

Photocatalytic Degradation of Malachite Green: A Systematic Review of Catalyst Performance, Mineralization, and the Reporting Gaps Limiting Environmental Application

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Systematic Review

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Abstract

Malachite green (MG) is a toxic, persistent dye that resists conventional water treatment, making photocatalytic degradation a promising alternative. This systematic review and comparative quantitative synthesis evaluated 24 studies (2020–2025) on MG photocatalysts, comparing removal efficiency, reaction kinetics, mineralization, and reusability, with rate constants recalculated where necessary to ensure cross-study consistency. Because reported decolorization is largely saturated (90–100%), meaningful performance differences emerged only when kinetics, adsorption capacity, mineralization, and reusability were evaluated together. Two distinct performance routes were identified rapid-kinetics catalysts (e.g., ZnO/ZnS, AC/TiO₂) and high-capacity adsorption–photocatalysis hybrids (e.g., NFO@C, Cu-MOFs) together with a third group of balanced composites (e.g., BC-TiO₂-ZnO, CQDs/MXene) performing credibly across all metrics, all driven by hydroxyl and superoxide radical generation and enhanced by heterojunction design and carbon or magnetic supports that suppress charge recombination and enable recovery. However, real-world translation remains limited by inconsistent light conditions, minimal real-wastewater validation, and sparse mineralization, toxicity, and durability data. Practical MG treatment will require reusable, LED-compatible photocatalysts validated under standardized protocols, with harmonized reporting enabling machine learning–guided catalyst optimization.

1. Introduction

Malachite Green (MG), a persistent cationic triphenylmethane dye, is a significant environmental contaminant owing to its toxicity, mutagenicity, and resistance to biodegradation; conventional treatments frequently fail to achieve complete mineralization, leaving hazardous by-products (Srivastava et al. 2004; Singh and Arora 2011; Kwan et al. 2020; Wilayat et al. 2024; Culp et al. 2006; Al-Tohamy et al. 2022). Widely used in textile dyeing, paper manufacturing, and aquaculture, MG is restricted in many regions following documented MG/leucomalachite green (LMG) contamination in fish and aquatic biota, with both compounds exhibiting genotoxic and carcinogenic potential (Srivastava et al. 2004; Singh and Arora 2011; Kwan et al. 2020; Wilayat et al. 2024; Culp et al. 2006; Al-Tohamy et al. 2022; Ouallal et al. 2024; Gharavi-nakhjavani et al. 2023).

Advanced photocatalytic degradation using engineered nanomaterials offers a promising MG removal solution with potential complete mineralization under visible, solar, or LED light (Al-Tohamy et al. 2022; Pare et al. 2022) though cross-study comparison remains difficult due to inconsistent reporting of kinetics, mineralization, and durability data (Singh and Arora 2011; Al-Tohamy et al. 2022; Ouallal et al. 2024). Traditional methods (adsorption, coagulation, and biological treatment) achieve decolorization without complete mineralization and often generate secondary pollution with high chemical/energy demands (Singh and Arora 2011; Al-Tohamy et al. 2022; Ouallal et al. 2024; Wang and Wang 2018). Heterogeneous photocatalysis, using UV/visible/LED light and semiconductor catalysts, offers reduced secondary waste and improved oxidative performance via ROS generation (Al-Tohamy et al. 2022; Bopape et al. 2024; Ren et al. 2021; Khan et al. 2024; Khosravi-Far et al. 2024; Zahedi et al. 2025; Tan et al. 2025; Zhang et al. 2021; Gao et al. 2022) aided by advances in bandgap tuning and heterojunction design (Ren et al. 2021; Khan et al. 2024; Khosravi-Far et al. 2024; Zahedi et al. 2025; Tan et al. 2025).

Despite strong laboratory performance, key limitations persist: LEDs remain underutilized relative to UV/xenon/mercury lamps (Khosravi-Far et al. 2024; Zahedi et al. 2025); durability is rarely tested beyond 3–5 cycles (Meena et al. 2024; Hasan et al. 2020); mineralization/toxicity assessment remains inconsistent (TOC/COD, LC-MS/GC-MS) (Guo et al. 2025); real-wastewater validation is largely absent (Ma et al. 2024); green synthesis lacks scale-up/cost analysis (Tanuj et al. 2024; Yulizar et al. 2023); and although machine learning is increasingly applied to nanomaterial design (Mahapatra and Singh 2023), none of the MG photocatalysis studies identified here employed AI-assisted optimization. Addressing these gaps through standardized LED-based protocols, long-term reusability testing, real-effluent validation, and AI-assisted design is essential for translating MG photocatalysis from bench-scale research to industrial application.

Aim of This Systematic Review

This systematic review compares 24 studies on photocatalyst design for malachite green (MG) degradation, evaluating experimental conditions, degradation efficiency, reusability, and reaction mechanisms. Its principal objective is to identify the most effective and reusable photocatalytic systems, while secondary objectives include standardizing experimental comparisons, assessing catalyst stability, clarifying dominant reaction mechanisms, and highlighting gaps limiting real-world scalability.

2. Methodology

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al. 2021). As the review analyzed previously published studies and involved no human or animal participants, ethical approval was not required. This review was not prospectively registered. PROSPERO (Booth et al. 2012) is restricted to systematic reviews reporting at least one health-related outcome in human populations, and a synthesis of catalyst performance falls outside its scope. The absence of a prospective protocol is acknowledged as a limitation.

2.1. Data Sources and Search Strategy

A systematic search was conducted in PubMed, Scopus, and Web of Science (WoS) to identify peer-reviewed articles published between January 2015 and March 2026. The search was first performed in June 2025 and updated in March 2026 using an identical strategy; the update retrieved no additional records meeting the eligibility criteria. Search terms relating to photocatalysis, photodegradation, LED, ultraviolet light, malachite green, organic dyes, wastewater treatment, and environmental pollution were combined using Boolean operators as follows: ((photocatalysis OR photodegradation OR LED OR ultraviolet light) AND (malachite green OR organic dyes) AND (wastewater treatment OR environmental pollution)). The search strategy combined free-text keywords with Medical Subject Headings (MeSH) terms where supported, notably in PubMed. Only articles published in English were considered. The same search string was applied across all three databases, with database-specific syntax adjustments where required.

Title

Photocatalytic Degradation of Organics dyes - Malachite Green Wastewater Treatment.

MeSH term

((photocatalysis OR photodegradation OR LED OR ultraviolet light) AND (malachite green OR organic dyes) AND (wastewater treatment OR environmental pollution)).

Question

what are the most effective photocatalytic material and conditions for malachite green degradation?

2.2. Eligibility Criteria

Articles were included if they met all of the following criteria PICO:

1. Problem: wastewater contaminated with malachite green contributing to environmental pollution;
2. Intervention: photocatalysis using LED, ultraviolet light, visible light or other oxidation processes;
3. Comparison: Conventional wastewater treatment methods (adsorption, chemical oxidation) or different photocatalysis;
4. Outcome: efficient degradation of organic dyes, reduction in water pollution, and improved sustainability;
5. Publication characteristics: peer-reviewed primary research articles published in English between January 2015 and March 2026.

Articles were excluded if they met any one or more of the following criteria:

1. Narrative or systematic reviews;
2. Editorials, expert opinions, comments (commentary), methodological article, or conference abstracts and proceedings;
3. Studies of non-photocatalytic degradation mechanisms, or studies focused on other dyes unless MG degradation was specifically reported;
4. Articles not published in English, and articles published outside the January 2015 to March 2026 window;

2.3. Data Extraction, Synthesis, and Comparative Quantitative Analysis

Records retrieved from the searches were managed in Zotero, and duplicate records were removed; titles and abstracts were then screened for relevance. Full texts of potentially eligible articles were then obtained and assessed against the inclusion criteria. Screening and data extraction were performed independently and in parallel by two reviewers (F.F. and A.Sh.), with any discrepancies resolved through discussion and cross-checking against the original publications. From each article the following information was extracted (Tables 1–2, Table S1, Online Resource 1): article title, publication year, country of origin, study aims, methodology, sample size, data collection and measurement approach, study quality, reported k_{app} , method of calculation of k_{app} (Tables S2–S3, Online Resource 1), normalization procedures, reaction time and kinetics, mineralization indicators (TOC/COD), cross-study comparison metrics, study population, catalyst type, synthesis method, lamp type, degradation efficiency, reaction time, degradation mechanism, reusability, and reported advantages.

Owing to substantial methodological heterogeneity among the included studies in catalyst loading, light source and intensity, reactor configuration, and initial MG concentration, a pooled statistical meta-analysis was not appropriate. A comparative quantitative synthesis without meta-analysis (SWiM) (Campbell et al. 2020) approach was therefore adopted: extracted performance metrics (removal efficiency, rate constants, reusability, and TOC/COD reduction where reported) were tabulated, normalized where possible, and compared descriptively across catalyst classes using Microsoft Excel. Where pseudo-first-order rate constants were not reported, they were recalculated from the reported removal efficiency and reaction time as $k = -\ln(1 - X)/t$, where X is the fractional MG removal at time t. For studies reporting 100% removal, X was capped at 0.9999 to permit calculation; such values are conservative estimates. Because no pooled effect estimates were computed, formal heterogeneity statistics (e.g., I^2) and sensitivity analyses were not applicable; robustness was instead addressed qualitatively through the study quality appraisal (Table S1, Online Resource 1) and by examining the influence of experimental conditions on reported outcomes. Three included studies employed hybrid or variant systems: sonophotocatalysis (Hasan et al. 2020), catalytic wet peroxide oxidation with added H_2O_2 and a photo-Fenton contribution (Bhasin and Mishra 2025), and MG oxalate rather than MG chloride (Meena et al. 2024). These studies were retained because photocatalysis was the principal degradation mechanism, but their results are not directly comparable with purely photocatalytic systems and were interpreted with this caveat.

2.4. Quality Appraisal

No validated risk-of-bias instrument exists for laboratory-based photocatalysis studies, as established tools such as Cochrane RoB 2 (Sterne et al. 2019) and ROBINS-I (Sterne et al. 2016) are designed for clinical and epidemiological research. A custom appraisal rubric was therefore developed for this review, informed by published reporting recommendations for heterogeneous photocatalysis and advanced oxidation process benchmarking frameworks. Each included study was appraised across thirteen domains: novelty of the photocatalyst; environmental relevance; clarity of the synthesis method; extent of material characterization; experimental design and control setup; completeness of reported reaction conditions; mechanistic analysis; evaluation of reusability and stability; assessment of mineralization by TOC or COD; inclusion of real-sample testing; statistical analysis and reproducibility; identification of research gaps; and discussion of environmental impact and scalability (Table S1, Online Resource 1). The appraisal was qualitative and domain-based: each domain was assessed descriptively rather than assigned a numeric score, since numeric weighting in the absence of a validated instrument would imply false precision. Per-domain assessments are reported narratively in Table S1, Online Resource 1. Appraisal was conducted independently by both

reviewers (F.F. and A.Sh.), with disagreements resolved by consensus. Risk of bias arising from missing results was assessed qualitatively rather than statistically: formal methods for detecting reporting bias, such as funnel plots or Egger's test, require pooled effect estimates and were therefore not applicable. Selective outcome reporting was instead captured through the appraisal domains covering mineralization, reusability and real-sample testing, and the resulting reporting gaps are quantified in Section 3.4. Certainty in the body of evidence was likewise appraised narratively across the thirteen domains rather than by GRADE, which is structured around clinical outcome domains and patient-important effects and does not transfer to laboratory catalyst performance; the consequent limits on confidence are stated in Section 4.6.

