WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Enhanced Removal of Dyes from Wastewater through Photocatalysis: Overview and Perspectives

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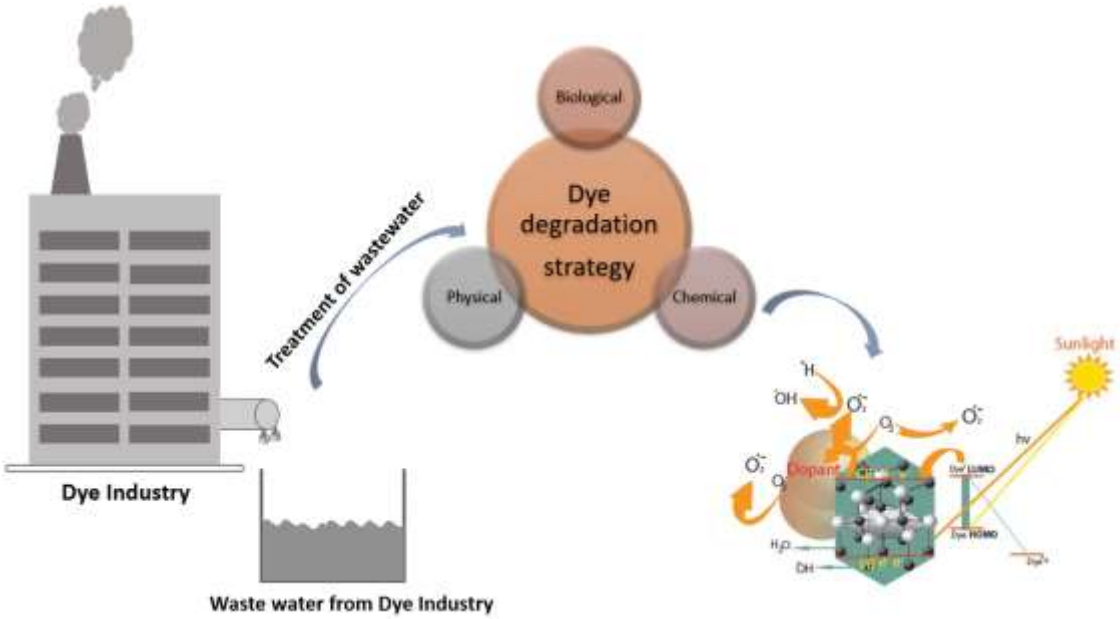
ABSTRACT

Dye removal from wastewater is a key environmental concern because of the adverse impacts that these compounds can have on aquatic ecosystems and human health. The management and disposal of concentrated wastewater, particularly dye-containing wastewater, poses significant environmental issues from generation to disposal. Conventional water treatment procedures including filtration, flotation, and adsorption are non-destructive physical separation processes. Photocatalysis has proven to be a promising and efficient approach for dye degradation in wastewater treatment operations. The process includes forming and interacting with extremely reactive hydroxyl radicals under specific activation conditions. These radicals effectively destroy and mineralize recalcitrant organic contaminants. This review begins with a brief introduction of dye pollution, dye classification, and dye treatment strategies then moves on to the process of photocatalytic degradation, the investigation of various photocatalysts for dye degradation, and the factors that influence dye photodegradation.

Graphical Abstract



Keywords: Catalyst, Dyes, Operating parameters, Photocatalytic degradation, Wastewater

Introduction

Dyes are essential to the dyeing and textile industries. Over 100,000 commercially available synthetic dyes are commonly utilised in these industries.[1, 2] Dyes are mostly generated from coal tar and petroleum intermediates, with an annual production of over 7×10^5 tons.[3] Textile waste effluents discharge around 15% (1,000 tons) of non-biodegradable textile dyes into natural streams and bodies of water annually.[4] Each kilogramme of cloth treated in dyeing and finishing operations consumes around 120-280 L of water.[2]

