the photocatalyst from the treated solution using an external magnetic field. This property enhances its reusability and economic viability [32]. Compared to other materials like TiO_2, g-C_3N_4, and graphene-based composites—which often suffer from wider bandgaps, non-magnetic properties, and cost-inefficient synthesis—$MgFe_2O_4$ provides a more practical alternative for photocatalytic applications.

Several studies have focused on optimizing the synthesis of $MgFe_2O_4$ to enhance its photocatalytic efficiency. For instance, Heidari et al. employed a solution combustion synthesis method using various fuels such as citric acid, EDTA, and glycine. X-ray diffraction (XRD) analysis confirmed a partially inverse spinel structure, with crystallite sizes ranging from 35 nm (for EDTA) to 57 nm (for glycine) [33]. Scanning electron microscopy (SEM) revealed differences in particle morphology depending on the fuel type.

In another study, Sripriya et al. synthesized magnesium ferrite using a microwave-assisted technique. The structural characterization via XRD showed a cubic spinel phase with a lattice constant of 8.347 Å and an average crystallite size of 15.42 nm. The optical bandgap, determined using the Kubelka–Munk function, was approximately 1.91 eV. Their samples demonstrated remarkable photocatalytic activity by degrading 96.48% of methylene blue dye, attributed to the high surface area of 71.85 m^2/g [34].

Similarly, Singh et al. utilized the sol–gel method followed by calcination at various temperatures (300°C to 450°C) to investigate the influence of thermal treatment on the material's properties. XRD confirmed the formation of pure $MgFe_2O_4$ with increasing crystallite size at higher calcination temperatures. The cation redistribution from B-sites to A-sites was observed with increasing temperature, influencing magnetic parameters. The saturation magnetization (Ms) increased from 7.52 to 23.54 emu/g, while coercivity (Hc) decreased, indicating reduced grain boundary pinning. The Curie temperature also declined slightly, likely due to weakened A–B super exchange interactions [35].

These findings underline magnesium ferrite's adaptability, strong photocatalytic performance, and structural tunability, making it a promising candidate for the degradation of organic pollutants in wastewater.

Studies have consistently demonstrated that magnesium ferrite possesses excellent structural and magnetic properties, which play a key role in enhancing photocatalytic degradation efficiency. Its properties can be tailored through various synthesis methods, offering significant potential to improve overall photocatalytic performance. These findings suggest promising opportunities for advancing degradation technologies using magnesium ferrite.

2.1.1 Magnesium Ferrite for Dye Degradation in Wastewater Treatment

Magnesium ferrite ($MgFe_2O_4$) has emerged as a highly promising photocatalyst for wastewater treatment due to its favorable electronic band structure and advantageous surface characteristics. Its photocatalytic efficiency enables it to effectively degrade various categories of dyes, including non-ionic, cationic, and anionic types.

Several studies have validated the efficiency of magnesium ferrite in dye degradation processes. Nguyen et al. reported that magnesium ferrite calcined at 500 °C exhibited a degradation efficiency of 89.73% for methylene blue (MB) within 240 minutes, whereas samples calcined at 600 °C showed a lower efficiency of 69.17%. The improved performance at 500 °C is attributed to the smaller particle size and increased surface area, which enhance photocatalytic activity [36].

In another investigation, Fardood et al. evaluated the degradation of malachite green (MG) using magnesium ferrite nanoparticles. With a fixed catalyst dosage of 0.015 g and dye concentration ranging between 5 and 20 mg/L, the degradation efficiency reached up to 98% in just 60 minutes [36-37].

Riyanti et al. explored the degradation of Congo red (CR) and found a degradation rate of 99.62% under specific conditions: pH 6, CR concentration of 10 mg/L, 2.5 mM H_2O_2, and 180 minutes of irradiation. These results underscore magnesium ferrite's high catalytic performance under optimized conditions [38].

