

**Photocatalytic Degradation of Maxilon Dye Pollutants using Nano-Architecture Functional
Materials: A Review**

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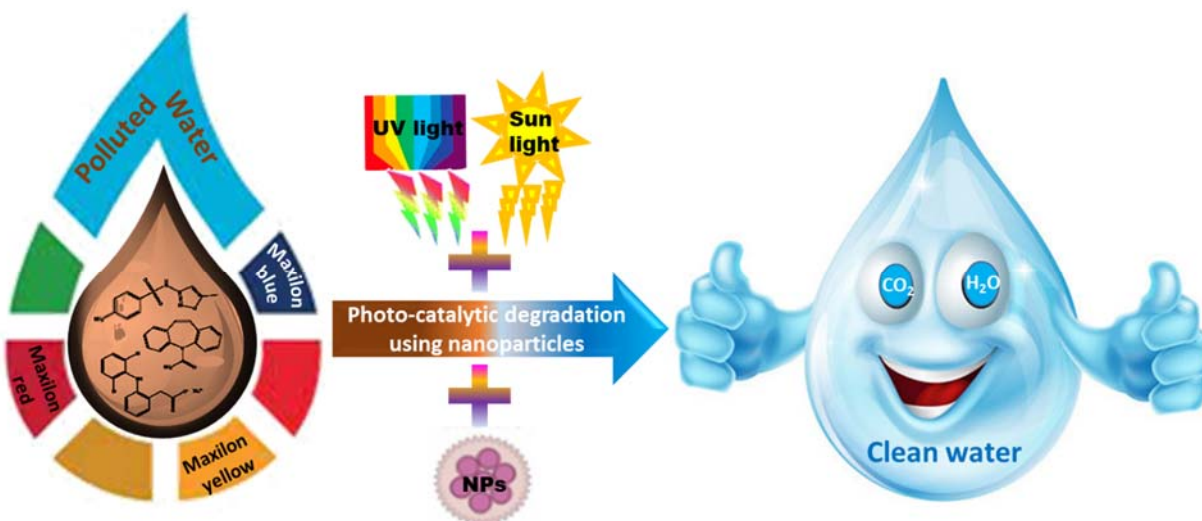
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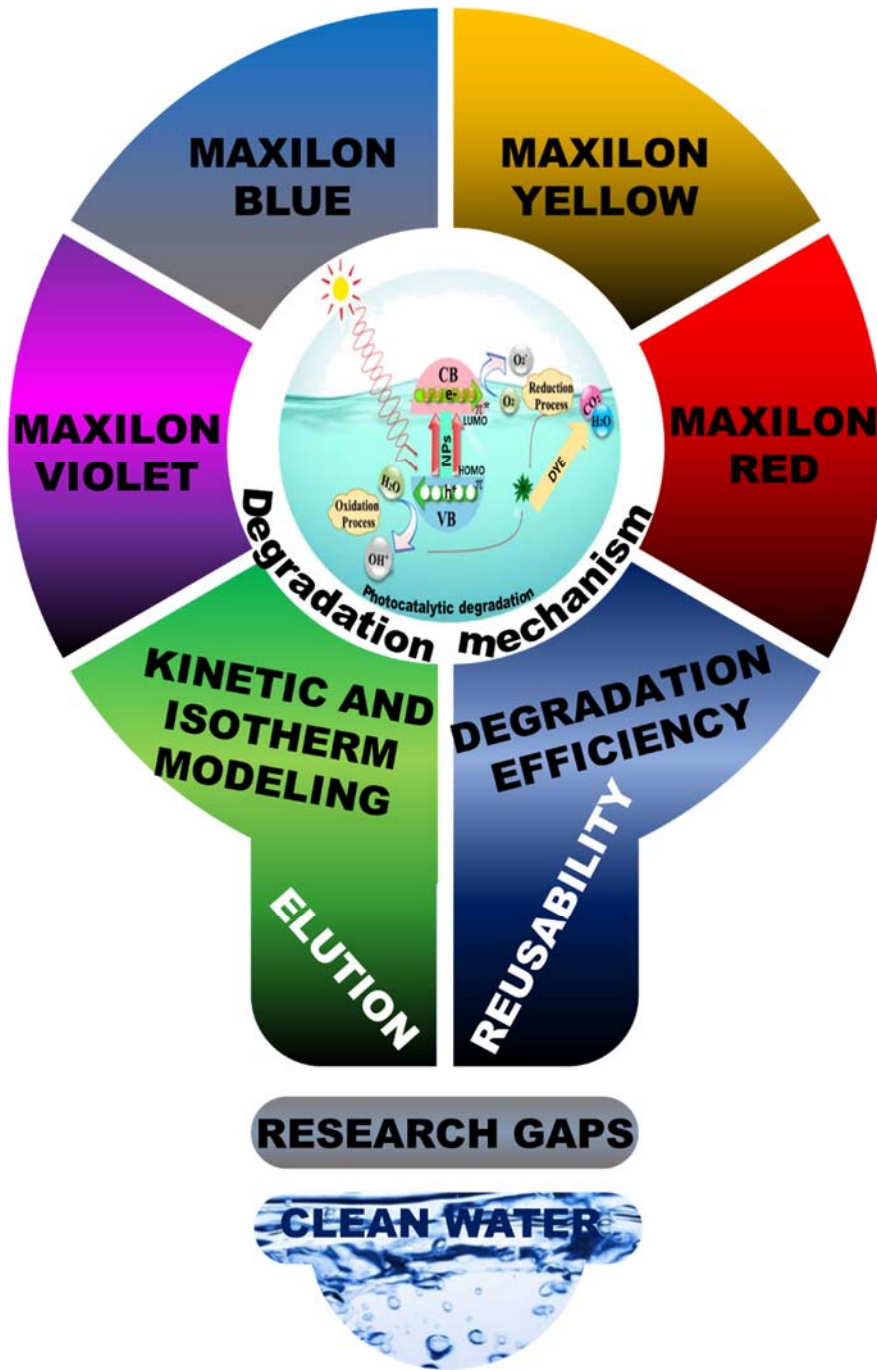
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Graphical abstract

This first review on the photocatalytic degradation of Maxilon dye revealed that the highest degradation efficiency was 100%, nanoparticles can be reused up to 4-6 cycles with >75% efficiency and the shortest degradation time was <1 hr with the oxidizing ability of nanoparticles taking into account of $\bullet\text{OH}$ and $\text{O}_2\bullet$



Frontispiece



Abstract

The most essential task in the twenty-first century is to fight the alarming growing pollution in the aquatic body in which effluent of one of the most colouring dye categories called maxilon dye is a major contributor. This review thus specifically focuses on the use of nanoparticles (NPs) for photocatalytic degradation of maxilon dye contaminants in water bodies. The work empirically presented the performance evaluation of NPs in degrading maxilon dyes under light irradiation alongside the underlying operational photocatalytic degradation mechanism. The stability of NPs was also critically analyzed by looking at the regenerability and reusability of expended NPs. From the study, it was discovered that $\bullet\text{OH}$ and $\text{O}_2\bullet$ played a vital role in the genesis of the oxidizing capacity of NPs for the photocatalytic breakdown of maxilon dye. Moreover, it was found that the degradation performance of most NPs is greater than 80 % and the shortest degradation period is < 1 hour with pseudo-first-order (PFO) being the most common kinetic best-fit to describe the adsorption process that occurred shortly before and during the degradation operation. At the end, knowledge gaps were identified in the area of regenerability, the lifecycle analyses of nano-photocatalyst fabrication and utilization, cost analysis for industrial scale-up, maxilon dye ecotoxicological study, and degradation pathways. The findings of this study can open up insightful innovation for readers and industries that are interested in pursuing zero water insecurity.

1. Introduction

Water pollution continues to rise at an alarming rate, and the entire world is in its malignant grip. Various industries, including the textile industry, discharge untreated effluents into near waterways, significantly contributing to current water pollution ^[1-4]. The most essential task in the

twenty-first century is to fight the growing pollution in the aquatic body^[5]. Dyes, pesticides, chloro-organics, and other pollutants constitute significant types of aquatic pollutants that have grown into a major cause of environmental contamination. Many research investigations are now being conducted on dye-contaminated wastewater treatment. In view of the complexities and diversity of dye compounds, it is becoming difficult to develop a single treatment technique that completely covers the effective eradication of all forms of dye pollutants ^[6].