3. Results

3.1. Study Selection

The systematic search identified 4,274 records (Scopus, $n = 1,247$; PubMed, $n = 591$; Web of Science, $n = 2,436$). Before screening, 769 records were removed: 350 duplicate records were removed using Zotero's duplicate detection function, and 419 review articles and systematic reviews were identified and removed manually by both reviewers on the basis of title and abstract. The remaining 3,505 records were screened by title and abstract, of which 3,164 were excluded as not relevant to the review question. The full texts of the remaining 341 reports were assessed for eligibility, and 317 were excluded for the following reasons: the study did not concern photocatalytic degradation ($n = 114$); the target pollutant was a dye other than malachite green ($n = 161$); insufficient data were reported on degradation efficiency or catalyst reusability ($n = 12$); and the irradiation source was not specified or fell outside the scope of the review ($n = 30$). A total of 24 studies met all eligibility criteria and were included in the final synthesis (Fig. 1) (Page et al. 2021).

Although the search window extended from January 2015 to March 2026, all 24 included studies were published between 2020 and 2025, reflecting the recent acceleration of research on engineered photocatalysts for malachite green degradation.

Figure 1 PRISMA 2020 flow diagram of the study identification, screening, and selection process

3.2. Characteristics of Included Studies

Table 1 summarizes 24 studies (2020–2025) on photocatalytic MG degradation, conducted across countries including India, China, Egypt, Iran, Saudi Arabia, South Africa, and Indonesia (Khosravi-Far et al. 2024; Zahedi et al. 2025; Meena et al. 2024; Hasan et al. 2020; Guo et al. 2025; Ma et al. 2024; Tanuj et al. 2024; Yulizar et al. 2023; Bhasin and Mishra 2025; Mostafa and Amdeha 2022; Zhu et al. 2021; Abdullah et al. 2024; Li et al. 2022; Mohan et al. 2021; Shao et al. 2023; El-Hout et al. 2020; Jasrotia et al. 2022; Himanshi et al. 2025; Liu et al. 2024; Pang et al. 2021; Tiwari et al. 2023; Devi et al. 2023; Wang et al. 2021; Mbuyazi and Ajibade 2025). Studies focused on novel photocatalysts (metal ferrites (Hasan et al. 2020; Jasrotia et al. 2022; Himanshi et al. 2025), MOFs (Bhasin and Mishra 2025), heterojunctions (Guo et al. 2025; Li et al. 2022), doped semiconductors (Tanuj et al. 2024; Yulizar et al. 2023), and carbon-based nanocomposites (Zahedi et al. 2025; El-Hout et al. 2020; Pang et al. 2021)), synthesized via hydrothermal, sol-gel, co-precipitation, or green methods, with characterization via XRD, SEM, FTIR, UV-Vis, and BET, and testing under UV, visible, or solar light (Khosravi-Far et al. 2024; Zahedi et al. 2025; Hasan et al. 2020; Guo et al. 2025; Ma et al. 2024; Tanuj et al. 2024; Yulizar et al. 2023; Bhasin and Mishra 2025; Mostafa and Amdeha 2022; Zhu et al. 2021; Abdullah et al. 2024; Li et al. 2022; Mohan et al. 2021; Shao et al. 2023; El-Hout et al. 2020; Jasrotia et al. 2022; Himanshi et al. 2025). MG concentrations ranged from 5–150 mg/L (Li et al. 2022; Liu et al. 2024; Tiwari et al. 2023), with several studies incorporating reusability testing (Khosravi-Far et al. 2024; Ma et al. 2024; Pang et al. 2021; Tiwari et al. 2023) and statistical optimization (Khosravi-Far et al. 2024; Tiwari et al. 2023; Mbuyazi and Ajibade 2025). Nearly all relied on synthetic dye solutions rather than real wastewater, with only a few testing additional pollutants (Tanuj et al. 2024; Wang et al. 2021; Mbuyazi and Ajibade 2025) or antibacterial effects (Guo et al. 2025), highlighting strong catalyst innovation but a persistent gap in real-wastewater validation (Guo et al. 2025; Ma et al. 2024; Tiwari et al. 2023; Devi et al. 2023).

Table 1
Characteristics of the included studies (From 24 articles)

Authors	Article Title	Publication Year	Location	Aims/Purpose	Methodology	Sample Size	Study Population
(Hasan et al. 2020)	Sonophotocatalytic Degradation of Malachite Green by Nanocrystalline Chitosan-Ascorbic Acid@NiFe ₂ O ₄ Spinel Ferrite	2020	India, Saudi Arabia	Evaluate sonophotocatalytic MG degradation using green-synthesized chitosan-ascorbic acid@NiFe ₂ O ₄ .	Co-precipitation synthesis; FTIR, XRD, SEM, TEM, UV-Vis, VSM; sonophotocatalytic tests.	20 mL MG (10–70 mg/L); 20 mg catalyst.	Synthetic MG solution.
(Khosravi-Far et al. 2024)	Efficient photocatalytic degradation of malachite green dye from wastewater using facilely synthesized ternary ZIF-8/Ag/Ag ₂ S nanocomposite: Optimization by RSM (CCD)	2024	Iran	Optimize MG degradation with ZIF-8/Ag/Ag ₂ S in a visible-light staircase reactor.	RSM-CCD optimization; FTIR, XRD, SEM, TEM, DRS, PL, BET, photocurrent, Mott–Schottky.	29 optimization runs; 5 reuse cycles.	Synthetic MG wastewater, visible light.
(Mostafa and Amdeha 2022)	Enhanced photocatalytic degradation of malachite green dye by highly stable visible-light-responsive Fe-based tri-composite photocatalysts	2022	Egypt (EPRI, Cairo)	Fabricate visible-light ZnVFeO ₄ tri-composite for MG degradation.	Precipitation at varied pH; XRD, FTIR, TEM, DRS, PL; visible-light tests.	5 catalysts; 5 cycles; 25–100 ppm; 0.25–1.5 g/L.	Synthetic MG solution (25–100 ppm).
(Zahedi et al. 2025)	Efficient visible light-driven Photodegradation of malachite green dye using carbon quantum dots-MXene nanocomposite: Synthesis, characterization, and performance evaluation	2025	Iran, India, China	Synthesize CQDs/MXene composite for visible-light MG photodegradation.	Hydrothermal CQDs (P. crispum leaves); etched MXene; self-assembly; XRD, SEM, FTIR, EDX.	10 mL MG (75 ppm); 6 mg catalyst per run.	Synthetic MG wastewater.
(Zhu et al. 2021)	Fabrication of a Novel BiVO ₄ /NiFe ₂ O ₄ /ATP Composite Photocatalyst with Enhanced Visible Light Photocatalytic Performance for Degradation of Malachite Green	2021	China (Southwest Petroleum Univ.)	Fabricate BiVO ₄ /NiFe ₂ O ₄ /ATP ternary composite for visible-light MG degradation.	Ultrasound-assisted hydrothermal; XRD, SEM, XPS, UV-Vis, BET; visible-light tests.	Varied ratios, conditions, concentrations; reuse test.	Synthetic MG water; also MB DP, LEF.
(Abdullah et al. 2024)	Visible-light-driven 2D carbonaceous-based SnSe nanohybrid soft materials: A photocatalyst for efficient photo reduction of malachite green dye	2024	Saudi Arabia, Egypt, Russia, UAE, India	Evaluate rGO/SnSe nanohybrid for visible-light MG photodegradation.	Hydrothermal synthesis; visible-light MG degradation tests.	10 mL dye solution per test.	Synthetic MG solution (10 ppm).
(Ma et al. 2024)	Preparation of K-doped g-C ₃ N ₄ composite loaded on magnetic attapulgite and its degradation performance for malachite green	2024	China (Jiangxi Univ. Sci. Tech.)	K-doped g-C ₃ N ₄ on magnetic attapulgite for MG degradation.	Synthesis; XRD, SEM, XPS; EPR radical analysis; LC-MS pathway.	Batch tests; 4 reuse cycles.	Synthetic MG water.
(Li et al. 2022)	Dual light-driven p-ZnFe ₂ O ₄ /n-TiO ₂ catalyst: Benzene-breaking reaction for malachite green.	2022	China (Guangdong, Guilin)	Visible-light ZnFe ₂ O ₄ /TiO ₂ (ZF-T) for MG degradation and mineralization.	Hydrothermal; SEM, EDS, XRD, FTIR, UV-Vis, LC-MS, XPS.	Varied wt.%; MG 5–20 mg/L.	Synthetic MG wastewater.
(Yulizar et al. 2023)	Green synthesis of novel YMnO ₃ -doped TiO ₂ for enhanced visible-light-driven photocatalytic degradation of malachite green.	2023	Indonesia	Green-synthesized TiO ₂ /YMnO ₃ for visible-light MG degradation.	A. muricata leaf-extract synthesis; FTIR, DRS, XRD, TEM, PL; ROS and reuse tests.	50 mL MG (6.0×10 ⁻⁶ M); 5–15 mg catalyst.	MG dye solution.