According to Konstantinou and Albanis, industrial and textile dyes are among the most hazardous chemical substances.[5] The textile finishing and dyeing industries contribute significantly to water pollution (17-20%), according to World Bank estimates.[6] Kant's study found that 72 of the primary hazardous compounds in wastewater were primarily generated by textile dyeing, with approximately 30 of these substances being untreatable.[7] In 1974, the Ecological and Toxicological Association of the Dyestuffs Manufacturing Industry (ETAD) was established to protect consumers and the environment by collaborating with the government to address concerns about the toxicological impact of their products.[8] In an ETAD survey, 90% of 4000 tested dyes were found to LD_{50} values exceed 2×10^3 mg/kg. The highest rates were seen in diazo, direct, and basic dyes.[9]

Azo dyes are the most common type of colourant, accounting for about 50% of all dyes used in industry. Azo dyes have a double bond of 40 nitrogen atoms (-N=N-), with at least one connected to an aromatic group (such as naphthalene or benzene rings). Table 1. shows the types, characteristics, applications and dye fixation % of dyes.[10, 11]

Table 1. Types, characteristics, applications and dye fixation % of dyes.[10, 11]

Dye Class	Characteristics	Applications	Dye fixation (%)	Pollutant
Acidic	Water-soluble anionic compounds	Cosmetics, silk wool, nylon, paper printing ink, food, leather,	80-93	Colour; organic acids; unfixed; dyes organic acids
Basic	Water-soluble, applied in weakly acidic dye baths	Inks, medicine, modified nylon, paper polyester	97-98	NA
Direct	Water-soluble, anionic compounds, applied without mordant	Cotton, leather, silk, rayon, silk, nylon	70-95	Colour; salts; unfixed dye; cationic fixing agents; surfactant;
Dispersive	Insoluble in water	Acetate, acrylic fibres, cellulose, nylon, polyamide, polyester, cotton, plastic	80-92	Colour; organic acids; carriers; levelling agents; lubricants; dispersants; defoamers; delustrants; phosphates; diluents
Reactive	Water-soluble, anionic compounds, largest dye class	Cellulosic, cotton, nylon, silk, wool	60-90	Colour; salt; alkali; unfixed dye; surfactants; defoamer; diluents; finish
Sulphur	Organic compounds containing sulfur or sodium sulfide	Cotton, leather, paper, polyamide fibres, rayon, silk	60-70	Colour; alkali; reducing agent; oxidizing agent; unfixed dye
Vat	Oldest dyes, chemically complex, water-insoluble	Cotton, cellulosic fibres, polyester-cotton, rayon, wool	60-70	Colour; alkali; oxidizing agents; reducing agents

Reusing and recycling wastewater effluents can supplement limited fresh water supplies and offset future water needs.[12] Over the years, several practical tactics have been used to produce effective wastewater treatment systems.[13] Biological treatments can produce secondary pollution, including health-

threatening bacteria and difficult-to-remove organic compounds, despite their short-term effectiveness in eliminating contaminants from wastewater.[14] Developing environmentally friendly and sustainable water treatment methods is crucial.[15]

Dye treatment strategies

The increasing production of dyes due to industrialization has necessitated appropriate treatment, regardless of their physical side effects and toxicity.[16] To address challenging effluents, many solutions have been tested to decrease their environmental impact.[17]

1. Biological treatment

The treatment method removes contaminants through logical action, focusing on biodegradable organic compounds.[17] Biological treatment is used in sectors like food processing, dairy, brewing, paper, plastics, and petrochemicals to deal with biodegradable materials.[18] Some dyes can be treated, but many are resistant to biological breakdown or cannot be transformed under aerobic conditions.[19] Anaerobic treatment has been shown to effectively degrade many synthetic colours.[20] Despite successful efforts to decolorize dyes under aerobic conditions, most azo dyes are still considered non-biodegradable in normal aerobic systems.[21] The biological technique is typically more cost-effective as it involves fungal decolorization, microbial degradation, adsorption by living or dead microbial biomass, and bioremediation systems.[22] To cleanse industrial wastewater, microorganisms like bacteria, yeast, algae, and fungi are used. This microbe can breakdown and collect a variety of contaminants.[23] However, its application is sometimes limited due to technical constraints.[24] The downsides of biological methods include the need for a huge surface area, sensitivity to diurnal variations, chemical toxicity, and limited design and operational flexibility.[25] Compared to conventional biodegradation procedures, this method does not effectively eliminate colour.[26] While certain organic compounds can be efficiently destroyed using this approach, others are unmanageable due to their complicated chemical structure and synthetic origin. This approach is not suitable for azo dyes due to their xenobiotic nature and inability to breakdown entirely.[27]