Consequently, several approaches for dye removal from aquatic bodies have been presented, including biodegradation, adsorption, coagulation, membrane processes, and advanced oxidation processes (AOPs) ^[7-9]. All of these strategies have certain benefits and drawbacks over others. A cautious strategy is thus required to assess the merits of selecting an effective procedure for degrading the dye in solution. Because of its simplicity and low cost, the absorption technique is commonly used in prerelease remediation approaches ^[10]. However, drawbacks such as low absorption efficacy, partial pollutant removal, and weak mechanical stability of adsorbents make efficient pollutant removal challenging^[11]. Photocatalytic degradation has grown in popularity during the last few years. The photocatalytic process involves diverse catalysis, in which the photocatalyst absorbs sunlight to break down the numerous contaminants under study, such as aquatic and pollutants. Photocatalytic degradation outperforms common wastewater treatment practices ^[12]. At room temperature, for example, active photocatalysts can degrade dye completely in a matter of minutes or hours. Furthermore, dye pollutants can be totally degraded to relatively non-hazardous elements without causing the production of secondary toxic substances ^[13]. The surface functionalization of NPs^[14] is used for photocatalytic degradation to effectively degrade hazardous contaminants ^[15,16].

The Maxilon dyes are a sort of basic mono-azo dye, a class of exceptionally colourful synthetic soluble dyes used by the textile industry. Maxilon dyes are an assortment of cationic dyes with both aromatic and aliphatic radicals. Pollution of water bodies by this class of dye is a significant environmental problem due to the fact that this group of dyes' colour lingers even after treatment, preventing light from penetrating and so restricting aquatic life's ability to photosynthesize ^[17,18]. This dye category is mutagenic, carcinogenic, teratogenic, and non-compatible with microorganisms ^[19]. They possess the capacity to harm an extensive variety of aquatic organisms and decrease the ability of the water body that receives them to keep itself clean. Even in trace amounts, their existence in aquatic bodies including rivers, oceans, lakes, seas, well, and other surface water, is noticeable and undesirable ^[20]. Maxilon Blue dye has recently been linked to genotoxicity and teratogenicity in zebrafish embryonic growth ^[21]. It was discovered that the Maxilon dye induces irreversible oxidative stress in the embryos, which leads to developmental abnormalities of deformity in the tail, microphthalmia, and twisted body structure ^[21]. Consequently, the degradation of Maxilon dyes from water bodies has recently attracted some interest, with numerous approaches being offered. However, many of the methods that are available do not entirely eliminate the dyes ^[22,23]. In this context, photocatalytic degradation is emerging as a viable option. The primary benefit of the method used by photocatalytic degradation is its intrinsic destructive character: it requires no mass transfer; it operates even under typical ambient conditions; and it has the potential to completely break down all organic carbon into carbon dioxides ^[24]. Whereas photocatalytic degradation is applicable to both organic and inorganic pollutants, this review focuses on Maxilon dyes. There have been various original research reports on the elimination of Maxilon dye through adsorption and photodegradation approaches. There also exists one review^[18] on Maxilon dye adsorption. However, to the best of

the information we have, there isn't any review that deals with the photocatalytic degradation overview of Maxilon dye pollutants. The current review offers insight into Maxilon dye photodegradation operations, with a particular emphasis on its degradation in aquatic bodies.

2. Research Methodology

Renowned scientific repositories were employed to gather publication data from 2001 to 2024 as laid out in the review methodology workflow blueprint presented in **Figure 1**. Some of the search query words included maxilon dye, photocatalytic degradation, nanoparticles, water pollutants, kinetic isotherm, and regenerability. All of the aforementioned search terms were used in different combinations, and non-English articles were not considered. Additionally, the bibliographies of any potential relevant publications were manually searched in order to find any articles that internet searches may have missed.

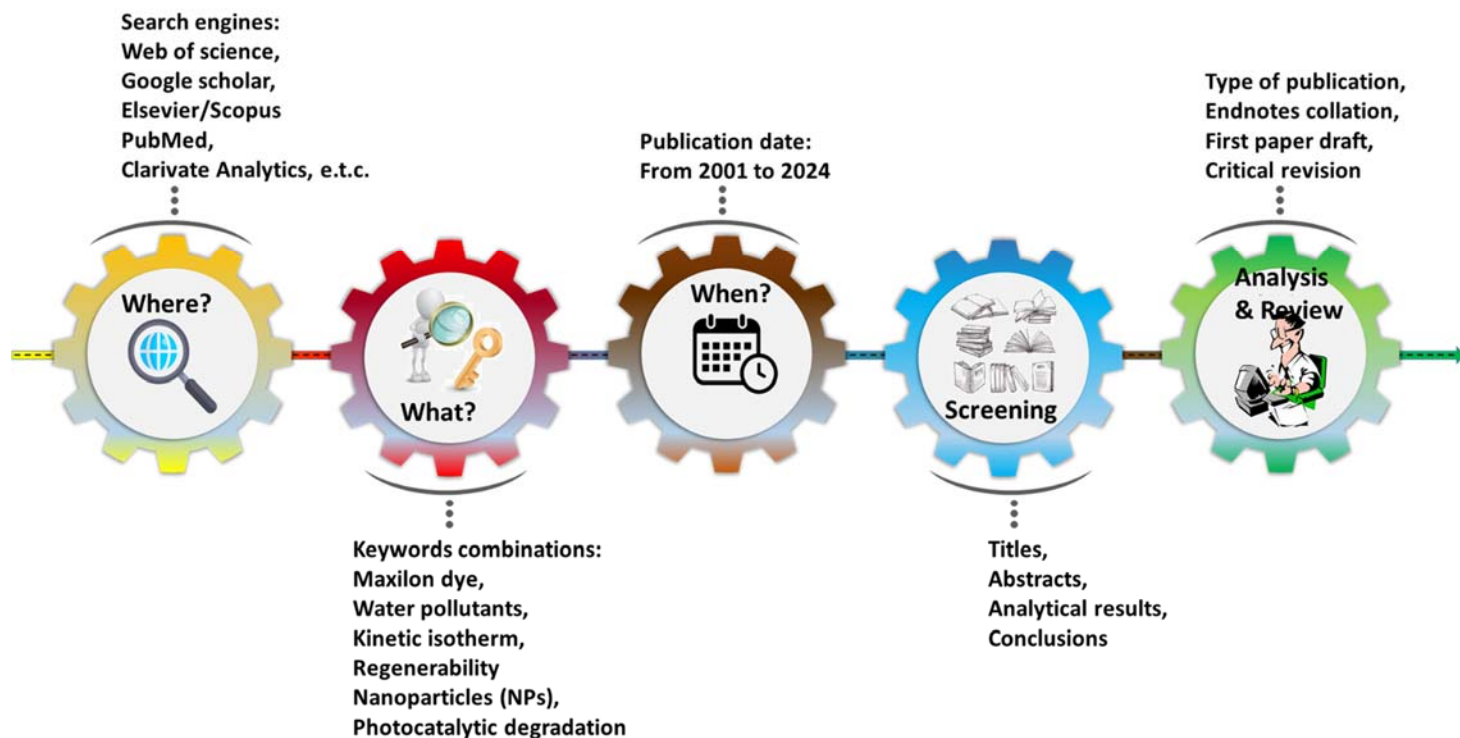


Figure 1: Review methodology pathway.