Authors	Article Title	Publication Year	Location	Aims/Purpose	Methodology	Sample Size	Study Population
(Mohan et al. 2021)	Fabrication of reusable polymer nanocomposite films made of thermoplastic polyurethane and modified BiVO ₄ for photodegradation of Malachite Green	2021	India (M S Ramaiah Univ., Bangalore)	Ti-doped BiVO ₄ /polyurethane films for reusable visible-light MG photodegradation.	Solid-state route + solution casting; XRD, Raman, SEM, UV-Vis.	250 mL MG (10 ppm); 0.25 g powder or 0.05–0.25 g film.	Synthetic MG solution (10 ppm).
(Guo et al. 2025)	Simultaneous water sterilization and photodegradation of malachite green based on Z-scheme heterojunction of bimetallic sulfide and zinc phthalocyanine	2025	China (Zhengzhou Univ. Light Industry)	Simultaneous sterilization and MG photodegradation via Ag ₂ S/MoS ₂ @ZnPc Z-scheme.	Hydrothermal; photocatalytic, antibacterial, and photothermal evaluation.	Batch experimental trials.	MG water with E. coli and S. aureus.
(Tanuj et al. 2024)	Exploitation of green synthesized chromium doped zinc oxide nanorods (NRs) mediated by flower extract of Rhododendron arboreum for highly efficient photocatalytic degradation of cationic dyes Malachite green (MG) and Fuchsin basic (FB).	2024	India, Mexico, UK	Green Cr-doped ZnO nanorods (R. arboreum extract) for MG and FB degradation.	Synthesis; XRD, UV-Vis, SEM; UV-light tests.	Cr doping varied 2–6%.	Synthetic MG/FB solutions (25 ppm).
(Shao et al. 2023)	Synthesis of SnO ₂ /g-C ₃ N ₄ flowerlike composites photocatalyst for enhanced photocatalytic degradation of malachite green	2023	China (Xi'an Polytechnic Univ.)	SnO ₂ /g-C ₃ N ₄ flowerlike composites for MG photodegradation.	Hydrothermal + ultrasonic calcination; XRD, SEM, TEM, XPS, BET, FTIR, DRS, PL; UV tests.	30 mL MG (10 mg/L); 30 mg catalyst per run.	Synthetic MG solution.
(Meena et al. 2024)	Gelatin Assisted Cerium-Copper Sulfide Nanoparticles as Efficient Catalysts for the Photocatalytic Degradation of Malachite Green Oxalate Dye Under UV-A Light	2024	India, Rep. of Korea, Saudi Arabia, USA	Gelatin-assisted Ce-CuS catalyst for MG oxalate degradation under UV-A.	Hydrothermal; tests across pH, dose, and dye concentration.	1.5 g/L catalyst; 3×10 ⁻⁴ M dye.	Synthetic MG oxalate solution.
(El-Hout et al. 2020)	Highly efficient sunlight-driven photocatalytic degradation of malachite green dye over reduced graphene oxide-supported CuS nanoparticles	2020	Egypt (CMRDI, Mansoura Univ.)	rGO/CuS composites for sunlight-driven MG photodegradation.	Co-precipitation; sunlight tests; XRD, FTIR, Raman, XPS, SEM, TEM, BET, PL.	Composites with 3–12% rGO.	Simulated MG solution (10 ppm).
(Bhasin and Mishra 2025)	Effective photocatalytic degradation of Malachite Green with water stable Cu based aliphatic di-carboxylate MOFs	2025	India (Gujarat Univ.)	Water-stable Cu di-carboxylate MOFs for MG degradation via CWPO.	Synthesis; PXRD, FTIR, BET, SEM, TGA; CWPO degradation tests.	150 mL MG (25 mg/L); several Cu-MOFs, repeated tests.	Simulated MG solution.
(Jasrotia et al. 2022)	Photocatalytic degradation of malachite green pollutant using novel dysprosium modified Zn-Mg photocatalysts for wastewater remediation	2022	India, Saudi Arabia, USA	Dy-doped Zn–Mg nano ferrites for sunlight MG degradation.	Sol-gel auto-combustion (Zn _{0.67} Mg _{0.33} Dy _{0.01} Fe _{2-0.01} O ₄); XRD, FESEM, UV-Vis, FTIR, Raman, VSM.	3 samples × 3 repeats = 9 tests.	Synthetic MG solution.
(Himanshi et al. 2025)	Insights into the photocatalytic removal of malachite green organic pollutant by highly efficient hard	2025	India, Saudi Arabia, Malaysia, China	Co/Dy co-doped BaFe ₁₂ O ₁₉ hexaferrites for sunlight MG degradation.	Sol-gel auto-combustion; structural, optical, magnetic, and photocatalytic characterization.	3 samples (HF1–HF3), varied dopants.	MG (10 mg/L), natural sunlight.

Authors	Article Title	Publication Year	Location	Aims/Purpose	Methodology	Sample Size	Study Population
	responsive Ba _{1-x} Co _x Dy _y Fe _{12-y} O ₁₉ catalysts.						
(Liu et al. 2024)	Ni _{0.4} Fe _{2.6} O ₄ /(Fe, Ni)-carbon core-shell magnetic mesoporous nanostructure for efficient adsorption and photocatalytic degradation of malachite green from wastewater	2024	China, UK, Turkey	Dual-function NFO@C for MG adsorption + photocatalytic degradation.	Molten-salt + mechanochemical synthesis; XRD, SEM, BET; kinetics monitored up to 450 min.	100 mL MG per test; each condition tested independently.	Simulated MG wastewater (75–150 mg/L).
(Pang et al. 2021)	Enhancement of Adsorption-Photocatalysis of Malachite Green Using Oil Palm Biomass-Derived Activated Carbon/Titanium Dioxide Composite	2021	Malaysia	Oil-palm AC/TiO ₂ composite for MG adsorption–photocatalysis.	Sol-gel; XRD, SEM-EDX, FTIR, TGA, BET; halogen-lamp tests.	Batch tests at varied weight ratios.	Synthetic MG solution.
(Tiwari et al. 2023)	Photocatalytic degradation of malachite green using TiO ₂ and ZnO impregnated on fecal sludge derived biochar	2023	India (KIIT; Mahindra Univ.)	Low-cost BC-TiO ₂ -ZnO from fecal-sludge biochar for MG removal.	Sol-gel; XRD, SEM-EDS, FTIR, TEM, BET; UV tests; RSM optimization.	30 RSM-CCD runs; 6 reuse cycles; 50–150 mg/L.	Simulated MG wastewater (100 mg/L).
(Devi et al. 2023)	Operational parameters and major active species responsible for the photodegradation of malachite green dye by ZnO/ZnS core-shell nanocomposite photocatalyst	2023	India (Manipur Univ.; IISc Kudapura)	ZnO/ZnS core–shell composites: MG degradation and operating parameters.	Synthesis at 2:1, 1:1, 1:2 ratios; XRD, FESEM, UV-Vis, PL; UV tests; parametric optimization.	MG 20 ppm; 0.2 g/L catalyst.	Synthetic MG wastewater (near real effluent).
(Wang et al. 2021)	Selective photodegradation of malachite green in water by Bi ₂ O ₃ -doped TiO ₂ supported on molecularly imprinted powdered activated carbon	2021	China (Changzhou Univ.)	Molecularly imprinted Bi ₂ O ₃ /TiO ₂ -PAC (MG-MI) for selective MG photodegradation.	Surface molecular imprinting; structure, adsorption, selectivity, and degradation evaluation.	Variants tested: Bi-Ti, BTC, MG-MI, MG-NI.	Synthetic MG and CV solutions.
(Mbuyazi and Ajibade 2025)	Enhanced photocatalytic degradation of malachite green and trypan blue using 3-aminopropyl triethoxysilane (APTES) functionalized iron oxide nanocomposite	2025	South Africa (Univ. KwaZulu-Natal)	APTES-functionalized Fe ₃ O ₄ @BC for MG and TPB photodegradation.	Co-precipitation + surface modification; XRD, FTIR, UV-Vis, HRTEM, XRF; RSM-BBD; 70 W Hg lamp.	29 runs (Box–Behnken design).	MG and TPB dye water, varied concentrations

3.3. Catalyst Performance and Reaction Conditions

Table 2 compares 24 photocatalysts for MG degradation. Light sources varied widely, many catalysts operated under visible light or solar irradiation (Khosravi-Far et al. 2024; Zahedi et al. 2025; Hasan et al. 2020; Guo et al. 2025; Ma et al. 2024; Bhasin and Mishra 2025; Mostafa and Amdeha 2022; Zhu et al. 2021; Abdullah et al. 2024; Li et al. 2022; Mohan et al. 2021; El-Hout et al. 2020; Jasrotia et al. 2022) (Himanshi et al. 2025; Wang et al. 2021), while others relied on UV/mercury lamps (Meena et al. 2024; Tanuj et al. 2024; Shao et al. 2023; Tiwari et al. 2023; Devi et al. 2023; Mbuyazi and Ajibade 2025) or LED (Liu et al. 2024), with one study combining UV–visible and NIR irradiation for simultaneous degradation and sterilization (Guo et al. 2025). Despite this variability, efficiencies remained consistently high (90–100%), with top performers including CTAS@NiFe₂O₄ (99.92%) (Hasan et al. 2020), ZnO/ZnS (100%) (Devi et al. 2023), and Fe₃O₄@BC/APTES (99.94%) (Mbuyazi and Ajibade 2025), driven mainly by hydroxyl/superoxide radical generation (Khosravi-Far et al. 2024; Zahedi et al. 2025; Meena et al. 2024; Mbuyazi and Ajibade 2025), often enhanced via heterojunction charge transfer (Guo et al. 2025; Ma et al. 2024; Yulizar et al. 2023; Zhu et al. 2021; Li et al. 2022; Shao et al. 2023). Reusability ranged from excellent (85% retained after 11 cycles (Tanuj et al. 2024)) to declining performance from fouling or byproduct adsorption (Mohan et al. 2021; Devi et al. 2023) with magnetic catalysts (Ma et al. 2024; Zhu et al. 2021; Jasrotia et al. 2022; Liu et al. 2024; Mbuyazi and Ajibade 2025), offering easier recovery.

Overall, while visible-light/solar systems are increasingly favored for energy efficiency, UV dependence remains common, reflecting a lack of standardized light-source selection across the field.