2. Physical treatment

Physical unit operation is a treatment method that primarily uses physical forces. Physical methods include adsorption as well as membrane-filtration technologies including nanofiltration, reverse osmosis, and electrodialysis.[28] Screening, mixing, flocculation, sedimentation, flotation, and filtration are commonly used industrial methods. Physical methods are utilised to enhance or treat wastewater without causing significant chemical or biological changes.[29] Adsorption, also known as equilibrium separation, is a good approach for water purification. Physical wastewater treatment exploits natural forces like gravity, electricity, and van der Waal to remove contaminants.[30] Physical therapy procedures often do not alter the chemical structure of target substances. Vaporisation and filtration can alter the physical state of substances and induce agglomeration.[31] Filtration technology is essential for drinking water and wastewater treatment, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis.[32] This has been evaluated for colour removal. Each membrane technique is best suited for specific water treatment purposes.[33]

3. Chemical treatment

Chemical unit methods are similar to physical treatment in that they do not involve any microorganisms in the treatment of wastewater.[11] Chemical treatment involves converting or removing pollutants.[34] Chemical treatments include precipitation and adsorption and disinfection. Chemical treatment is commonly employed to clean industrial wastewater due to the presence of contaminants that microorganisms cannot effectively eliminate.[35] Additionally, the procedure requires adding substances like aluminium, calcium, or ferric ions to the dye effluent to promote flocculation.[36] Other agents have also been utilised in the procedure. Combining two factors can enhance the process.[37] Although economically feasible, the method might be costly because to the high cost of chemicals. The technique has a downside of producing significant amounts of concentrated sludge that is pH-dependent.[38]

4. Photcatalytic treatment

Photocatalysis is a method that uses light irradiation and a semiconductor photocatalyst to do both oxidation and reduction.[39] This method varies from previous treatment procedures. Fig 1. Shows advantages of photocatalyst in wastewater treatment.[40] Various semiconductor materials, such as TiO_2, ZnO, Fe_2O_3, SnO_2, ZrO_2, CdS, and ZnS, have been utilised as catalysts to degrade organic contaminants and dyes.[41] Photocatalysis is a dependable and effective way to degrade dyes in water, as evidenced by numerous research.[42] Table 2. summarises photocatalytic dye degradation methods used in previous literature.

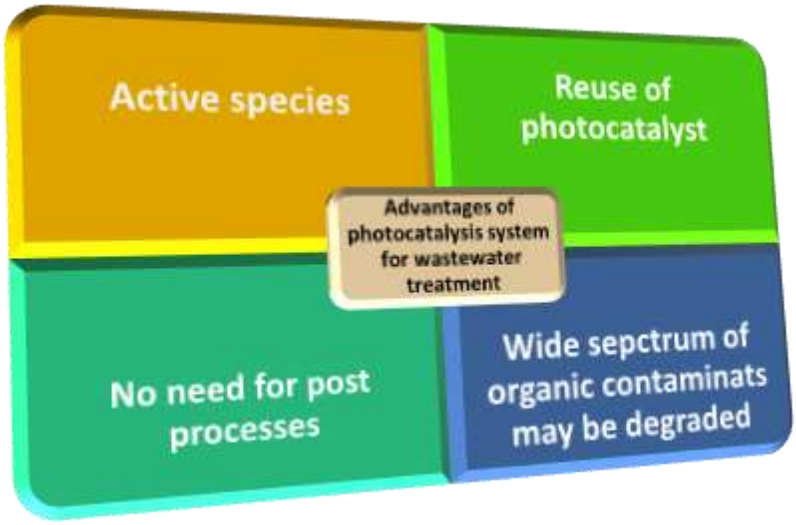


Fig 1. Advantages of photocatalyst in Wastewater treatment[40]