3. Eco-toxicity of Maxilon Dyes

Maxilon dyes represent a distinct class or series of basic mono-azo dyes, distinguished by their unique molecular structure. Its characteristic attribute of vibrant coloration has contributed to their widespread utilization in various textile applications, making them a prominent and sought-after choice in the realm of dyeing and coloring textiles ^[18]. The massive usage of this azo-dye family has shown that the majority of their reaction intermediates/byproducts are extremely carcinogenic, and are persistent and non-biodegradable due to the presence of aromatic and other architectural functional groups. In most cases, the introduction of synthetic dyes, like maxilon dyes, into aquatic ecosystems triggers a cascade of detrimental consequences. These negative impacts become evident as these dyes find their way into water bodies in the environment. A prominent effect is the obstruction of light penetration through the water column, leading to a disturbance in the critical process of photosynthesis among aquatic plants. This interruption in light availability interferes with the fundamental ability of aquatic flora to carry out photosynthetic activities, thereby disrupting the overall ecological balance. These dyes pose a multifaceted threat not only to the environment but also to the well-being of various organisms, including humans, fish populations, and microorganisms residing within aquatic ecosystems. The recognition of these risks underscores the necessity for stringent regulatory measures and responsible disposal practices to mitigate the adverse impacts associated with these dyes' release into aquatic environments ^[25-29]. The series of maxilon dyes including Maxilon Yellow (MXY) 4GL, Maxilon Golden Yellow (MXG-Y), Maxilon Blue (MXB) 5G, MXB GRL, Maxilon Red (MXR) GRL, MXR BL-N, MXR SL, and MXY 3GL^[18] have been documented in the scientific literature with significant negative effects on the ecosystem as summarized in the following paragraphs.

For example, in a recent research conducted by ^[21], MXB has been linked to a range of deleterious effects, encompassing toxicity, teratogenicity, and genotoxicity. These adverse outcomes have been particularly evident during the critical stage of zebrafish embryonic development. The dye has been found to induce developmental abnormalities that include conditions like yolk sac edema, pericardial edema, a distorted body axis, tail malformation, and microphthalmia. These manifestations strongly indicate its potential to detrimentally affect reproductive success in zebrafish populations. Additionally, it was reported that maxilon dye' influence extends to the molecular level, as it has been observed to trigger DNA damage, primarily due to oxidative stress. This oxidative stress-related DNA damage can lead to irreversible harm to embryos and larvae, further compounding the detrimental effects of the dye. Upon discharge into aquatic environments, it poses a tangible threat to both aquatic organisms and their habitats. The evidence underscores the urgency of understanding and addressing the potential harm that this dye can inflict upon ecosystems, reinforcing the importance of responsible usage, disposal, and regulatory measures to mitigate its impacts.

An ecotoxicological investigation focusing on earthworms and their exposure to MXB 5G dye has unearthed significant discoveries. The research indicated that this dye can induce adverse effects at the cellular and tissue levels within earthworm organisms. Notably, exposure to Maxilon Blue 5G dye was associated with various forms of cell damage. Among these cellular injuries, degeneration and necrosis were observed. Furthermore, at the tissue level, deformities and atrophy were noted in earthworm muscles. These tissue-level alterations were found to encompass not only muscular deformations but also broader tissue damage. The examination of earthworms exposed to the dye revealed the presence of severe tissue injuries, including necrosis in epidermal tissue and necrosis in the intestinal epithelium. Vascular changes, such as hyperemia in vessels, were

also observed, indicating the extent to which the dye impacts the physiological integrity of earthworms [30].

4. Mechanism of Maxilon Dye Photocatalytic Degradation using NPs

Photocatalysis is a chemical process that transforms contaminants into non-toxic spinoffs like CO₂, and H₂O^[31]. In this process, When a nano-photocatalyst is subjected to light with an energy greater than its band gap, it induces the excitation of e⁻ from the valence band (VB) to the conduction band (CB), resulting in +ve holes (h⁺) in the valence band while allowing e⁻ without causing the NPs to disintegrate at the conduction band^[8,28,29,31-40]. The surface-adsorbed H₂O molecules in the VB trapped the highly oxidative h⁺ to form OH, while the adsorbed molecular O₂ scavenges e⁻ to generate the superoxide radical anion (O₂^{•-})^[8,28,29,31-34,38,40-42]. The e⁻/h⁺ charge carriers that are produced as a result then move toward the outer layer (surface). In addition, [•]OH radicals are also produced by further interaction between the O₂^{•-} radical anion and the H₂O molecule. The [•]OH and O₂^{•-} radicals then attack the molecules of maxilon dye, converting them into less complex and non-toxic chemicals^[8,28,29,31-34,36,38,39,41-44]. The degradation by this radical attack is often established or judged by the rupture of the primary carbon bonds of the dye pollutant, the disintegration of the dye pollutant aromatic ring, C-N bond, and C=N cleavage^[28,33,45].

The plausible mechanism and stepwise equation of the explanation in the foregoing paragraph as per maxilon dye photodegradation using NPs when exposed to light are provided in **Figures 2 and 3** respectively. Although, on the other hand, after excitation and formation of the e⁻/h⁺ pair, the photoinduced h⁺ and e⁻ can also interact directly with moieties/molecules of maxilon dye and produce unstable exciting dye (Dye*). The unstable excited dye (Dye*) then changes to anionic (Dye⁻) or cationic (Dye⁺) radicals. In the end, these Dye⁻ and Dye⁺ radicals spontaneously break down into non-toxic and less complex compounds^[39].

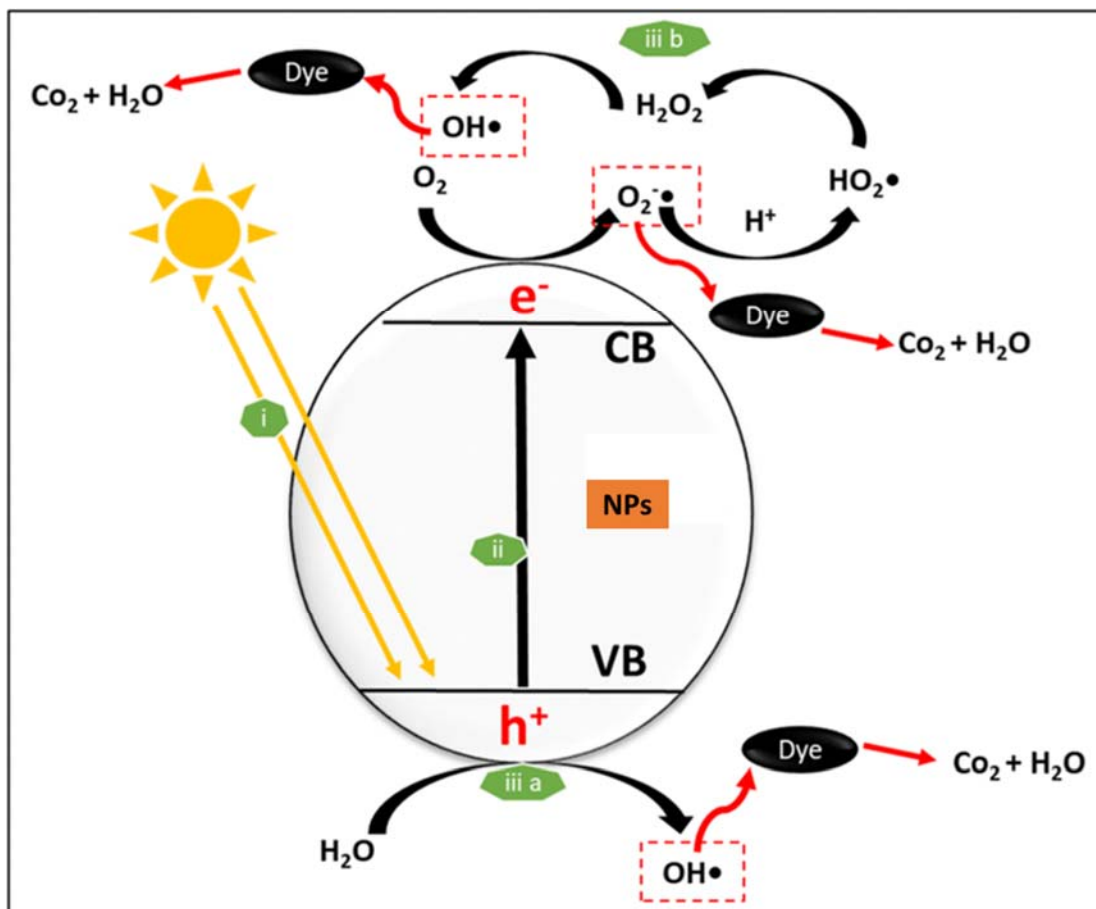


Figure 2: Typical mechanism of maxilon dye degradation by NPs when exposed to light. Reproduced from ref.^[46], Copyright 2020, with authorization (Order code: 501890986) from Springer Nature.