Table 2
Analysis of the 24 included studies

Authors	Catalyst Type	Synthesis Method	Lamp Type	Efficiency	Time	Mechanism	Reusability
(Hasan et al. 2020)	Chitosan–ascorbic acid@NiFe ₂ O ₄ (CTAS@NiFe ₂ O ₄) spinel MNPs	Green chemical co-precipitation (chitosan + ascorbic acid; no external reductants)	Visible (solar)	99.92%	90 min	•OH generation with h ⁺ /e ⁻ involvement; scavenger-confirmed (IPA); pseudo-first-order kinetics	Yes; no structural change after reuse; no secondary pollution
(Khosravi-Far et al. 2024)	AgNPs/Ag ₂ S/ZIF-8 composite	ZIF-8 doping; co-precipitation + ultrasonic-assisted	Visible (solar staircase reactor, 4.5–5 kW/m ²)	98.60%	30 min	•O ₂ ⁻ dominant with h ⁺ and •OH; scavenger-confirmed	Yes; 5 cycles, stable
(Mostafa and Amdeha 2022)	ZnVFeO ₄ photocatalyst (Fe-based visible-light-responsive tri-composite)	Precipitation at pH 3, 9, 12	Visible (tungsten, λ > 400 nm); UV (8 W, 254 nm)	98% (25 ppm); 92% (100 ppm)	180 min	Low bandgap; •OH > •O ₂ ⁻ > h ⁺ ; scavenger-confirmed	Yes; 5 cycles, stable
(Zahedi et al. 2025)	CQDs/Ti ₃ C ₂ (OH) ₂ MXene nanocomposite	Green hydrothermal CQDs (parsley leaves) + KOH-etched MXene + self-assembly	Visible (35 W halogen)	96.10%	25 min	MXene→CQDs electron transfer; reduced recombination; •O ₂ ⁻ /•OH; L–H model, k = 0.1382 min ⁻¹	Yes; 3 cycles, stable
(Zhu et al. 2021)	BiVO ₄ /NiFe ₂ O ₄ /ATP ternary composite	Ultrasound-assisted hydrothermal	65 W energy-saving lamp (visible)	99.25%	60 min	Type-II heterojunction; h ⁺ dominant; enhanced absorption and charge transfer	Yes; 3 cycles, 94% retained
(Abdullah et al. 2024)	Reduced graphene oxide with SnSe nanohybrid	Hydrothermal SnSe; modified Hummer's rGO; combined hydrothermally	Visible (150 W Xe)	95.52%	180 min	SnSe→rGO electron transfer; improved bandgap and separation; ROS generation	Yes; 86.45% retained
(Ma et al. 2024)	K-doped g-C ₃ N ₄ on attapulgite + Fe ₃ O ₄ (non-metallic semiconductor composite with magnetic support)	Thermal polymerization + solvothermal + mechanical grinding	500 W Xe (visible)	> 98%	120 min	Z-scheme; Fe ²⁺ Fenton-like path; K-doping/Fe ₃ O ₄ enhance separation; •OH/•O ₂ ⁻ ; LC-MS-confirmed	Yes; 4 cycles, > 80% retained
(Li et al. 2022)	ZnFe ₂ O ₄ /TiO ₂ Z-scheme heterostructure	Hydrothermal + calcination (400°C, 2 h)	Visible (500 W Xe, 350–780 nm)	90.1% (TiO ₂ alone: 53.5%)	240 min	Z-scheme transfer; h ⁺ and •O ₂ ⁻ main species; benzene-ring cleavage, complete degradation	Yes; 5 cycles, 81.4% retained
(Yulizar et al. 2023)	TiO ₂ /YMnO ₃ heterojunction nanoflakes	Green synthesis (A. muricata leaf extract, two-phase hexane–water,	Visible (125 W Philips HPL-N, λ = 454 nm)	95.34%	120 min	Type-I p–n heterojunction; reduced bandgap; •O ₂ ⁻ and h ⁺ generation	Yes; 5 cycles, stable

Authors	Catalyst Type	Synthesis Method	Lamp Type	Efficiency	Time	Mechanism	Reusability
		high-speed stirring)					
(Mohan et al. 2021)	Ti-doped BiVO ₄ in TPU film	Solid-state reaction (powder); solution-cast films	400 W Hg lamp with $\lambda > 420$ nm cutoff filter	100% (powder); 96% (film)	180 min	Ti-doping bandgap tuning; e ⁻ /h ⁺ separation; •OH and •O ₂ ⁻ radicals	3 cycles; film declined 96→65→53% (surface fouling)
(Guo et al. 2025)	Z-scheme heterojunction (Ag ₂ S/MoS ₂ /ZnPc)	In-situ hydrothermal growth	UV–visible (degradation) + 808 nm NIR (sterilization)	96.3% MG + 100% sterilization	100 min	e ⁻ dominant; •O ₂ ⁻ , •OH, ¹ O ₂ ; H ₂ O ₂ self-supply; photothermal/photodynamic synergy; controlled Ag ⁺ release	93% after 5 cycles; stability confirmed by XRD/SEM
(Tanuj et al. 2024)	Cr-doped ZnO nanorods (NRs) synthesized using Rhododendron arboreum flower extract (green synthesis)	R. arboreum flower-extract synthesis; 2–6% Cr doping	9 W UV Hg lamp	99.60% (MG); 99.88% (FB)	60 min	e ⁻ +O ₂ →•O ₂ ⁻ ; h ⁺ +OH ⁻ →•OH; pseudo-first-order; high selectivity	Yes; 11 cycles, 85% retained
(Shao et al. 2023)	Flowerlike SnO ₂ /g-C ₃ N ₄ composite	Hydrothermal + ultrasonic calcination	UV (500 W Hg)	95.09%	80 min	Type-II heterojunction; g-C ₃ N ₄ →SnO ₂ e ⁻ transfer; •O ₂ ⁻ dominant; high surface area	Yes; 5 cycles, 89% retained
(Meena et al. 2024)	Gelatin-assisted Ce-loaded CuS nanocomposite	Hydrothermal with gelatin	UV-A	98.5% (MGO, optimal)	120 min	Ce ³⁺ /Ce ⁴⁺ cycle traps e ⁻ ; •O ₂ ⁻ /•OH for mineralization; GC-MS intermediates	4 cycles; 98.5→78.3%
(El-Hout et al. 2020)	Reduced graphene oxide-CuS nanocomposite	One-pot co-precipitation with in-situ GO reduction	Direct sunlight	97.60%	90 min	rGO-enhanced charge transfer; •OH/•O ₂ ⁻ ; high TOC removal (76%)	Yes; 5 cycles, ~96.5% retained
(Bhasin and Mishra 2025)	Cu-MOFs (Cu(Seba), Cu(Azla), Cu(Pima), Cu(Suba))	Aliphatic dicarboxylate linkers with Cu paddle-wheels	350 W halogen (340–850 nm), visible	Cu(Seba) 98%; Cu(Azla) 97%	400 min	CWPO / photo-Fenton-like Cu ²⁺ /Cu ⁺ redox; •OH with H ₂ O ₂ ; linker-length effect	Yes; 4 cycles, 76–79% retained
(Jasrotia et al. 2022)	Dy ³⁺ -doped Zn-Mg ferrite	Sol-gel auto-combustion	Natural sunlight	94.23%	60 min	e ⁻ /h ⁺ pairs → •OH/•O ₂ ⁻ ; bandgap 2.18–2.34 eV; spinel structure	Yes; 4 cycles, minimal loss (magnetic recovery)
(Himanshi et al. 2025)	Co-Dy doped barium hexaferrite	Sol-gel auto-combustion (SGAC)	Natural sunlight	94.36%	90 min	•OH/•O ₂ ⁻ under sunlight; bandgap tuning 1.61–1.75 eV; magnetic analysis	Yes; 5 cycles, 4.78–6.47% loss
(Liu et al. 2024)	Ni _{0.4} Fe _{2.6} O ₄ /(Fe, Ni)-@carbon core-shell nanostructure	Mechanochemical pre-treatment + molten salt + PET-derived carbon shell	365 nm UV LED	> 99%	450 min	Dual adsorption + photocatalysis; e ⁻ main species; •O ₂ ⁻ and •OH involved	Magnetically recoverable (ferromagnetic)
(Pang et al. 2021)	Activated carbon/TiO ₂ composite	Sol-gel	Halogen lamp	96.30%	7.5 min	Dual adsorption + photocatalysis; pseudo-first-order kinetics	Yes; 1 cycle, 83.1% retained

Authors	Catalyst Type	Synthesis Method	Lamp Type	Efficiency	Time	Mechanism	Reusability
(Tiwari et al. 2023)	BC-TiO ₂ -ZnO (biochar impregnated with TiO ₂ and ZnO)	Sol-gel + biochar preparation	UV (8 W, λ = 340 nm)	98%	30 min	Adsorption + photocatalysis; L-H kinetics; $\bullet\text{OH}/\bullet\text{O}_2^-$; biochar inhibits recombination	Yes; 6 cycles, only 4–5% loss
(Devi et al. 2023)	ZnO/ZnS core-shell nanocomposites (ratios 1:1, 1:2, 2:1)	Co-precipitation (Zn acetate, NaOH, Na ₂ S)	8 W UV Hg lamp (Philips)	100%	20 min	Electrons primary reactive species (scavenger-confirmed)	Declined; 3 cycles, 100→75→58% (byproduct adsorption)
(Wang et al. 2021)	Bi ₂ O ₃ -doped TiO ₂ supported on molecularly imprinted powdered activated carbon (PAC) (MG-MI)	Surface molecular imprinting + nanocomposite doping	Visible light	98.7% (calc.)	80 min	Imprinted cavities selectively adsorb MG; S-scheme Bi ₂ O ₃ /TiO ₂ heterojunction enhances separation; pseudo-first-order, $k = 0.054 \text{ min}^{-1}$	Yes; imprinted structure stable after reaction
(Mbuyazi and Ajibade 2025)	Fe ₃ O ₄ @BC/APTES(biochar-capped iron oxide nanoparticles functionalized with APTES)	Co-precipitation + TEOS silica coating + APTES functionalization	70 W Hg lamp	99.94%	105 min	$\text{e}^- \rightarrow \bullet\text{O}_2^-$, $\text{h}^+ \rightarrow \bullet\text{OH}$; APTES/biochar prolong separation; RSM-BBD optimized	Yes; 5 cycles, no significant loss

3.4. Study Quality Assessment

Table S1 (Online Resource 1) evaluates 24 studies on multiple quality dimensions. Most demonstrated strong novelty (green synthesis, heterojunctions, MOFs, doped ferrites, waste-derived catalysts) (Zahedi et al. 2025; Hasan et al. 2020; Tanuj et al. 2024; Guo et al. 2025; Yulizar et al. 2023; Bhasin and Mishra 2025; Zhu et al. 2021; Abdullah et al. 2024; Li et al. 2022; Mohan et al. 2021; Shao et al. 2023; El-Hout et al. 2020; Jasrotia et al. 2022; Himanshi et al. 2025; Pang et al. 2021; Tiwari et al. 2023; Mbuyazi and Ajibade 2025), clear synthesis methods, and thorough characterization (XRD, SEM, FTIR, UV-Vis, XPS, BET), with some using advanced techniques like LC-MS or EPR (Meena et al. 2024; Guo et al. 2025; Ma et al. 2024; Li et al. 2022). Experimental design was generally well-controlled, with reaction conditions (pH, dose, time) reported consistently, and ROS-based mechanisms (hydroxyl/superoxide radicals) confirmed via scavenger tests in most studies (Khosravi-Far et al. 2024; Hasan et al. 2020; Ma et al. 2024; Tanuj et al. 2024; Bhasin and Mishra 2025; Li et al. 2022; Mohan et al. 2021; Jasrotia et al. 2022; Mbuyazi and Ajibade 2025). Reusability was tested in nearly all studies (typically 3–6 cycles, up to 11 in one case (Tanuj et al. 2024)), one study omitted reuse testing entirely (Liu et al. 2024) and two further studies reported qualitative stability after reuse without stating the number of cycles (Hasan et al. 2020; Wang et al. 2021).