Heterogeneous photocatalysis utilising semiconductor materials typically involves a light harvesting antenna and many active species to degrade pollutants. The photon triggered surface undergoes a series of chain oxidative-reductive processes, as proposed as follows:[43]

$$\text{Photocatalyst} + h\nu \rightarrow h^+ + e^- \quad (1)$$

$$h^+ + H_2O \rightarrow OH\cdot + H+ \quad (2)$$

$$h^+ + OH^- \rightarrow OH\cdot \quad (3)$$

$$h+ + \text{Dye} \rightarrow (\text{Dye})^+ \quad (4)$$

$$e- + O_2 \rightarrow \cdot O_2- \quad (5)$$

$$\cdot O_2- + H+ \rightarrow HO_2\cdot \quad (6)$$

$$2HO_2\cdot \rightarrow H_2O_2 + O_2 \quad (7)$$

$$H_2O_2 + O_2 \rightarrow OH\cdot + OH^- + O_2 \quad (8)$$

$$H_2O_2 + h\nu \rightarrow 2OH\cdot \quad (9)$$

$$\text{Pollutant} + (OH\cdot, h^+, OOH\cdot \text{ or } O_2) \rightarrow \text{degradation product} \quad (10)$$

When a semiconductor is exposed to ultra-band-gap light ($h\nu > E_g$), a valence band (VB) electron (e^-) is stimulated to the conduction band (CB), resulting in a photogenerated hole (h^+) at the VB. The generated e^-/h^+ couples can move to the semiconductor surface and participate in redox processes.[44] Photocatalytic reactions typically involve three active species: hydroxyl radical (·OH), h+, and superoxide radical (·O_2-). ·OH is the major oxidant in pollutant breakdown in aqueous solution. There are typically two routes for generating ·OH radicals.[45] (i) Photogenerated h^+ can easily oxidise H_2O and OH- in water to form ·OH radicals. (ii) Photogenerated e can reduce O_2 in aqueous solution to form ·O_2- radicals, which can then react with h+ to form ·OOH radicals.[46] Photogenerated h+ is an effective oxidant for degrading organic contaminants, with varying capacities depending on catalyst type and oxidation circumstances.[47] Photo-induced e^- can easily recombine with h^+ when there are no electron or hole scavengers present.[48] Scavengers play an important role in reducing rate of recombination of charge carriers and improving efficiency of photocatalytic. Fig 2. depicts schematic illustration of generation of reactive oxygen species on surface of photocatalytic semiconductor.[49]

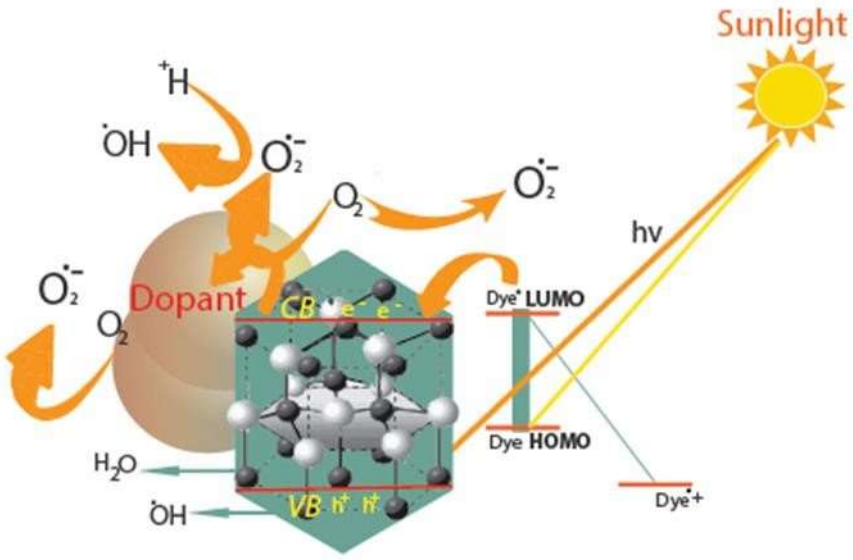


Fig 2. Schematic illustration of generation of Reactive Oxygen Species on surface of photocatalytic semiconductor[49]

Table 2. Various photocatalysts studied for the degradation of dyes.