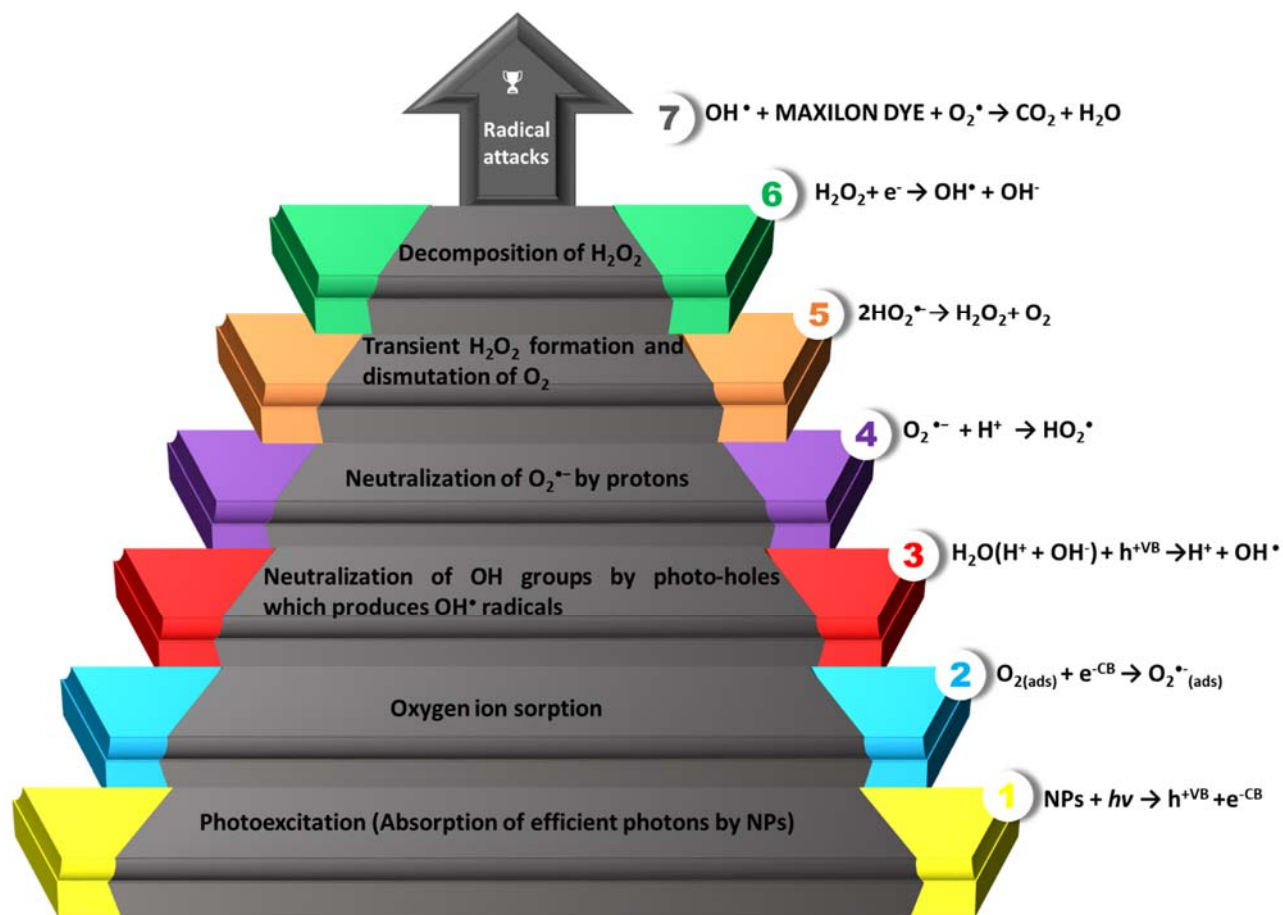


Figure 3: Probable stepwise photocatalytic degradation of maxilon dye by NPs when exposed to light. Reproduced from ref.^[8], Copyright 2023, with open access permission from Elsevier.

5. Evaluation of Photocatalytic Degradation Efficiency of Maxilon Dyes

Research executed on the degradation of maxilon dye pollutants using nanoparticles was discussed in this section. For example, to study the photodegradation of MXR, Farouq et al. ^[47] used a coupling adsorption process employing rice straw combined with a TiO₂ photocatalyst. The authors claimed that by sequentially operating adsorption and photocatalytic degradation over TiO₂ when exposed to visible light, the MXR removal efficiency increased. About 65.51% of MXR was degraded within 120 minutes, according to the report ^[47]. Similarly, Alborayi et al. ^[48] synthesized TiO₂ NPs and employed this as a potentially effective photocatalyst to investigate the

relative photodegradation proficiency of MXB (GRL) dye pollutants. Investigation of the photocatalytic capability of the fabricated TiO₂ NPs revealed that catalyst loading, light intensity, initial solution concentration, and initial solution pH all had an impact on the catalyst activity. They observed significant MXB GRL decolorization efficiency under UVA light ^[48]

Also, a study conducted by Lenzi et al. ^[49] showed comparable photocatalytic discoloration and adsorption outcomes for three NPs, namely Fe/TiO₂, Fe/ZnO, and Fe/TiO₂-ZnO, in a synthetic effluent containing MXB dye 5G. All photocatalysts completely discolored the reaction system ^[49]. In 2021, Dantas et al. ^[50] used Co-doped molybdenum carbides, which are regarded as potential photocatalytic materials to investigate the behavior of Mo₂C and Co-doped Mo₂C in maxilon dye photocatalytic degradation reactions. Under tungsten light, the photodegradation of Mo₂C and Mo₂C-Co in the MXB GRL basic dye was 90.5 and 74.4%, respectively as shown in **Table 1** ^[50]. An analogous result was reported by the same research group ^[51] in a different investigation carried out in 2020. The authors fabricated Ni-doped molybdenum carbide to degrade the textile dye MXB GRL 300. All catalysts were present when tungsten light was used to destroy MXB GRL 300. The effectiveness of the photocatalysis procedure for the synthesized material was tested under both acidic and basic pH conditions, with the degradation performance reaching up to 92% at the final dye concentration ^[51].

Similarly, by assessing the photocatalytic degradation efficiency of maxilon blue dye under UV light irradiation, Hashim et al. ^[52] described the photocatalytic action of the (Ag, Pd)/ZnO NPs. The experimental findings demonstrated that increasing the Ag and Pd doping improved the photocatalytic efficacy of the ZnO NPs. When compared to Ag/ZnO or Pd/ZnO NPs, the (Ag, Pd)/ZnO NPs showed better photocatalytic effectiveness, which may be explained by the transfer

of photogenerated e^- from ZnO to Pd and Ag, lowering the likelihood of recombination and photoluminescence intensity ^[52]. The same author investigated the degradation of MXB GRL dye pollutants under UV light irradiation. According to these findings, the synthesized ZnO/Fe₂O₃ nanocomposite exhibited good photocatalytic activity when exposed to UV light. Within 200 minutes of irradiation, the degradation efficiency of GRL dye was found to be 81.1% ^[53].

In another experiment, Alkaim ^[54] and his colleagues used an efficient and practicable green precursor-based technique to synthesize ZnO. The nanoparticles used glutamine as a biotemplate and a sonochemical/hydration-dehydration technique to degrade maxilon blue GRL up to 98% in 1 h ^[54]. A similar scenario was reported by Mekatel et al. ^[55] when ZnO was synthesized from zinc acetate and employed as a photocatalyst to reduce the remaining MXR concentration. Photodegradation was conducted in a double-walled borosilicate reactor exposed to sunlight, and the incident flux was determined using a calibrated light meter. They discovered that the photocatalytic action of ZnO for the breakdown of the MXR dye was quite good. According to the kinetic investigation, MXR virtually vanished (by a margin of 99% after 90 min of exposure to solar radiation). The distinct characteristics of ZnO, including its large surface area, high electron mobility, and potent oxidizing power, are believed to be responsible for its photocatalytic activity ^[55].

In another research, by using TiO₂ and silver-loaded TiO₂, Sokmen et al. ^[56] investigated the photodegradation of maxilon red GRL. The authors found that the Ag loading significantly increased the degradation process. With Ag-loaded TiO₂, the rate of maxilon red GRL degradation increases to approximately 100% (Sökmen et al., 2001). This is in agreement with the study carried out by Aljeboree et al. ^[57], who photodegraded MXB GRL using TiO₂ NPs in the presence of UV

light irradiation. Photosynthesized holes at the surface of TiO_2 and (OH^\cdot) in the solution bulk were used in the photocatalytic process as oxidizing species of the MXB GRL [57].