Furthermore, Sundararajan et al. demonstrated the enhanced performance of magnesium-doped cobalt ferrite ($Co_{0.6}Mg_{0.4}Fe_2O_4$), which achieved a 99.5% degradation efficiency for Rhodamine B (RhB). In contrast, undoped cobalt ferrite ($CoFe_2O_4$) exhibited a significantly lower efficiency of 73.0%, indicating the beneficial role of magnesium incorporation in improving catalytic activity [39].

Collectively, these findings highlight the significant potential of magnesium ferrite-based materials as efficient photocatalysts for the degradation of a wide range of organic dyes in wastewater treatment applications.

2.2 Factors Influencing the Photocatalytic Activity of Magnesium Ferrite ($MgFe_2O_4$)

The photocatalytic efficiency of magnesium ferrite in degrading organic dyes is strongly influenced by several parameters, including the synthesis method, dopant incorporation, and composite formulation. These factors alter the material's structural, morphological, and electronic characteristics, thereby affecting its overall performance in photocatalysis.

2.2.1 Influence of Synthesis Method

Several synthesis routes have been employed to fabricate magnesium ferrite nanoparticles, such as co-precipitation, sol-gel, combustion, glycine–nitrate, hydrothermal, solvothermal, and ball milling [26,40,41]. Each of these methods results in variations in particle size, crystallinity, surface area, and magnetic properties, all of which play a crucial role in determining photocatalytic activity. Furthermore, the choice of synthesis method can significantly impact the cost-

effectiveness and scalability of the photocatalyst production.

2.2.1.1 Sol-Gel Technique

The sol-gel method is a versatile and widely used bottom-up technique for synthesizing nanomaterials. It involves three primary steps: the preparation of a homogeneous precursor solution (typically using metal nitrates), gelation through hydrolysis and condensation, and thermal treatment to obtain metal oxide nanoparticles. In many cases, citric acid is used as a chelating agent, and ammonia serves to adjust the pH of the solution. The addition of ethylene glycol may also aid in the polymerization and gelation process.

One of the key advantages of this method is the ability to produce materials with small crystallite size, high purity, and homogeneous phase distribution at relatively low calcination temperatures. This results in improved catalytic performance due to enhanced surface activity and better dispersion of active sites.

For instance, Nguyen et al. reported that magnesium ferrite synthesized via combustion methods exhibited a crystallite size increase from 18 nm to 61 nm depending on the calcination temperature, with a maximum methylene blue (MB) degradation efficiency of 89.73% under light and in the presence of H_2O_2 [36].

In another study, Cabrera et al. compared the auto-combustion and polymerization methods. They found that crystallite sizes ranged from 7–16 nm, and the material degraded 75% of MB dye under light irradiation [42].

Furthermore, Fardood et al. prepared magnesium ferrite using a sol-gel method without any organic solvents. The resulting nanoparticles had a crystallite size of approximately 11 nm and achieved a remarkable 98% degradation of malachite green (MG) under visible light within 60 minutes at an initial dye concentration of 20 mg/L [37].

These findings underline the crucial role of synthesis technique, particularly the sol-gel method, in tailoring the properties of magnesium ferrite for enhanced photocatalytic performance.

2.2.1.2 Solid-State Method

The solid-state reaction method is one of the most traditional and widely employed techniques for producing ceramic materials at industrial scale. This process typically involves the thermal decomposition and interdiffusion of solid precursors at elevated temperatures to form a new crystalline phase with defined stoichiometry and structure. Commonly used precursors include metal oxides, nitrates, and alkoxides, which are mixed in stoichiometric ratios and subjected to high-temperature treatment to drive the reaction forward.

This technique is advantageous due to its simplicity, scalability, and cost-effectiveness, making it suitable for the mass production of nanomaterials. Mechanical methods such as ball milling are often used to enhance homogeneity before thermal processing. However, a limitation of this method is the formation of materials with larger particle size, higher degree of agglomeration, and lower phase purity compared to wet-chemical methods like sol-gel.