Dye	**Photocatalyst**	**Experimental conditions**	**Degradation Percentage/Remarks**	**Reaction Kinetics**	**References**
MB	Ferrite Bismuth nanoparticles	Direct solar irradiation; $[MB]_0$ = 15 79mg/L; acidic medium; photocatalyst (0.5 g/L)	95% of MB was degraded after 80 min	Pseudo-first-order	[50]
RB5	TiO_2	Low-pressure Hg UV-C lamp (15 W, 254 nm); $[TiO_2]_0$ = 0.5 g/L; $[RB5]_0$ = 25–125 mg/L; pH 6.4–6.9	82% TOC and 76% COD removal were achieved after 210 min	Pseudo-first-order	[51]
Procion Blue HERD (PBH)	TiO_2 and ZnO	UV lamp (30W); $[PBH]_0$ = 10–100 ppm; photocatalyst loading = 0.5–2 g/L; pH 2–10	100% decolorization of dye with ZnO at pH 7 and with TiO2 at pH 4.	First-order	[52]
Methyl orange (MO)	Ag-doped titania-silica	Medium-pressure Hg lamp (150W, 350–400 nm); $[MO]_0$ = 100 µM; pH 7.3; T = ~20 _C; 0.15 g catalyst	After 30 min, photolysis (45.7%) degraded more than photocatalysis.	Pseudo-first-order	[53]

Orange F3R	C-N-codoped TiO_2	UV (10 W, 365 nm), visible (13 W), solar irradiation; $[dye]_0$ = 30 mg/L; dosage of C-N-codoped TiO_2 is 3–15 mg	39.05% degraded under UV light after 180 min	N/A	[54]
MG	TiO_2	UV lamp (15 W, 365 nm); $[MG]_0$ = 40 mg/L; 20 mg of TiO_2	99.9% MG degraded after 1 h.	N/A	[55]
Remazol Brilliant Blue (RBB)	ZnO	High-pressure Hg lamp (125W, 365 nm), [ZnO] = 1.5 g/L, $[RBB]_0$ = 100 mg/L	100% degradation of RBB	Pseudo-first-order	75
MB	ZnO/PDMS	Three different types of light sources such as halogen (100 W), metal-halide (150 W), and UV (4 W) light sources.	The highest degradation of MB achieved was 93% under UV/Vis irradiation after 3 h.	N/A	[56]
Rhodamine B (RhB)	TiO_2	Low-pressure UV lamp (15 W, 254 nm), 120 mg TiO_2, pH 4.5, $[RhB]_0$ = 5 mg/L	Color removal achieved 29% after 60 min and TOC, 25%	Pseudo-first-order	[57]
RO16—anionic monoazo dye	UV-C/TiO_2 and UV-C/H_2O_2/TiO_2	UV-C germicidal tubes (8 W), pH 6.5	UV-C/H_2O_2 is the most effective process compared to UV/TiO_2 or UV-C/H_2O_2/TiO_2	Pseudo-first-order	[58]
MO, RhB, MB	Ag-doped titania-silica	Medium-pressure mercury lamp (150W, 350–400 nm), Catalyst was prepared by sol-gel, catalyst loading is 0.15 g, T = 20 ºC	The degradation rate of MO by photolysis was higher than photocatalysis The degradation of (RhB) by photocatalysis was higher than photolysis, after 30 min	Pseudo-first-order	[53]
Violet-3B	C-N-codoped TiO_2	Visible-halogen lamp (500 W), $[dye]_0$ = 5 mg/L, catalyst dosage is 0.3 g/L, pH 5.6	The degradation of violet-3B with visible light and catalyst after 4 h achieved 96% color removal and, due to mineralization, 44% TOC was removed.	Pseudo-first-order	[59]
Tartrazine	UV-C/TiO_2 and UV-C/H_2O_2/TiO_2	UV lamp (6W, 254 nm),	The most effective degradation of the	Pseudo-first-order	[60]