Ghaly et al. [58] also reported the use of titanium dioxide to study the solar photocatalytic oxidation of the basic dye maxilon navy 2 RM. H_2O_2 was added to maxi-ion navy 2RM dye, which significantly improved the decolorization rate. After 90 min of irradiation, 99.9% of the color was removed from the effluent under ideal operating conditions. The dye was mineralized by 60% within 90 min and by 75% within 240 min, indicating that the dye was also successfully degraded under these conditions, according to measures of total organic carbon loss. Solar photocatalytic oxidation can be employed as a quick, effective, and affordable method for treating wastewater containing basic dyes owing to efficient decolorization and mineralization, respectively [58].

Also, under visible-light photoelectrocatalysis, Ayoubi and colleagues [59] researched the photocatalytic activity of $\text{Dy}_2\text{O}_3/\text{graphite}/\text{TiO}_2/\text{Ti}$ nanocomposites in the degradation of MXB. The outcomes demonstrated that the photocatalytic efficacy of the nanocomposite electrode was higher than those of the individual components. The photoelectrocatalytic process has a synergy index of approximately 2.5, which means that when compared to the individual processes, the combined system improved the degradation efficiency [59]. In another study in which graphite was integrated as part of the photocatalyst, Al-khatani et al. [40] provided evidence of the ability of maxilon CI to degrade when exposed to solar light. The photocatalytic action of the NPs was assessed, and after 120 min of exposure to light, the results revealed that the $\text{CS}/\text{CoFe}_2\text{O}_4/\text{GONCs}$ catalyst exhibited high photocatalytic activity, with a degradation efficiency of 98.5%. This high photocatalytic activity can be ascribed to the interaction between graphene oxide nanosheets (GONCs) and CoFe_2O_4 . CoFe_2O_4 serves as a photocatalyst and GONCs serve as sensitizers,

increasing the ability of the catalyst to absorb light. Additionally, the excellent separation of photogenerated carriers produced by the combination of CoFe_2O_4 and GONCs increased the catalytic activity of the catalyst^[40]. The performance of NPs with extraordinary degrading efficacy against maxilon dye as reported in the literature are summarized in **Table 1**.

Table 1: Photocatalytic degradation effectiveness of some nanoparticles towards different types of maxilon dyes

| NPs | Geometry, and size(nm) | Light source | Maxilon dye degraded | DT(mins) | DE (%) | References |
|---------------------|-------------------------------|---------------------|-----------------------------|-----------------|---------------|-------------------|
| TiO ₂ | Crystal 5-10 | UV | Maxilon red | 120 | 65.51 | [47] |
| TiO ₂ | Irregular 12-20 | LED/UVA | Maxilon blue GRL | 60 | 62.93 | [48] |
| Fe–TiO ₂ | - | UV | Maxilon blue 5G | 40 | 100 | [49] |
| Fe–ZnO | - | UV | Maxilon blue 5G | 40 | 100 | [49] |

| | | | | | | |
|-------------------------------------|--------------------------------------|----------------------|--------------------|-----|-------|------|
| Fe-TiO ₂ -ZnO | - | UV | Maxilon blue 5G | 50 | 100 | [49] |
| Mo ₂ C | Irregular plate like 24.9-40.7 | Tungsten filament | Maxilon blue GRL | 60 | 90.5 | [50] |
| Mo ₂ C-Co | Rod 24.9-40.7 | Tungsten filament | Maxilon blue GRL | 60 | 74.7 | [50] |
| Chitosan- CoFe ₂ O-GO | 47 | Sunlight | Maxilon C.I. basic | 120 | 70 | [40] |
| Ag/Pd/ZnO | Rod-like | UV | Maxilon blue GRL | 60 | 95.67 | [52] |
| ZnO | Rod-like | UV | Maxilon blue GRL | 60 | 55.5 | [52] |

| | | | | | | |
|------------------------------------|----------|-----|------------------|-----|------|------|
| Ag/ZnO | Rod-like | UV | Maxilon blue GRL | 60 | ~60 | [52] |
| Pd/ZnO | Rod-like | UV | Maxilon blue GRL | 60 | >80 | [52] |
| ZnO | Rod-like | UVA | Maxilon blue GRL | 60 | 98 | [54] |
| ZnO/Fe ₂ O ₃ | 15.0 | UV | Maxilon blue GRL | 200 | 81.1 | [53] |
| TiO ₂ /Ag | - | UV | Maxilon red GRL | 60 | ~100 | [56] |
| TiO ₂ | - | UV | Maxilon red GRL | 60 | ~100 | [56] |

| | | | | | | |
|---|---|----------|----------------------|-----|------|------|
| Mo ₂ C-Ni | Platelets and rod-like 34.7 to 37.5 | Tungsten | Maxilon blue GRL 300 | 60 | 92 | [51] |
| TiO ₂ | - | UV | Maxilon Blue GRL | 60 | ~100 | [57] |
| Dy ₂ O ₃ /graphite/Ti O ₂ /Ti | - | UV | Maxilon Blue GRL | 180 | >80 | [59] |
| ZnO | Hexagonal | Solar | Maxilon red | 90 | 99 | [55] |
| TiO ₂ | - | Solar | Maxoline Navy | 90 | 99 | [58] |
| TiO ₂ | - | UV | Maxilon Blue | 210 | 100 | [60] |

| | | | | | | |
|----------------------|------|---------------------|-------------|-----|-----|------|
| ZnO-AC | - | Fluorescent lamp | Maxilon red | 120 | 100 | [61] |
| CeO ₂ -AC | Wavy | Fluorescent lamp | Maxilon red | 60 | 100 | [61] |

Where DE = Degradation efficiency (%), DT = Degradation time in minutes, NPs = Nanoparticles

6. Kinetics and Isotherm Modelling of Photocatalytic Degradation

The orientation of the degrader (NP) surface, the arrangement of functional groups, and the interactions of forces involving maxilon dye all have an essential part in how it interacts between the degrader and the maxilon dye during the sorption phase that occurs during degradation the process. The adsorption isotherm is a key modeling tool that describes the interaction between the amount of a material adsorbed for each degrader-adsorbent unit mass at a fixed temperature and known concentrations at equilibrium ^[62]. Once an equilibrium situation occurs, the adsorption isotherm describes the adsorbate's behavior as well as its distributions within liquid and solid phases. It is critical to figure out and refine the adsorption procedure before developing an appropriate adsorption isotherm model. A few models were developed to assess the equilibrium adsorption of Maxilon-based dyes during degradation operation. The classical Langmuir model was demonstrated to be the best-fitting isotherm in a large part of the studies examined (**Table 2**). This finding reveals that Maxilon dyes adsorb to diverse degraders/photocatalysts regardless of whether they are monolayer (i.e., homogenous) or multilayer (i.e., heterogeneous). Because they only involve two factors, they may be easier to compute ^[63]. Isotherm models may be described using linear and non-linear techniques via the approach known as regression ^[64]. The Langmuir isotherm is a theoretical framework that matches monolayer adsorption onto a homogeneous surface having a finite number of sites for adsorption ^[65]. Also, the metal oxide NPs are tiny in size, which may increase the possibility of monolayer uptake. The energetically homogeneous nature of the metal oxide NP activities makes this possible.

Kinetic adsorption data can be utilized to assess the adsorption process's kinetics regarding order and rate constant. Kinetics models also play a key role in apprehending and interpreting the intricate details of the adsorption-degradation operation, including the manner, mechanism, and

speed at which adsorption occurs in batch experiments before proper photodegradation begins^[66-69]. NPs were utilized to remove contaminants such as Maxilon dyes. Pseudo-first-order (PFO)^[66,67] and pseudo-second-order (PSO)^[70,71] models can be used to simulate the kinetics of these dye pollutants removal. As a result of the literature review, it can be deduced that the adsorption-degradation of Maxilon dye contaminants by NPs was observed to follow the PFO kinetic model in the majority of the studies, with the exception of Mekatel et al. (2021), who observed the PSO. The R^2 value was used to establish the best fit, and a value of 0.9999 indicates a perfect fit that follows the PSO, as shown in **Table 2**. It may be drawn that PFO is the best-fit model for Maxilon dye adsorption-degradation. This model is based on the idea that chemical adsorption, which involves valence forces via electron sharing or exchange across degrader and adsorbate, is the rate-limiting phase^[62].