Despite these drawbacks, researchers are increasingly exploring this approach to reduce synthesis costs and develop environmentally sustainable production routes. For example, Das et al. synthesized magnesium ferrite using a solid-state method, achieving an average crystallite size of 12.4 nm. Remarkably, the material demonstrated complete degradation (100%) of malachite green (MG) dye within 50 seconds in the presence of hydrogen peroxide under visible light irradiation [42].

2.2.1.3 Co-Precipitation Method

The co-precipitation technique is a popular wet-chemical synthesis method that involves the simultaneous precipitation of multiple metal ions from a solution by adding a precipitating agent, usually a strong base such as NaOH or NH_4OH. Metal nitrates, acetates, or chlorides are typically dissolved in solvents like water or ethanol to create a homogeneous solution. The process yields fine, uniform nanoparticles with controlled morphology, high surface area, and low agglomeration.

The primary advantages of this method include lower synthesis temperature, precise stoichiometric control, and smaller crystallite size. However, the requirement for strong alkaline agents can raise concerns about waste disposal in large-scale production.

In one study, George et al. fabricated Cu-doped magnesium ferrite ($MgFe_2O_4$) via co-precipitation. Metal nitrates were dissolved in water, and 2 M NaOH was used to maintain a pH of 13. After heating the mixture at 80 °C for 3 hours, the resulting precipitates were washed, dried, and calcined at 650 °C for 8 hours. XRD analysis showed crystallite sizes in the 12–44 nm range. The samples exhibited strong absorption in the visible spectrum and demonstrated a 97% degradation efficiency of methylene blue (MB) dye under UV light irradiation for 3 hours with H_2O_2 as a sacrificial agent [43].

Similarly, Ajeesha et al. synthesized Ni-substituted $MgFe_2O_4$ ($Mg_{1-x}Ni_xFe_2O_4$, $0 \le x \le 1$) via co-precipitation. A pH of 13 was maintained using hydroxide solution, and the mixture was heated at 80 °C. The resulting precipitate was centrifuged, washed, and calcined at 650 °C for 8 hours. The samples attained a cubic spinel structure with crystallite size of 24 nm and a surface area ranging from 11.76 to 20.48 m^2/g. Photocatalytic evaluation under visible light for MB degradation showed an efficiency of 86% after 3 hours [Ajeesha et al., 2021].

2.2.1.4 Hydrothermal Method

The hydrothermal method is a solution-based synthesis approach that utilizes high-temperature and high-pressure conditions within a Teflon-lined autoclave to promote crystal growth in aqueous media. The technique is especially effective for producing high-purity, well-crystallized nanomaterials without requiring subsequent calcination.

Metal salts like nitrates are commonly used as starting materials. The hydrothermal environment allows for controlled nucleation and crystal growth, resulting in fine particles with uniform size and good crystallinity. The temperature and duration of treatment, as well as the concentration of the reactants, play a critical role in determining the final morphology and phase structure.

For instance, Khaliq et al. synthesized pure, Ni-doped, and Cr-doped magnesium ferrite using the hydrothermal route. Metal nitrates were dissolved in deionised water, and 1.5 M NaOH was added to adjust the pH. After continuous stirring, the solution was transferred to a Teflon-lined autoclave and heated at 150 °C for 20 hours. The resulting brownish precipitates, with a pH between 10 and 11, were washed thoroughly to remove contaminants. These materials exhibited strong photocatalytic activity toward the degradation of crystal violet dye, demonstrating the method’s efficacy in producing active photocatalysts [45-48].

2.2.1.5 Specimen Drying and Synthesis Approaches

To obtain the final product, the prepared specimens were dried at 120 °C for four hours. The photocatalytic activity was evaluated using crystal violet dye, achieving a maximum degradation efficiency of 97% within 100 minutes [45]. These findings highlight that the choice of synthesis method significantly impacts the photocatalytic performance of magnesium ferrite. Therefore, selecting a suitable synthesis strategy is essential for developing efficient and cost-effective magnesium ferrite photocatalysts.