Key weaknesses were mineralization and real-world validation: only ten studies confirmed mineralization via TOC/COD (Khosravi-Far et al. 2024; Zahedi et al. 2025; Meena et al. 2024; Hasan et al. 2020; Guo et al. 2025; Abdullah et al. 2024; Li et al. 2022; El-Hout et al. 2020; Pang et al. 2021; Tiwari et al. 2023) and only one study validated performance in a genuine real-wastewater matrix (Tiwari et al. 2023), with one further study applying the catalyst to a bacterial assay in wastewater while conducting MG degradation in synthetic solution (Guo et al. 2025). Statistical analysis remained basic across most studies, with limited error/reproducibility reporting beyond standard kinetic fitting. Nearly all studies discussed scalability and environmental impact, citing magnetic recovery, low-cost synthesis, or green chemistry as future pathways.

3.5. Comparative Quantitative Synthesis

A comparative quantitative synthesis of photocatalysts for malachite green (MG) degradation was performed using each study's reported optimal conditions (Tables S2 Online Resource 1), extracting degradation efficiency (%) and reaction time verbatim for traceability. Because reported efficiencies are often saturated and reporting is heterogeneous, standardized calculated metrics were derived to enable cross-study comparability (Table S3 Online Resource 1).

Figure 2a, b (bar plot) indicates that the identification of superior MG photocatalysts requires simultaneous consideration of reaction rate, mass-normalized capacity (mg g^{-1}), and irradiation source, since removal efficiency alone is uniformly high and thus non-discriminating. Kinetics-dominant systems such as ZnO/ZnS ($k = 0.461 \text{ min}^{-1}$) and AC/TiO₂ ($k = 0.440 \text{ min}^{-1}$) achieve rapid decolorization at the expense of capacity (Fig. 2a), whereas capacity-dominant materials such as NFO@C (404 mg g^{-1}) and Cu-MOFs (245 mg g^{-1}) exhibit strong uptake but slower kinetics (Fig. 2b). The most defensible performers are balanced catalysts (CQDs/MXene and BC-TiO₂-ZnO), which combine appreciable rate constants with high capacity, while several intermediate systems ($k = 0.05\text{--}0.10 \text{ min}^{-1}$), including CTAS@NiFe₂O₄, Fe₃O₄@BC/APTES, and BiVO₄/NiFe₂O₄/ATP, additionally offer magnetic recoverability. Overall, no single catalyst maximizes both speed and capacity, as rapid kinetics are favored by heterojunction and carbon-based architectures and high capacity by magnetic and MOF composites; moreover, systems performing strongly under visible or LED illumination are considered more scalable and convincing than UV-driven systems, in which higher photon energy may inflate apparent reaction rates.

Figure 2 Apparent rate constants (k , min^{-1}) (a) and mass-normalized adsorption capacity (mg g^{-1}) (b) for the 24 included MG photocatalysts

Figure 3 (box plot) compares MG removal efficiency across seven light sources. Most sources achieve high removal (~95–100%), with Hg lamp, Halogen, and UV showing tight, consistently near-complete removal, while Sunlight performs well but with more variability due to natural solar fluctuations, and Xe lamp shows the widest spread and lowest central tendency, suggesting greater sensitivity to catalyst and operating parameters. LED data is limited and should be interpreted cautiously. Overall, the results suggest catalyst design and experimental conditions (rather than light source alone) are the main drivers of variability in MG removal efficiency.

Figure 3 Distribution of MG removal efficiency under Hg lamp, Xe lamp, LED, Halogen lamp, Sunlight, visible light and UV light

Figure 4 illustrates the MG degradation mechanism: irradiation generates electron–hole pairs that are transferred through Z-/S-scheme junctions, preserving strongly reducing electrons and oxidizing holes for superoxide and hydroxyl radical formation. This reactive oxygen species drive MG breakdown to intermediates and ultimately mineralization, while carbon mediators (rGO, biochar, CQDs/MXene, activated carbon) suppress recombination and enhance oxygen reduction, explaining the superior performance of carbon-assisted and heterojunction photocatalysts.

Figure 4 Proposed photocatalytic degradation mechanism of MG via Z-/S-scheme charge transfer and ROS generation

Figure 5 shows a bubble plot linking catalyst dose (log scale), reaction time (bubble area), light source (colour), and MG removal efficiency across the 23 included studies; MG-MI is omitted, as no catalyst dose was reported. Most catalysts achieved 94–100% removal across a wide dose range (0.02–2.5 g/L), but treatment time varied by nearly two orders of magnitude. Some systems reached high efficiency rapidly AC/TiO₂ (96.3% in 7.5 min) and ZnO/ZnS (100% in 20 min) while others required far longer despite low dosing, such as NFO@C (99% in 450 min) and Cu-MOFs (98% in 400 min). ZnFe₂O₄/TiO₂ recorded the lowest efficiency in the set (90.1%) despite a 240 min reaction, confirming that kinetics and catalyst/light design, rather than dose alone, drive real performance differences. Details of data extraction and plot construction are given in Text S1 and the underlying dataset in Online Resource 1.

Figure 5 Influence of catalyst dose, reaction time, and light source on MG degradation efficiency. Bubble area is proportional to reaction time (min); colour denotes light source. Catalyst dose is plotted on a logarithmic scale. The MG-MI (Bi/Ti/AC molecularly imprinted) system is omitted as no catalyst dose was reported, detailed in Online Resource 1

Figure 6 (radar plot) shows that removal efficiency (90–100%) is nearly uniform across catalysts and thus not a strong differentiator; real distinctions emerge in kinetics, capacity, and reusability. A small kinetics-dominant group (notably ZnO/ZnS and AC/TiO₂) shows fast removal but weaker mass-handling capacity, while capacity-dominant platforms (NFO@C, Cu-MOFs, Gel-Ce-CuS) show high throughput but slower turnover. Reusability data are uneven: although cycling was assessed in nearly every study, only a few catalysts (BC-TiO₂-ZnO, Cr-doped ZnO) were tested deeply enough to support scale-up confidence. Overall, three performance regimes emerge: fast-kinetic catalysts, high-capacity catalysts, and balanced, "application-credible" candidates (e.g., BC-TiO₂-ZnO, CQDs/MXene, AgNPs/Ag₂S/ZIF-8, Ag₂S/MoS₂@ZnPc) that perform well across all metrics. The inclusion of light-source scoring further shows that UV/Hg conditions can inflate apparent kinetics, whereas catalysts maintaining strong performance under visible/solar or LED light offer more realistic evidence for practical MG treatment. Normalization procedures for all six metrics are detailed in Text S2, and the underlying dataset in Online Resource 1.

Figure 6 multi-metric radar comparison of photocatalysts based on normalized efficiency, kinetics, capacity, time, reusability, light source. Normalization procedure detailed in Online Resource 1. Scores reflect reported performance only and are not a measure of study quality

4. Discussion

This review synthesized 24 studies published between 2020 and 2025 (notably, despite a search window beginning in 2015, no study published before 2020 met the inclusion criteria, which indicates how rapidly this field has developed in the past five years), on the photocatalytic degradation of malachite green. Three findings dominate. First, decolorization efficiency has become non-discriminating: virtually all reported systems achieve 90–100% removal, so removal percentage alone cannot rank catalyst quality. Second, once normalized metrics are applied, two distinct performance regimes appear (rapid-kinetics systems and high-capacity adsorption–photocatalysis hybrids) with a small group of balanced composites performing credibly across all metrics. Third, and most consequentially, the principal obstacle to practical deployment is not catalyst chemistry but evaluation practice: fewer than half confirmed mineralization, and only one used a genuine real-wastewater matrix. The following sections examine each of these findings and their implications for research standardization.

4.1. Structure–Performance Relationships

Across 24 studies, MG decolorization is consistently high (>90%), so removal percentage alone cannot discriminate catalyst quality or scalability (Khosravi-Far et al. 2024; Zahedi et al. 2025; Hasan et al. 2020; Yulizar et al. 2023; Mostafa and Amdeha 2022; Li et al. 2022; Shao et al. 2023; El-Hout et al. 2020; Jasrotia et al. 2022; Himanshi et al. 2025; Liu et al. 2024; Pang et al. 2021; Tiwari et al. 2023; Wang et al. 2021; Mbuyazi and Ajibade 2025). Performance instead depends mechanistically on efficient charge separation through Z-/S-scheme heterojunctions that suppress recombination and sustain ROS generation mainly hydroxyl and superoxide radicals, as confirmed by scavenger or ESR/EPR studies (Meena et al. 2024; Hasan et al. 2020; Guo et al. 2025; Li et al. 2022; El-Hout et al. 2020; Himanshi et al. 2025; Devi et al. 2023). Higher-performing systems couple adsorption and photocatalysis via conductive carbon scaffolds (Zahedi et al. 2025; El-Hout et al. 2020; Pang et al. 2021; Tiwari et al. 2023), molecular imprinting (Wang et al. 2021), magnetic recovery (Hasan et al. 2020; Ma et al. 2024; Zhu et al. 2021; Liu et al. 2024), and surface functionalization such as APTES modification (Mbuyazi and Ajibade 2025).

4.2. Environmental Relevance and Real Wastewater Applicability

Most reported performances come from simplified lab water, which overestimates efficiency: real effluents contain salts, NOM, competing ions, turbidity, and variable pH that quench ROS, scatter light, foul catalysts, and alter adsorption (Khosravi-Far et al. 2024; Zahedi et al. 2025; Hasan et al. 2020; Mostafa and Amdeha 2022; Mohan et al. 2021; Liu et al. 2024; Pang et al. 2021; Tiwari et al. 2023; Wang et al. 2021; Mbuyazi and Ajibade 2025; Cates 2017; Hübner et al. 2024; Kowalczyk et al. 2022; Hodges et al. 2018; Qudsieh et al. 2025). Typical conditions (alkaline pH favoring electrostatic adsorption, moderate MG concentrations, and 0.1–1 g/L loading) achieve high removal within tens of minutes (Khosravi-Far et al. 2024; Zahedi et al. 2025; Hasan et al. 2020; Guo et al. 2025; Mostafa and Amdeha 2022; Li et al. 2022; Tiwari et al. 2023; Devi et al. 2023; Mbuyazi and Ajibade 2025). Comparability is further limited by irradiation heterogeneity: Hg/Xe lamps dominate, LEDs are rare, and radiometric details (irradiance, photon flux) are seldom reported, biasing kinetic comparisons (Khosravi-Far et al. 2024; Zahedi et al. 2025; Li et al. 2022; El-Hout et al. 2020; Devi et al. 2023; Hübner et al. 2024; Qudsieh et al. 2025; Hoque and Guzman 2018).