Table 2: Summary of BFI and BFK models for various maxilon dye degradation using nanoparticles

| NPs | Maxilon dye degraded | BFI | R² | BFK | R² | References |
|--------------------------|-----------------------------|----------------------|----------------------|------------|----------------------|-------------------|
| TiO ₂ | Maxilon blue GRL | Langmuir–Hinshelwood | 0.944 | PFO | NA | [48] |
| Fe–TiO ₂ | Maxilon blue 5G | NA | NA | PFO | 0.911 | [49] |
| Fe–ZnO | Maxilon blue 5G | NA | NA | PFO | 0.923 | [49] |
| Fe–TiO ₂ –ZnO | Maxilon blue 5G | NA | NA | PFO | 0.921 | [49] |

| | | | | | | |
|------------------|------------------|--------------------------|--------|-----|--------|------|
| ZnO | Maxilon blue GRL | Langmuir– Hinshelwood | 0.9359 | PFO | | [54] |
| ZnO | Maxilon red | Langmuir | 0.9938 | PSO | 0.9999 | [55] |
| TiO ₂ | Maxoline Navy | NA | NA | PFO | 0.985 | [58] |

Where PFO = Pseudo-first-order, PSO = Pseudo-second-order, BFI = Best-fit-isotherm, BFK = Best-fit-kinetics, NA = Not available.

7. Reusability and Regenerability Studies

Choosing an effective photocatalyst with exceptional performance poses a considerable challenge within the context of the adsorption/degradation process. This challenge arises due to the necessity of evaluating a multitude of additional criteria beyond mere performance. These criteria encompass factors such as cost-effectiveness, operational simplicity, safety considerations, the overall environmental impact, and most importantly reusability and re-generability of the nanomaterial [72,73]. The regeneration and recyclability of the nanocatalyst material constitute pivotal elements that play a paramount role in enabling and optimizing the process of adsorption/degradation on an industrial scale. By integrating these measures, the overarching objective is to establish a process that not only meets economic viability but also aligns harmoniously with environmental sustainability, ultimately fostering a holistic approach to process friendliness. The high adsorption and degradation capacity, regeneration, and reusability of the degrader(NPs) determine how effectively the photodegradation process treats wastewater [29,32,72,74–80]. The regeneration process can be summed up as the swift recovery and reuse of the exhausted NPs by a method that is both technically and economically feasible providing economic and environmental advantages as illustrated in **Figure 4** [72,81,82]. Reusability and regeneration are of utmost relevance when evaluating NPs, particularly for financial reasons. Failure to regenerate could lead to polluted NPs release into the environment or necessitate storage [72].

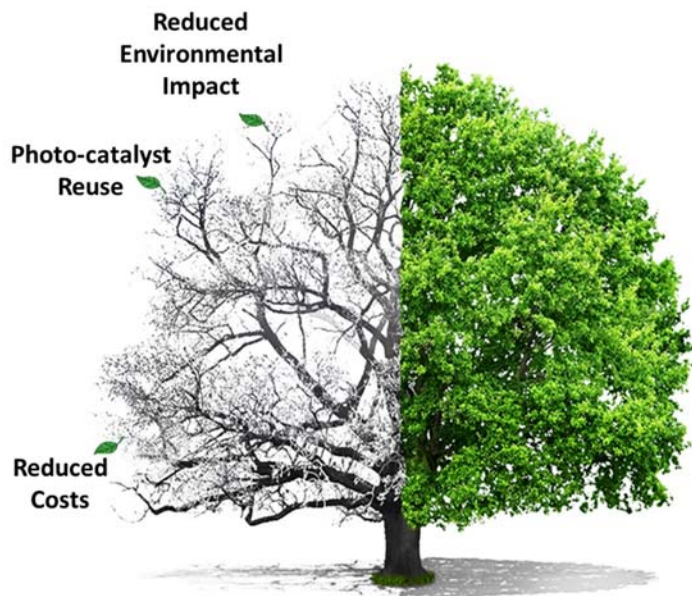


Figure 4: Advantages of reusability and regenerability of spent adsorbents. Adapted from ref.^[72], Copyright 2022, with authorization (Order code: 5631141289776) from Elsevier.

It is therefore imperative to consider and stress sustainable management of used NPs, including the procedures entailed in their regeneration and reclamation for reuse. Different methods for recovering and regenerating used adsorbents have been developed^[83]. These methods include filtration, thermal decomposition, chemical, supercritical fluid and thermal desorption, and microbial-aided method, as well as field-flow fractionation, centrifugation, magnetic separation, and electric field methods ^[74,76,84–96]

The subsequent paragraphs provide an overview of recent research concerning the revitalization of utilized adsorbents and photocatalysts, along with the retrieval of Maxilon dyes from dye-loaded nanoparticles. Additionally, these paragraphs present insights into the specific adsorbents and photocatalysts for dye up to the *n*th adsorption-desorption cycle.

The photodegradation of Maxilon C.I. within an aqueous solution containing CS/CF/GONCs (chitosan/cellulose fiber/graphene oxide nanocomposites) was investigated by Al-Kahtani and

Abou Taleb ^[40]. The results of their research revealed a remarkable level of efficiency in the catalyst's performance, with an impressive 99 % repeatability observed during the initial two cycles of operation. Notably, even after being subjected to multiple cycles, the catalyst exhibited a minor decline of only 15 % in its activity up to the fourth cycle following its magnetic removal. Furthermore, the study emphasized a key practical aspect of the CS/CF/GONCs catalyst – its exceptional retrievability and reusability. This unique property was attributed to the catalyst's inherent ability to undergo easy precipitation, enabling its separation from the reaction solution. This practical advantage of swift catalyst separation contributed to its potential for reapplication in subsequent cycles. This finding underscores the eco-friendliness and economic viability of the CS/CF/GONCs catalyst, as it not only displayed outstanding degradation capabilities but also exhibited a sustainable and efficient cyclic utilization approach^[40].

In another study reported by Alkaim's team^[54], rod-like ZnO nanoparticles were recovered through a process that involved filtration, followed by a washing step employing deionized water, which culminated in a drying phase. The results of the study indicated that, upon subsequent usage, the ZnO nanoparticles exhibited a noticeable decline in their photocatalytic activity. Specifically, the photodegradation efficiency witnessed a reduction from an impressive 97.99 % during the initial use to a still considerable 82.39 % after being subjected to the sixth repeated use, as illustrated in **Figure 5**. Despite the decrease in photocatalytic activity over multiple cycles, the nanoparticles retained their functionality to a considerable extent. This observation supports the notion that while the photocatalytic efficiency may experience a gradual decrease over successive uses, the nanoparticles remain structurally sound and capable of contributing significantly to ongoing catalytic processes.

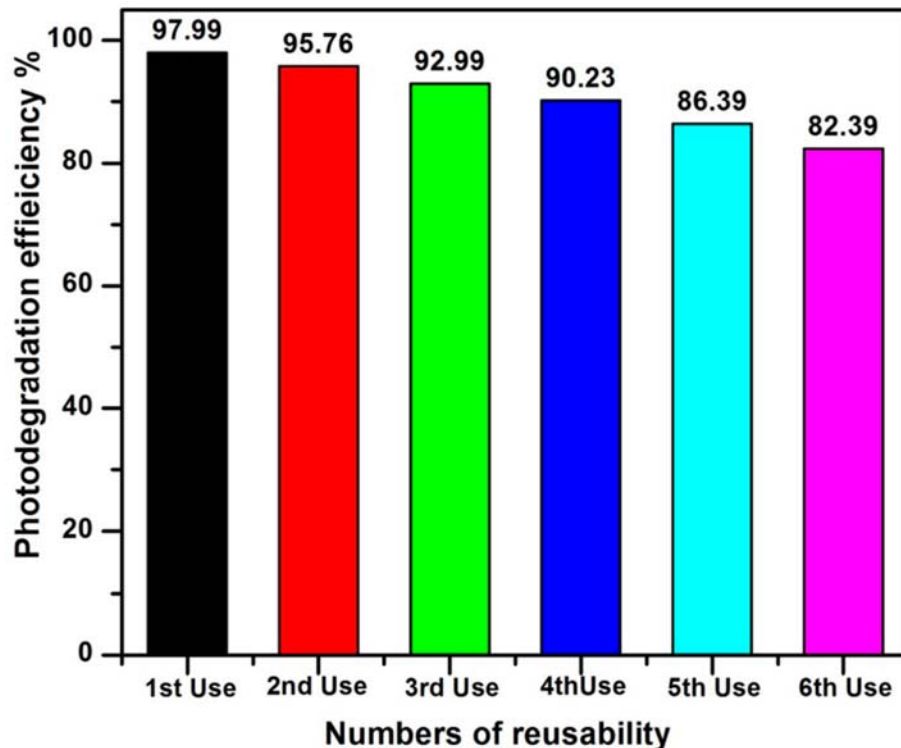


Figure 5: Recyclability tests for ZnO nano-photocatalyst for maxilon blue dye degradation. Reproduced from ref.^[54], Copyright 2016, with permission (Order code: 501890985) from Taylor & Francis.