Furthermore, the synthesis technique plays a critical role in enabling large-scale industrial production. Methods such as the solid-state synthesis are feasible for industrial applications and can yield bulk quantities of magnesium ferrite. However, such physical methods may compromise the crystallinity and limit control over crystallite size. In contrast, chemical synthesis techniques offer enhanced precision in tailoring the structural and functional properties of magnesium ferrite. Despite their superior control, these methods face challenges regarding scalability and cost-effectiveness, which hinders their broader industrial implementation [46-48]. Hence, further research is necessary to optimize synthesis processes that balance scalability, efficiency, and economic viability for industrial applications.

2.2.2 Influence of Dopants on Photocatalytic Activity

Doping has been identified as a powerful strategy to enhance the photocatalytic efficiency of ferrites. As semiconducting materials, ferrites are inherently suitable for photocatalytic processes, and doping can further refine their performance by modifying properties such as crystallite size, band gap, charge separation, and material stability. However, the specific effects of doping depend on the type, concentration of the dopant, and synthesis route employed. To optimize doping strategies, researchers typically examine key parameters like band structure, charge carrier behavior, and surface reactivity.

Several studies have reported significant enhancements in magnesium ferrite photocatalytic activity through

doping. For instance, Bessy et al. synthesized cobalt-doped magnesium ferrite using a combustion route involving egg white as a bio-template. The metal nitrates were added to a homogenized egg white solution and stirred for 60 minutes, followed by drying at 80 °C and calcination at 500 °C for 2 hours. Increasing cobalt doping reduced the crystallite size from 23 to 18 nm and improved the degradation efficiency from 91% to 95% [49].

Similarly, Vishnu et al. employed a microwave-assisted combustion technique to produce $NixMg1{-}xFe2O4$ (x = 0–0.6) nanoparticles for degrading Rhodamine B and methylene blue dyes. The optimized composition, $Ni0.4Mg0.6Fe2O4$, demonstrated remarkable degradation rates of 98.1% for MB and 97.9% for RhB within 120 minutes [50].

Singh et al. prepared titanium-doped magnesium ferrite nanoparticles ($Mg1{-}xTixFe2O4{+}\delta$, x = 0–1.0) via a sol-gel method to investigate the degradation of Rhodamine B. Increasing Ti content led to reduced particle size (e.g., 37.6 to 23.4 nm for x = 0.25 to 0.75) and a corresponding change in the band gap from 2.53 eV (x = 0) to a minimum of 2.24 eV (x = 0.5), followed by a slight increase at higher doping levels. The sample with x = 0.5 exhibited the best photocatalytic performance, achieving 98% degradation efficiency at pH 6.0 [51].

These studies confirm that doping is a crucial tool for modulating structural and electronic properties, leading to improved photocatalytic outcomes. Dopants that reduce crystallite size tend to enhance the surface area and active sites, resulting in greater degradation efficiencies.

2.2.3 Role of Composites in Enhancing Photocatalysis

Another effective strategy for improving photocatalytic degradation efficiency is the formation of composite materials. By combining magnesium ferrite with other substances, such as semiconductors or carbon-based materials, synergistic interactions can be achieved that enhance photocatalytic performance.

Das et al. synthesized a composite consisting of zinc, hydroxyapatite, and magnesium ferrite ($Zn/HAP/MgFe_2O_4$) using a solid-state method followed by composite formation. The system achieved complete (100%) degradation of malachite green (MG) in the presence of hydrogen peroxide and followed first-order kinetics [52].

Alhashmialameer et al. developed a series of materials including undoped magnesium ferrite (MgF), copper-doped magnesium ferrite (CMgF), and a composite with reduced graphene oxide (CMgF@rGO) for the degradation of benzimidazole and methylene blue. The MB degradation efficiencies of MgF, CMgF, and CMgF@rGO were 54.54%, 76.5%, and 92.4%, respectively, over 240 minutes. For benzimidazole, the CMgF@rGO composite achieved 50% degradation within the same time frame [53].