4.3. Standardization Needs for Photocatalysis Reporting

The main barrier to cross-study inference is non-standardized reporting rather than insufficient removal. Because degradation saturates near complete decolorization, comparison requires multi-metric evaluation (kinetics, time-to-target, adsorption capacity, and operating conditions) filtered by mineralization and durability evidence (Khosravi-Far et al. 2024; Zahedi et al. 2025; Hasan et al. 2020; Mostafa and Amdeha 2022; Mohan et al. 2021; Jasrotia et al. 2022; Liu et al. 2024; Tiwari et al. 2023; Devi et al. 2023; Mbuyazi and Ajibade 2025; Hoque and Guzman 2018). Studies should report lamp spectrum with irradiance/photon flux, matrix composition, and explicit kinetic methods; stronger claims additionally require TOC/COD mineralization, ≥ 10 reuse cycles as a minimum durability benchmark, and ICP-based leaching/safety data (Hasan et al. 2020; Mostafa and Amdeha 2022; Mohan et al. 2021; Jasrotia et al. 2022; Liu et al. 2024; Tiwari et al. 2023; Mbuyazi and Ajibade 2025). This aligns with photocatalysis reporting guidance (Hoque and Guzman 2018; Parrino et al. 2019), IUPAC terminology (Braslavsky et al. 2011), AOP benchmarking frameworks recommending energy/photon-normalized metrics such as EEO and AQE (Bolton et al. 2001; Keen et al. 2018) and chemical actinometry as a practical standardization tool (Rabani et al. 2021).

4.4. Future Research Roadmap

Deployment-ready MG photocatalysts should combine heterojunction charge management with conductive carbon supports and recovery-enabling (magnetic or immobilized) designs (Zahedi et al. 2025; Guo et al. 2025; El-Hout et al. 2020; Liu et al. 2024; Pang et al. 2021; Tiwari et al. 2023; Mbuyazi and Ajibade 2025). Priority steps are standardized LED/solar protocols with radiometric reporting, real-wastewater validation, ≥ 10 -cycle durability testing with leaching control and post-use verification, and mineralization/toxicity profiling via TOC/COD, LC-MS/GC-MS, and ecotoxicity screening (Hasan et al. 2020; Mostafa and Amdeha 2022; Mohan et al. 2021; Jasrotia et al. 2022; Liu et al. 2024; Tiwari et al. 2023; Mbuyazi and Ajibade 2025). Translation should further employ AI/ML-driven screening on standardized, ML-ready, energy-normalized datasets (Hoque and Guzman 2018; Bolton et al. 2001; Keen et al. 2018), alongside scale-up work on LED energy demand, reactor design, catalyst recovery, and cost/life-cycle assessment (LCA).

4.5. Environmental Implications

Photocatalysis delivers consistently high MG decolorization across diverse catalysts under laboratory conditions (Khosravi-Far et al. 2024; Zahedi et al. 2025; Hasan et al. 2020; Guo et al. 2025; Ma et al. 2024; Tanuj et al. 2024; Yulizar et al. 2023; Mostafa and Amdeha 2022; Zhu et al. 2021; Li et al. 2022; Shao et al. 2023; El-Hout et al. 2020; Jasrotia et al. 2022; Himanshi et al. 2025; Liu et al. 2024; Pang et al. 2021; Tiwari et al. 2023; Devi et al. 2023; Wang et al. 2021; Mbuyazi and Ajibade 2025), but real-world reliability remains conditional on matrix effects. "High removal" is therefore credible only when supported by real-effluent validation, standardized irradiation reporting, mineralization, leaching control, and ecotoxicity screening warranted by the known toxicity of MG and leucomalachite green (Srivastava et al. 2004; Culp et al. 2006; Hasan et al. 2020; Mohan et al. 2021; El-Hout et al. 2020; Jasrotia et al. 2022; Tiwari et al. 2023). The most implementation-ready strategies are thus recoverable, durable heterojunction photocatalysts on conductive carbon or magnetic supports, benchmarked with standardized radiometry, kinetics, mineralization, leaching, and toxicity metrics to support industrial adoption and ML-ready optimization (Zahedi et al. 2025; Guo et al. 2025; Mohan et al. 2021; Liu et al. 2024) (Pang et al. 2021; Tiwari et al. 2023; Mbuyazi and Ajibade 2025; Hoque and Guzman 2018; Braslavsky et al. 2011; Bolton et al. 2001; Keen et al. 2018; Rabani et al. 2021).

4.6. Limitations

Several limitations apply. Methodological heterogeneity in catalyst loading, irradiation, reactor configuration, and initial MG concentration precluded a pooled meta-analysis, so the synthesis is descriptive and robustness was appraised qualitatively (Table S1, Online Resource 1). Where rate constants were not reported they were recalculated assuming pseudo-first-order kinetics with conversion capped at 0.9999, yielding conservative approximations rather than measured constants; three studies also used hybrid or variant systems (Meena et al. 2024; Hasan et al. 2020; Bhasin and Mishra 2025) that are not strictly comparable with purely photocatalytic ones. Normalization in Fig. 6 is relative to the included studies rather than to an absolute benchmark, and the appraisal rubric, though applied independently by both reviewers, is not externally validated. The review was also not prospectively registered, so the protocol was not publicly available in advance of data extraction. Finally, the search covered three databases and English-language publications only and extends no later than March 2026; with mineralization confirmed in ten of the 24 studies and real-wastewater validation in one (Tiwari et al. 2023), the rankings reported here describe laboratory performance and should not be extrapolated to full-scale treatment without further validation.

5. Conclusions

This systematic review and comparative quantitative synthesis of 24 studies (2020–2025) shows that MG photocatalysis has evolved from single-phase semiconductors to multifunctional platforms integrating adsorption, enhanced light harvesting, and engineered charge transfer. A central lesson of this analysis is that removal percentage alone is no longer a meaningful benchmark: with decolorization saturated at 90–100% across the literature, catalysts can only be differentiated by jointly evaluating kinetics, adsorption capacity, mineralization, and reusability. On this basis, two complementary design strategies emerge (rapid-kinetics catalysts (e.g., ZnO/ZnS, AC/TiO₂) suited to fast treatment, and high-capacity adsorption–photocatalysis hybrids (e.g., NFO@C, Cu-MOFs) suited to high-load effluents) both relying on hydroxyl/superoxide radical generation, heterojunction design, and carbon/magnetic supports for

recombination suppression and catalyst recovery. The principal barrier to real-world deployment is not catalyst chemistry but evaluation practice: inconsistent testing conditions, sparse LED benchmarking, minimal real-effluent validation, and uneven mineralization, toxicity, and durability reporting prevent reliable comparison and scale-up decisions. Future work should therefore prioritize standardized LED-based protocols with consistent mineralization, reusability, leaching, and real-wastewater testing; such harmonized reporting would also create the structured datasets needed for AI-guided catalyst optimization, moving the field toward scalable, practical MG treatment.

Abbreviations

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 guidelines

MeSH: Medical Subject Headings

PICO: Population, Intervention, Comparison, Outcome

MG: Malachite Green

LMG: Leucomalachite Green

SWiM: Synthesis Without Meta-analysis

TOC/COD: Total Organic Carbon / Chemical Oxygen Demand

PROSPERO = Prospective Register of Systematic Reviews

RSM/CCD: Response Surface Methodology / Central Composite Design

ROS: Reactive Oxygen Species

AQE/EEO: Apparent Quantum Efficiency / Electrical Energy per Order

EPR: Electron Paramagnetic Resonance

ESR: Electron Spin Resonance

IUPAC: International Union of Pure and Applied Chemistry

AOP: Advanced Oxidation Process(es)

NOM: Natural Organic Matter

LCA: Life Cycle Assessment

ICP: Inductively Coupled Plasma

LC-MS: Liquid Chromatography–Mass Spectrometry

GC-MS: Gas Chromatography–Mass Spectrometry

Declarations

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Consent for publication: Not applicable.

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Reporting guideline: This systematic review was conducted and reported in accordance with the PRISMA 2020 statement. The completed PRISMA 2020 checklist is provided as Online Resource 3.