Another study^[59] delved into the repeatability assessment of Dy₂O₃/graphite/TiO₂/Ti nanocomposites to degrade Maxilon blue GRL. The findings from this investigation showcased that, even after undergoing four consecutive recycling cycles under optimal conditions, the decolorization efficiency exhibited minimal deviations compared to the performance of the original catalyst. A key highlight of the study was the notable observation that the particles of Dy₂O₃, graphite, and TiO₂ exhibited strong adhesion to the surface of the titanium grid sheets. This cohesive adherence contributed to the sustained performance of the nanocomposite over four multiple cycles ^[59].

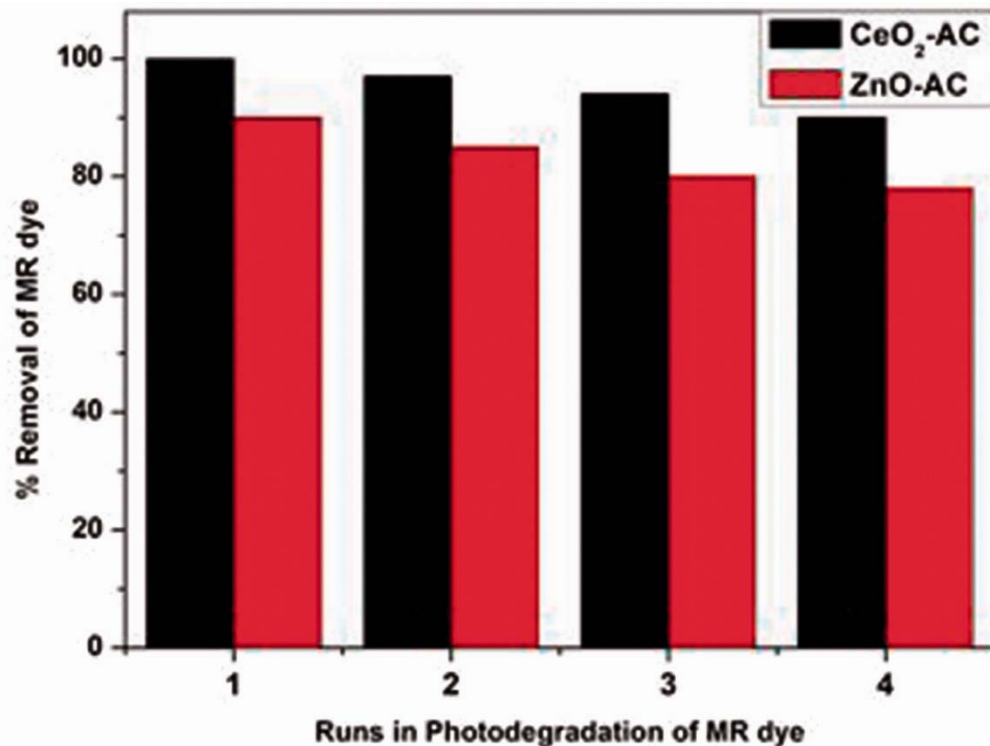


Figure 6: Recyclability tests for CeO₂-AC and ZnO-AC nanoparticles. Reproduced from ref.^[61], Copyright 2017, with open access permission from Sage.

In another stability test, CeO₂-AC and ZnO-AC nanoparticles were successfully reclaimed from the regeneration solution through a process involving filtration, thorough washing, and subsequent drying. As illustrated in **Figure 6**, the outcomes of this study indicated that the CeO₂-AC nanoparticles, upon preparation, demonstrated notably enhanced photocatalytic degradation potential and sustained stability when dealing with maxilon red dye, persisting up to the fourth cycle. The photocatalytic efficiency of the ZnO-AC nanoparticles experienced a decline from an initial value of 90 % down to 78 % by the fourth cycle while that of CeO₂-AC nanoparticles experienced only a slight decline of about 10 % from the original 100 %. This divergence in behavior underscores the comparative performance trajectories of the two catalysts over multiple usage cycles. Therefore, it was concluded that the CeO₂-AC catalyst exhibited superior

photocatalytic efficacy and stability when compared to the ZnO-AC counterpart in the context of maxilon red dye degradation ^[61]

In a recent scientific investigation, magnetic AuNi@AC NPs that were purposely created demonstrated a remarkable capability for efficient reusability. After undergoing five consecutive cycles of the degradation process targeting MXB 5G dye, these NPs exhibited an impressive reusability efficiency rate of nearly 70 %. While this reusability efficiency might appear relatively lower compared to findings from earlier studies, it still stands as a commendable outcome ^[97]. It was reported that there was a drop in NPs activity from 95 % to 64 % as a result of five tests, as shown in **Figure 7**, as well as the interaction between AuNi@AC nano-catalyst and MXB, leading to change in absorption peaks as depicted in **Figure 7b**. This outcome underscores the value of these NPs as an effective tool for addressing dye contamination sustainably, thus contributing to both environmental preservation and resource efficiency.

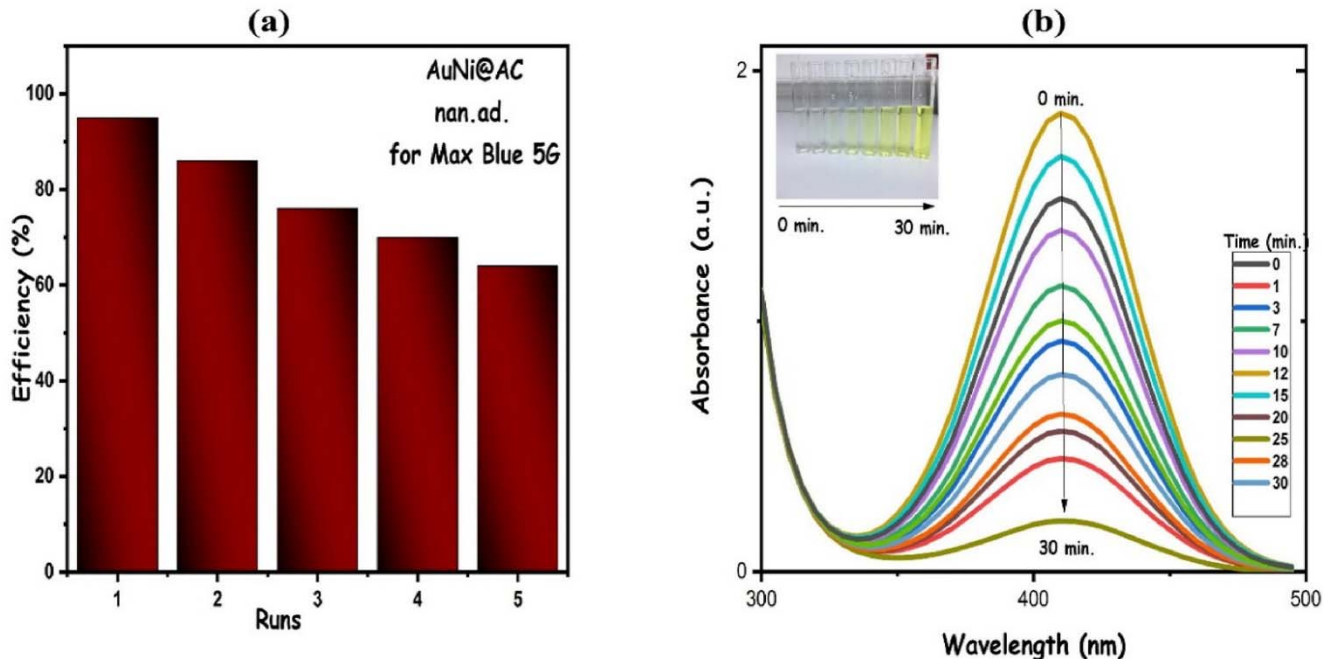


Figure 7: Recyclability tests for AuNi@AC NPs. Reproduced from ref.^[97], Copyright 2022, with permission (Order code: 5631150820505) from Elsevier.