These results demonstrate that incorporating other functional materials with magnesium ferrite can significantly enhance photocatalytic activity, either by facilitating charge transfer, reducing recombination rates, or increasing light absorption capabilities.

A composite of magnesium ferrite and magnesium titanate was synthesized to enhance the degradation of acid black dye. Initially, 0.2 g of polyvinyl alcohol (PVA) was dissolved in 20 ml of ethylene glycol, while 0.1 g of $MgFe_2O_4$ was dispersed in 20 ml of methanol and sonicated for 15 minutes. After stirring the solution for 10 minutes, 0.22 g of titanium tetra isopropoxide (yielding 0.1 g of $MgTiO_3$) was added, followed by 0.5 ml of acetic acid. The mixture was again subjected to ultrasonication for 10 minutes. To adjust the pH to 4–5, 17 ml of ethylene glycol was gradually introduced, and the entire solution was further sonicated for 2 hours. The mixture was aged in a water bath at 35 °C for three days, then dried at 120 °C for six hours and finally calcinated at 700 °C for two hours. The resulting composite showed a significantly higher degradation efficiency—reaching up to 80% in 180 minutes—compared to pure magnesium titanate, which achieved less than 60% under identical conditions [54-55].

3. Future Perspectives and Challenges

Magnesium ferrite has demonstrated promise as an efficient and cost-effective photocatalyst, with a range of synthesis techniques enabling control over its physicochemical properties. However, significant research gaps remain in enhancing its photocatalytic performance, particularly for practical applications. Several limitations continue to hinder the widespread adoption of magnesium ferrite-based photocatalysis,

including issues related to cost-efficiency, catalyst recovery, and the design of scalable and robust photocatalytic reactors.

One of the key findings in recent studies is the positive influence of doping on improving the photocatalytic activity of $MgFe_2O_4$. In addition to doping, parameters such as pH, pollutant type, and catalyst dosage also play vital roles in determining degradation efficiency. Nonetheless, most investigations have been limited to controlled laboratory settings and have evaluated performance primarily under ideal conditions.

Real-world wastewater is far more complex, typically containing a mixture of pollutants, varying pH levels, high salinity, and reduced light penetration. These factors can significantly affect the degradation capability of the catalyst. Therefore, future research should focus on evaluating magnesium ferrite under such realistic conditions and developing strategies to maintain its activity in challenging environments. Emphasis should also be placed on designing scalable systems and enhancing the recyclability and long-term stability of the catalyst to ensure feasibility for industrial-scale wastewater treatment.

A comprehensive analysis of magnesium ferrite-based photocatalysis, particularly considering aspects such as recoverability, reusability, and environmental sustainability, is essential for advancing research in this field. Greater emphasis should be placed on practical, real-world applications, with careful selection of synthesis methods that enhance cost-effectiveness. Although magnesium ferrite photocatalysts exhibit strong potential for wastewater treatment, their successful implementation on a larger scale is currently limited. Addressing these challenges will be key to unlocking their full capabilities and establishing them as efficient and viable photocatalysts for environmental remediation.

4. Conclusions

Magnesium ferrite has proven to be a highly effective and versatile photocatalyst for the degradation of various organic pollutants in wastewater, including dyes and antibiotics. Its notable photocatalytic efficiency, combined with favorable properties such as magnetic recoverability, chemical stability, and low toxicity, makes it a strong candidate for sustainable wastewater treatment technologies. This review has highlighted not only its high degradation potential—often exceeding 90% in a short period—but also the key parameters influencing its performance, including pH, catalyst loading, temperature, and light source.

While the laboratory-scale results are promising, practical implementation at the industrial scale requires further research focused on catalyst optimization, reactor design, cost-effectiveness, and energy efficiency. Future advancements should also consider the integration of renewable energy sources to enhance sustainability.

Overall, magnesium ferrite offers a promising pathway toward eco-friendly, efficient, and economically viable water purification. Continued research and innovation in this field can significantly contribute to global efforts in pollution control, water conservation, and environmental sustainability.

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