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Figures

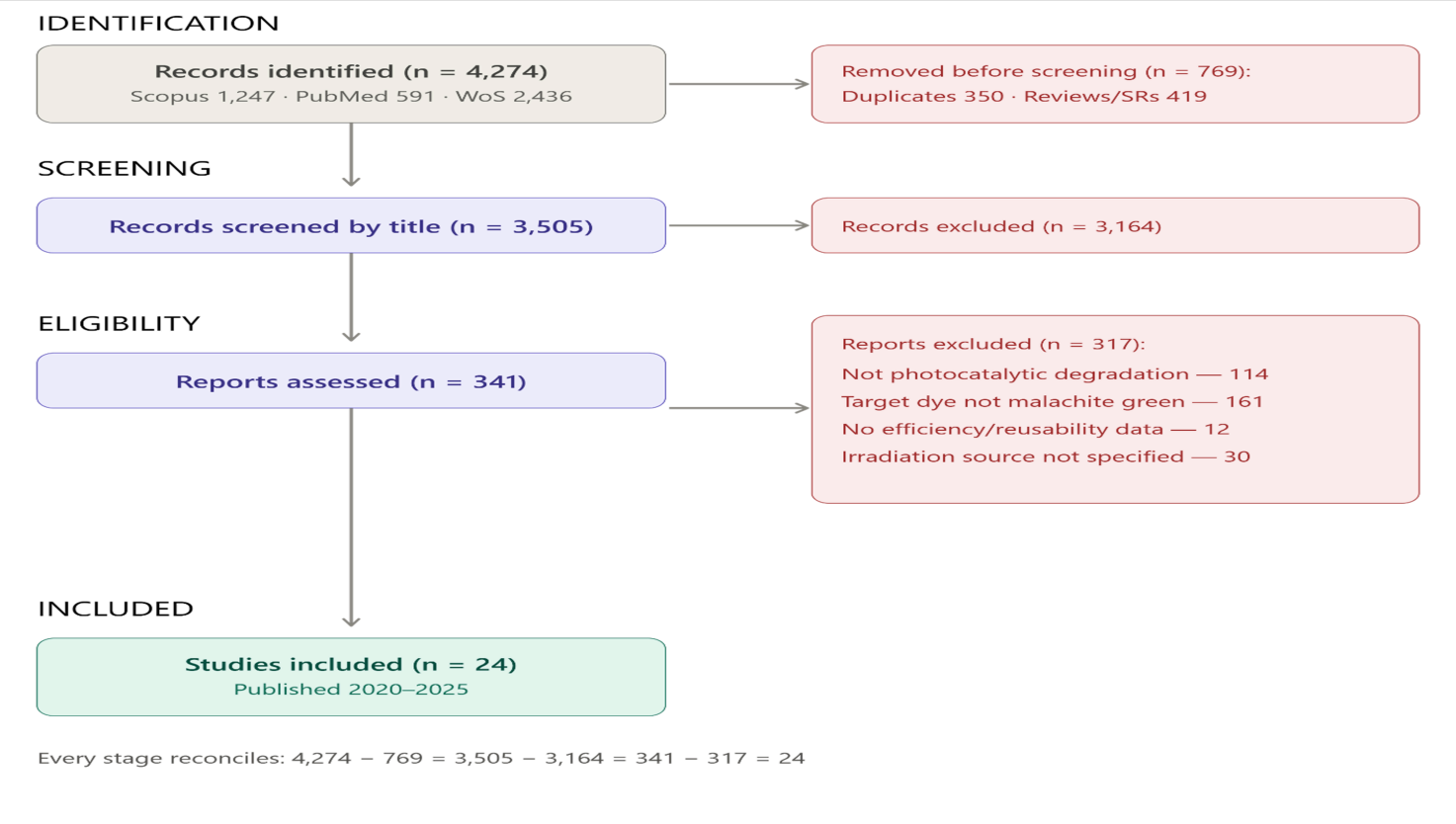


Figure 1

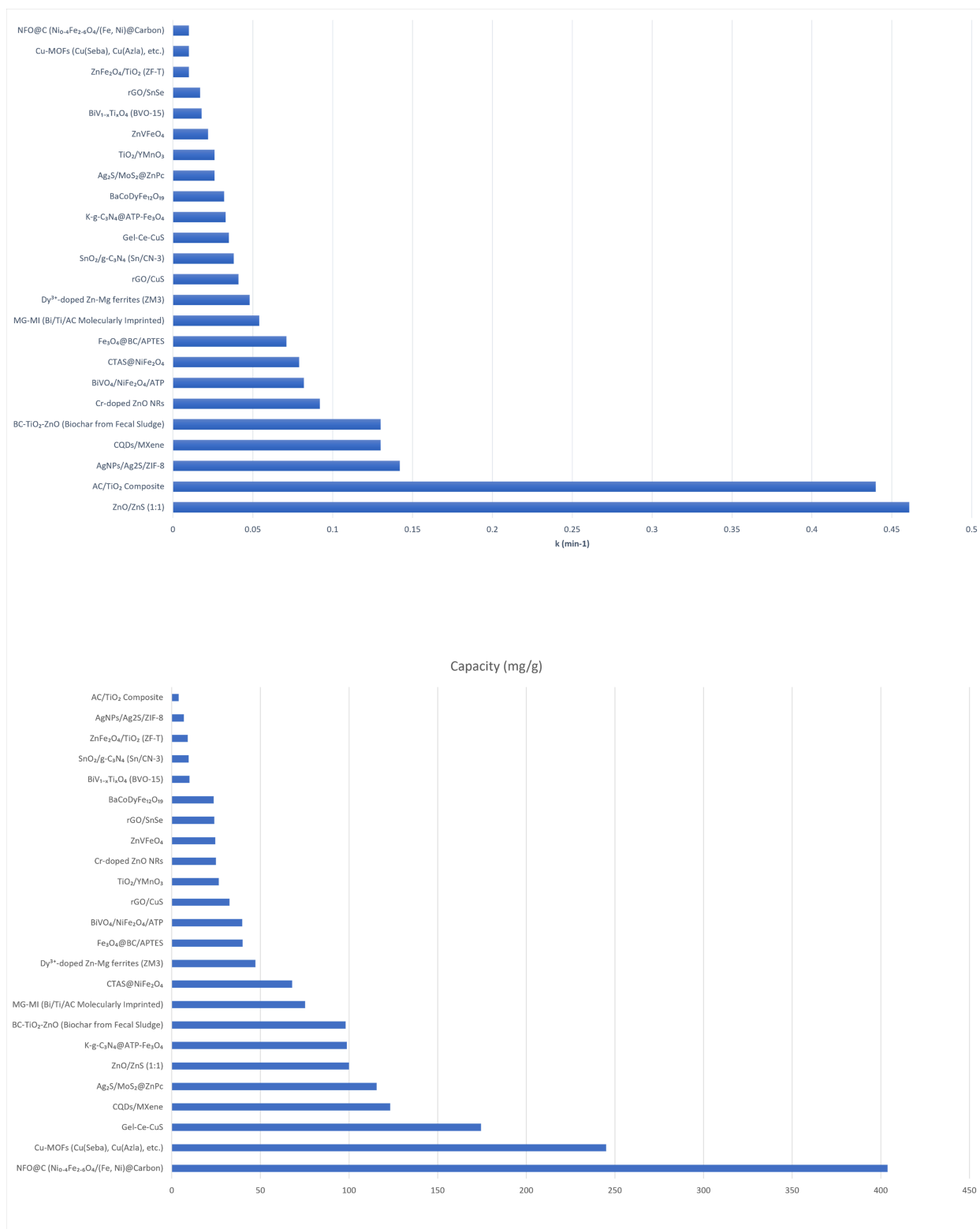


Figure 2

Apparent rate constants (k , min^{-1}) (a) and mass-normalized adsorption capacity (mg g^{-1}) (b) for the 24 included MG photocatalysts

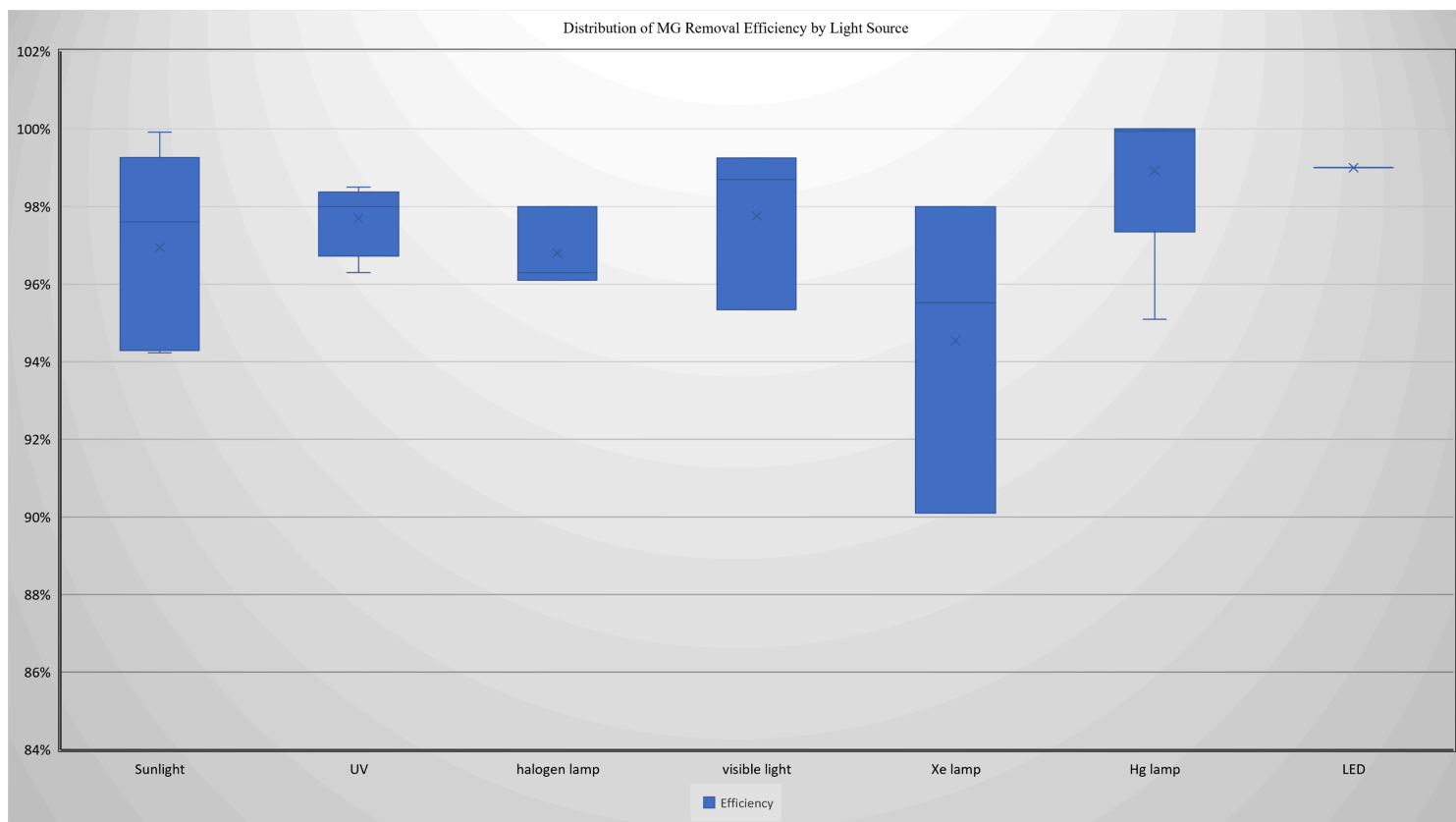


Figure 3

Distribution of MG removal efficiency under Hg lamp, Xe lamp, LED, Halogen lamp, Sunlight, visible light and UV light