		[dye]0 = $2x10^{-5}$ to $8x10^{-5}$ M, pH 2.2–11, 0.02–0.18 mg/L catalyst dosage, T = 30 ºC	dye was achieved with the combination of $UV/H_2O_2/TiO_2$		
MG	$ZnO–TiO_2$/clay	UV-A lamp (100W, 365 nm), catalyst dosage = 1 g, $[dye]_0$ = 75 mg/L, pH 5.2	Nearly complete mineralization was achieved after 30 min.	Pseudo-first-order	[61]
MG	TiO_2 dip-coating	UV lamp, solar irradiation,	92.15%, 94.28% and 98.43 % for 5, 10 and 15 g of catalysts respectively	Pseudo-first-order	[62]
AO8, AC29, AB113 (Azo dyes)	VUV/TiO_2	Low-pressure Hg lamp (18 W, 185 nm), TiO2 dosage = 0.5 g/L, $[dye]_0$ = 0.0523 mM, T = 25 ºC, pH 3, 5, 7, 9 and 11	Degradation of the dyes is more efficient under an acidic medium	Pseudo-first-order	[63]
MB	TiO_2, Sn–F/TiO_2 NPs	Sol-gel method, UV, and visible light irradiation	Under UV irradiation, the degradation efficiency of MB was 72% and 91% for TiO_2 and Sn-F/TiO_2 NPs, respectively	Pseudo-first-order	[64]
RB5—anionic dye	TiO_2	UV lamps (40 W, 365 nm), pH (3–11), catalyst load (0.5–3.0 g/L), and $[RB5]_0$ = 20–100 mg/L	Maximum degradation rate of 26.5 mg/g of dye after 30 min was at pH 3 and a catalyst load of 1.5 g/L	Pseudo-first-order	[65]
MB—cationic dye	TiO_2, TiO_2 ENR	Fluorescent lamp,	Alkaline medium was favourable	Pseudo-first-order	[66]
MB	TiO_2	UV-A, UV-B, UV-C and solar light, $[MB]_0$ = 2–10 ppm, pH (4–10), t = 1 h.	Complete degradation of MB was achieved within 14 min with UV-C irradiation, 18 min with UV-B irradiation, and 20 min with UV-A irradiation	First-order	[67]
RB5—azo dye	ZnO, TiO_2	Catalyst load = 0.5–1.5 g/L, $[RB5]_0$ = 25–150 mg/L), pH = 3.0–11.0	The color removal efficiencies of RB5 were 99.8% and 58.1% using ZnO and TiO_2 after 60 min.	Pseudo-first-order	[68]

RB5	ZnO, TiO_2	UV lamp (20 W, 365 nm), Catalyst load = 1.25 g/L, $[RB5]_0$ = 10–100 mg/L), pH = 3.0–11.0	Complete decolorization with ZnO and 75% decolorization with TiO_2 after 7 min	Pseudo-first-order	[69]
Reactive orange 4 (RO4)	TiO_2, ZnO	UV lamp (20 W, 365 nm), Catalyst load = 1.0 g/L, $[RO4]_0$ = 10–100 mg/L), pH = 3.0–11.0	92% decolourization with ZnO and 62% decolorization with TiO_2 after 7 min	Pseudo-first-order	[69]
MB-cationic	Ta-doped ZnO	Xe arc lamp (300 W), $[MB]_0$ = 10 mg/L, 50 mg, pH 8	1 mol% Ta-doped ZnO annealed at 700 ºC exhibits the highest degradation rate.	Pseudo-first-order	[70]
AO7	TiO_2	High-pressure mercury lamp (400 W)	Complete removal of 0.086 mM AO7 after 20 min at pH 6.8	First-order	[71]
Reactive red	TiO_2	High-pressure mercury lamp (400 W)	Complete removal of 0.086 mM of RR2 after 20 min at pH 6.8	First-order	[71]
Procion yellow H-EXL	N-doped TiO_2	UV lamp (100 W)	Optimum conditions were found to be at pH 5 with a TiO_2 dosage of 1 g/L.	N/A	[72]
Tartrazine—anionic azo dye	TiO_2	Solar UV, UV lamp (24 W, 365 nm), t = 300 min, flow rate of solution = 60 mL/s, $[dye]_0$ = 10 mg/L, TiO_2 dosage = 0.3 mg/cm^2, pH 8.2–8.5	The removal efficiency was 97% for the solar reactor and 30% for the lamp reactor.	N/A	[54]
CV, Methyl red (MR), Basic blue (BB)	ZnO, TiO_2, SnO	Solar irradiation, $[dye]_0$ = 10 mg/L, pH 9	COD removal: 92% for CV, 95% for BB, and 89% for MR after 5 h irradiation with the presence of ZnO.	N/A	[73]
MG	ZnS, Mn-doped ZnS	Medium-pressure lamp (125 W), pH 2–5, t = 90 min, $[MG]_0$ = 25 g/L	Degradation efficiency increased from 60 to 72% as the pH increased from 2 to 4	Pseudo-secondorder	[74]