Similarly, another study^[98] also delved into examining the stability and reusability of Fe₃O₄@MWCNT magnetic NPs across six consecutive cycles, all conducted under constant parameters for the degradation of MXB 5G dye. The process involved retrieving the magnetic NPs magnetically from the degradation solution after each treatment, followed by a meticulous washing using ultrapure water, subsequent drying, and eventual reuse. Initially, the degradation efficiency stood at a substantial 88.51 %, signifying a high level of dye degradation. However, as the reusability trials progressed, this efficiency gradually decreased to around 67.85 % in the sixth cycle. Despite the diminishing trend in efficiency, the magnetic NPs maintained a significant capacity for dye removal throughout multiple cycles^[98].

Overall, as seen from regenerability and reusability data collected in **Table 3**, the least number of recyclability was 4, and the maximum number of recyclability was 6 with the average photocatalytic degradation efficacy after the nth cycle being greater than 75 %.

Table 3: Summary of dye regeneration and recyclability.

| NPs | Maxilon dye degraded | Eluting agent | % DE @ n = 1 | No. of cycle | % DE @ nth cycle | References |
|---|-----------------------------|---|---------------------|---------------------|-------------------------|-------------------|
| Chitosan-CoFe ₂ O-GO | Maxilon C.I. basic | Magnet | 99 | 4 | 84 | [40] |
| ZnO | Maxilon blue GRL | Filtration + Deionized H ₂ O | 97.99 | 6 | 82.39 | [54] |
| Dy ₂ O ₃ /graphite /TiO ₂ /Ti | Maxilon Blue GRL | NA | >80 | 4 | >80 | [59] |
| ZnO-AC | Maxilon red | Filtration + Hot H ₂ O | 90 | 4 | 78 | [61] |
| CeO ₂ -AC | Maxilon red | Filtration + Hot H ₂ O | ~100 | 4 | ~90 | [61] |

| | | | | | | |
|---|-----------------|---|-------|---|-------|------|
| AuNi@AC | Maxilon blue 5G | NA | 95 | 5 | >63 | [97] |
| Fe ₃ O ₄ @MWC NT | Maxilon blue 5G | Magnet + Ultrapure H ₂ O | 88.51 | 6 | 67.85 | [98] |

Where DE = Degradation efficiency (%), NA = Not available, NPs = Nanoparticles

8. Knowledge Gap and Future Research Direction

The key knowledge gaps that can serve as future research hotspots are presented in **Figure 8**. There are very few studies on the toxicological impact of maxilon dye pollutants and thus more require more focus in future studies. Also, unlike other dye pollutants, the degradation pathway of maxilon dye pollutant using GS-MS and other ultramodern instrumentations has not been explored and it is worthy of consideration for a holistic understanding of the photocatalytic degradation process of maxilon dye. Furthermore, there is a severe lack of research on regenerability and recyclability because there is so little literature in this area and thus scientists should pay more attention to this study aspect in the future. In addition, since the adsorption process is an integral part of photocatalytic degradation, researchers should pay more attention to thermodynamic, kinetic, and isotherm modeling. Also, for future work, the lifecycle analyses of nano-photocatalyst fabrication and utilization, and cost analysis be performed. Moreover, there is no work on the use of biogenic NPs (NPs fabricated using biological entities like plants and microorganisms that contain plethora of hydroxyl and oxygenated functional groups ^[99–104]) for photocatalytic degradation of maxilon dyes and this could be an interesting future research hotspot. Lastly, since

maxilon dyes are one of the most emerging colourful dyes, their photocatalytic degradation in real-life scenarios on an industrial scale needs to be explored.

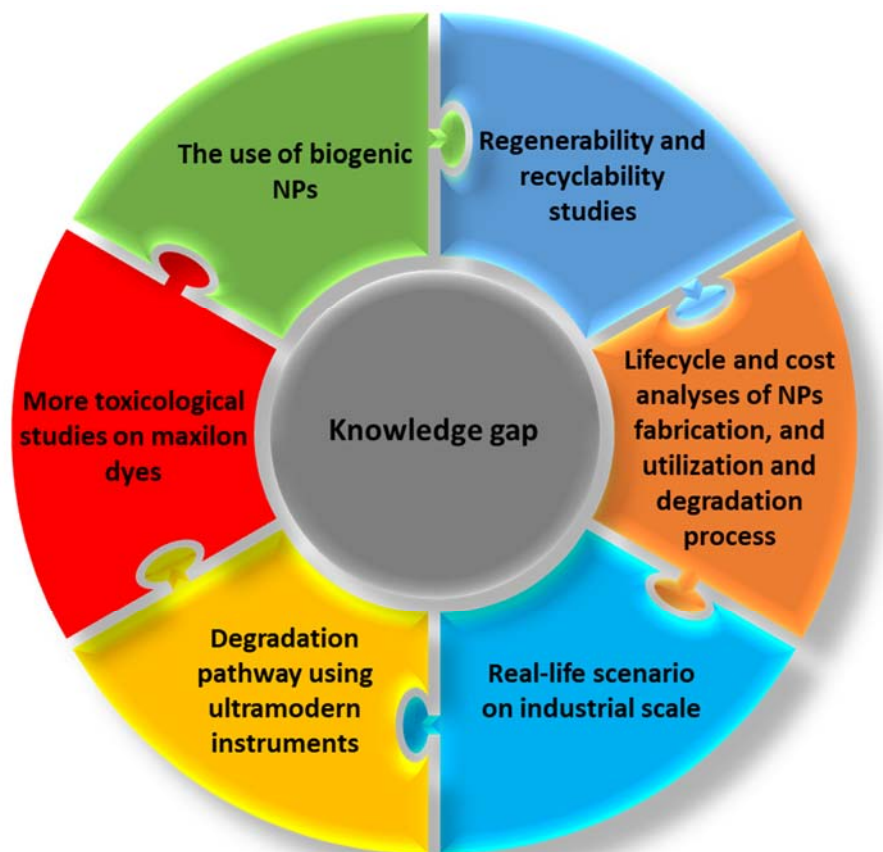


Figure 8: Key knowledge gap identified.

9. Conclusion

In this study, photocatalytic degradation of maxilon dye pollutants by nanoparticles was reviewed. This review produced a number of important conclusions. It was discovered that $\bullet\text{OH}$ and $\text{O}_2\bullet$ played a vital role in the genesis of the oxidizing capacity of NPs for the photocatalytic breakdown of maxilon dye. It was also seen that during degradation, the small size of NPs results in a superior possibility of monolayer uptake of the dye, which allows the attacking hands of the radicals to

reach the stubborn maxilon dye pollutants swiftly and break them down. This was also expedited by the energetically heterogeneous profile of the active spots on the NPs. Additionally, studies showed that most NPs had a degradation score of more than 80%, and the shortest degradation period is < 1 hour with PFO being the most common kinetic best-fit to describe the adsorption process that occurred shortly before and during the maxilon dye degradation operation. Another key finding is that one or two research works showed that NPs are stable in aquatic settings and can be recycled up to 4 to 6 times during degradation and thus, can be applied at industrial scale level if given more attention. Finally, knowledge gaps were identified in the area of regenerability, maxilon dye ecotoxicological study, degradation pathways, and industrial scale-up and these can overall open up insightful innovation for readers and industries that are interested in pursuing sustainable effluent treatment schemes for zero water insecurity.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Keywords: Maxilon dye, Nanoparticles (NPs), Photocatalytic degradation, Photocatalyst, Regenerability, Water pollutants

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