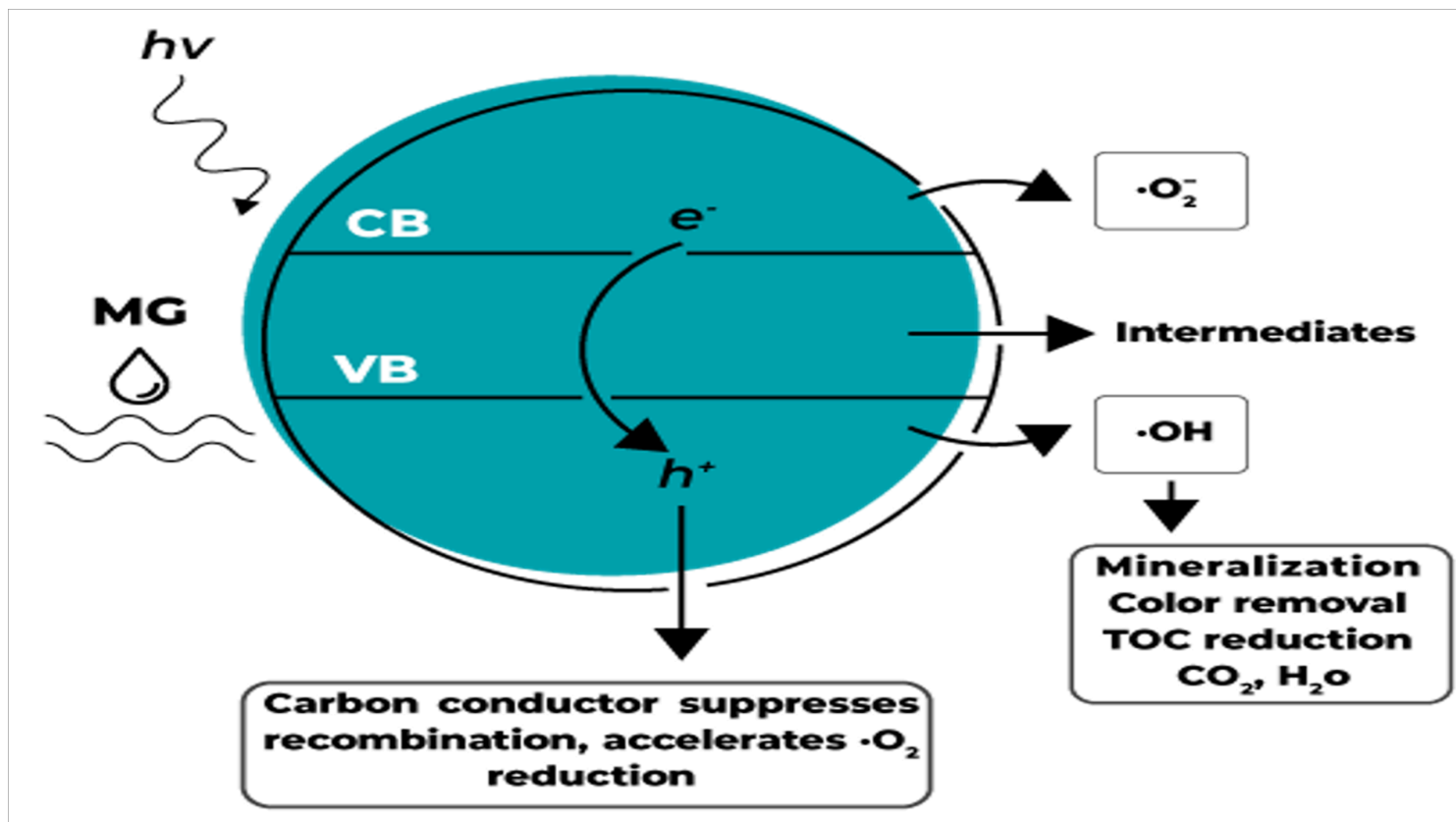


Figure 4

Proposed photocatalytic degradation mechanism of MG via Z-/S-scheme charge transfer and ROS generation

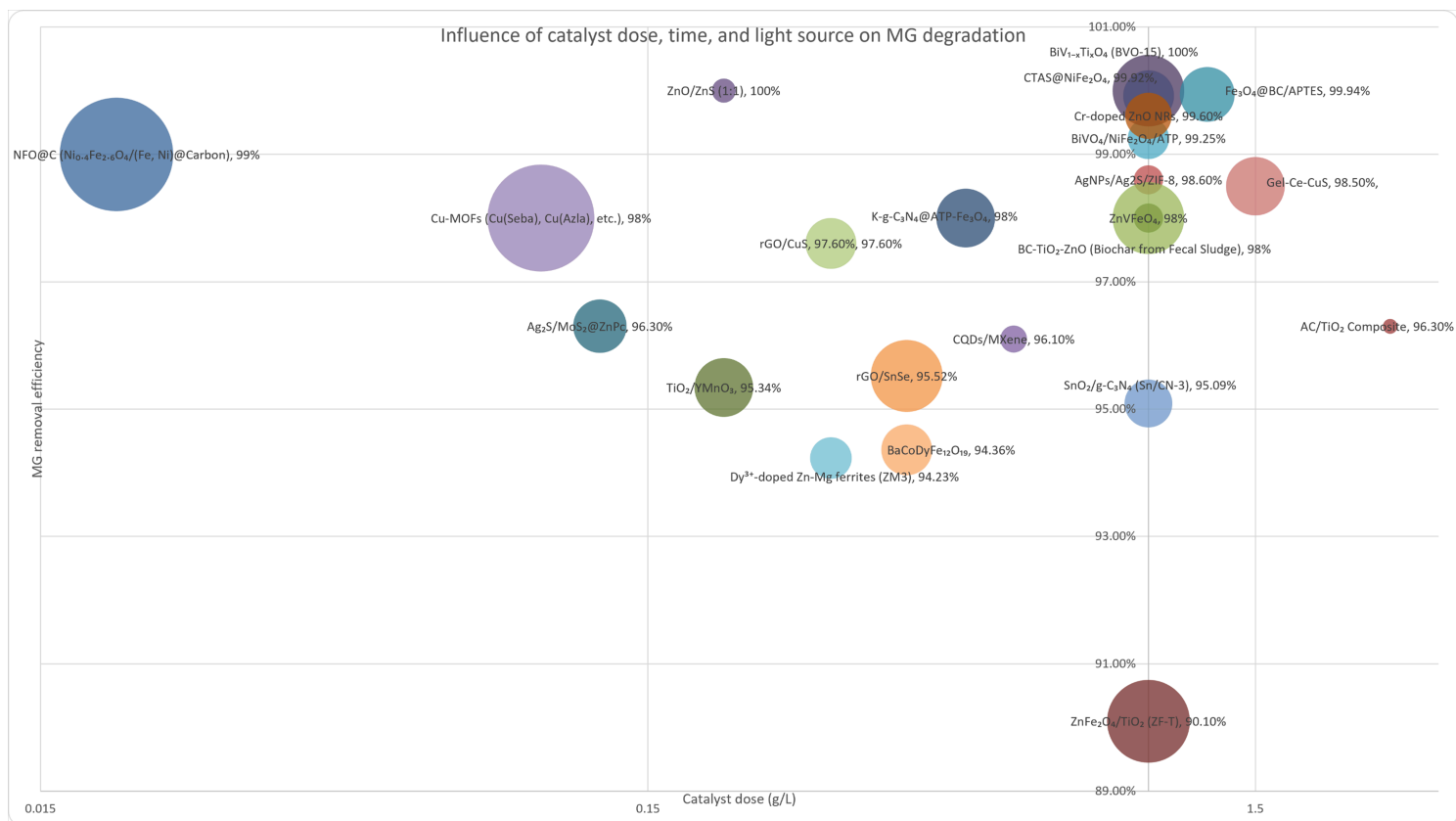


Figure 5

Influence of catalyst dose, reaction time, and light source on MG degradation efficiency. Bubble area is proportional to reaction time (min); colour denotes light source. Catalyst dose is plotted on a logarithmic scale. The MG-MI (Bi/Ti/AC molecularly imprinted) system is omitted as no catalyst dose was reported, detailed in Online Resource 1

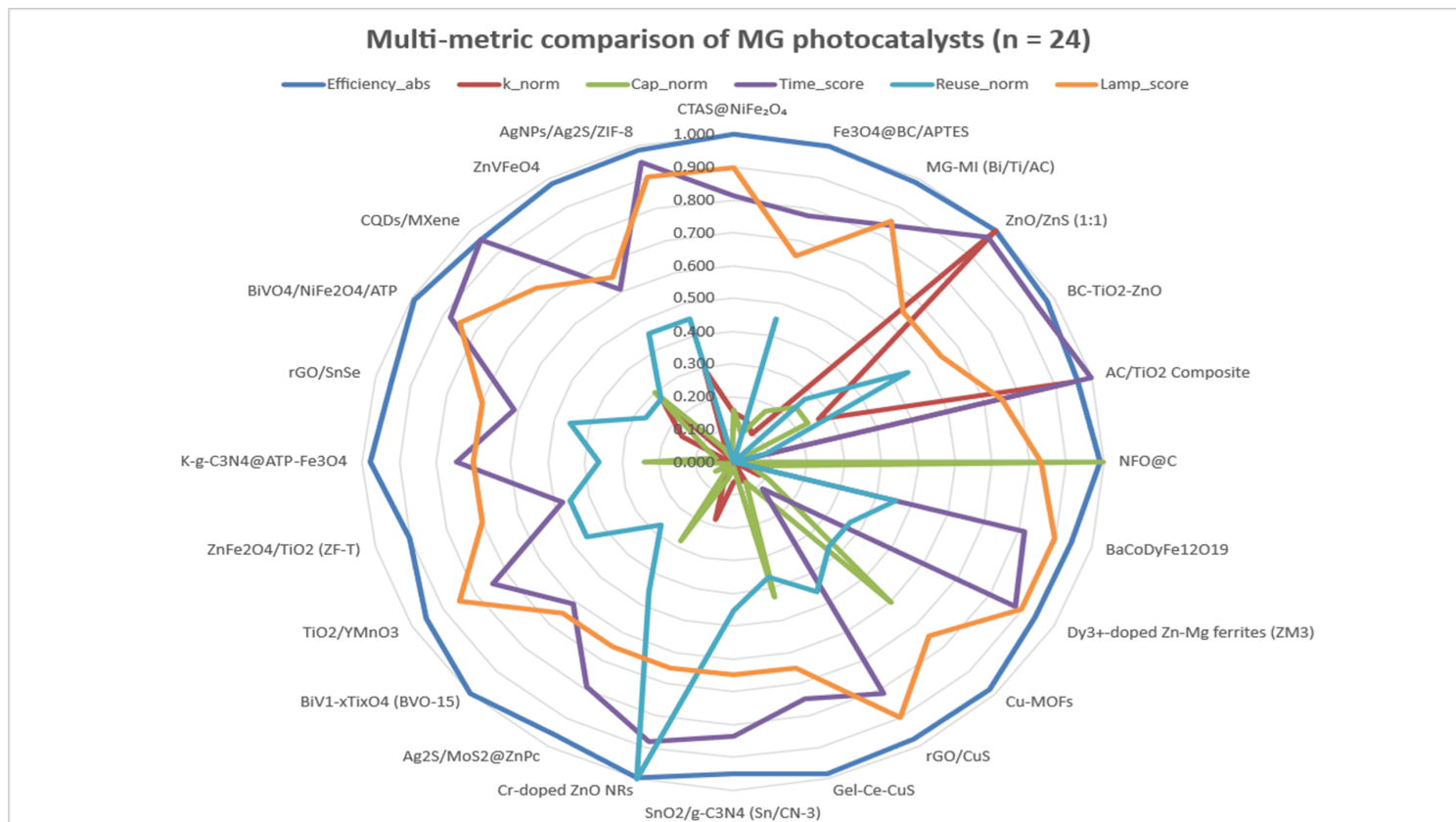


Figure 6

multi-metric radar comparison of photocatalysts based on normalized efficiency , kinetics , capacity , time, reusability , light source. Normalization procedure detailed in Online Resource 1. Scores reflect reported performance only and are not a measure of study quality

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