Factors affecting the degradation of dyes

Operating parameters, including pH, catalyst dosage, adsorption of dyes, initial concentration, and light wavelength, temperature, influence photocatalytic degradation of organic contaminants.[75] The parameters that affect photocatalytic breakdown of organic pollutants will be discussed sequentially.

1. Effect of initial concentration

The initial dye concentration in a photocatalysis is another important component to consider.[76] Research suggests that when dye concentration increases, percentage degradation decreases while maintaining a constant catalyst concentration.[77] As the concentration of the dye increases, more organic molecules are adsorbed on the catalyst surface, resulting in less photons reaching the catalyst surface and less •OH formation, thus inhibiting the degradation.[78]

2. Effect of pH

The pH of dyes has a considerable impact on photodegradation effectiveness. Changing the pH of a solution influences the surface charge of catalyst particles and the probability of catalytic reactions.[79] The adsorption of dye on the surface changes, altering the reaction rate. The reactions listed below can be used to protonate or deprotonate the catalyst's surface under acidic or alkaline circumstances:

$$\text{Photocatalyst} + H^+ \rightarrow \text{Photocatalyst } H^+$$

$$\text{Photocatalyst} + OH^- \rightarrow \text{Photocatalyst} + H_2O$$

Surface of photocatalyst maintain a positive charge in acidic and negative charge in alkaline environments.[52] If a catalyst has a stronger oxidising activity at lower pH, however too much H+ can slow down the reaction. Acid Yellow17, an anionic dye, degrades most quickly at pH 3, while Orange II and Amido Black 10B deteriorate the most at pH 9.[44, 57]

3. Effect of catalyst dose

The amount of photocatalyst used also influences dye degradation.

Increased catalyst concentration leads to dye degradation, indicating heterogeneous photocatalysis.[80] Increasing the amount of catalyst on the photocatalyst surface leads to more active sites and more •OH radicals, which can contribute to dye discolouration.[81] When the catalyst level exceeds a particular threshold, the solution becomes turbid, preventing UV rays from reaching the process. As a result, percentage degradation decreases.[82]

4. Adsorption of dyes

The adsorption of dyes on photocatalyst surfaces has a major impact on dye degradation performance. Dye molecules adsorb on catalyst surfaces through electrostatic interactions and binding affinities. Adsorption of dyes on catalyst surfaces is crucial for photodegradation of dyes. Dye adsorption, whether strong or weak, leads to decreased photocatalytic efficacy in catalysts. Strong adsorption poisons catalysts, whereas weak adsorption attaches dyes to catalyst surfaces for photodegradation reactions.[83] High dye adsorption on catalyst surfaces prevents photons from reaching the surface. Strong adsorption leads to decreased photocatalytic activity. The Sabatier principle suggests that for optimal photocatalytic activity, dye molecules should not attach strongly or weakly to catalyst surfaces. The moderate is helpful due to the synergy between photocatalysis and adsorption for enhanced photodegradation performance.[84]

5. Intensity of light

Light energy plays an important role in the photocatalytic degradation of dyes.

Irradiation causes photocatalysts to produce positive holes and electrons in their valence and conduction bands.[85] Positive holes and electrons can only arise when radiation energy exceeds or equals the photocatalyst's band gap.[86]

6. Effect of temperature

Experiments have been conducted to investigate how temperature affects the rate of organic compound breakdown. Several studies have examined the impact of photocatalytic activity on temperature.[87] As temperature rises, charge carriers recombine and adsorbed reactants desorb, leading to decreased photocatalytic activity.[88] According to the Arrhenius equation, the apparent first order rate constant (K_{app}) increases linearly with $\exp(-1/T)$.

Intermediate species

Photocatalytic degradation of organic contaminants should result in the release of water, carbon dioxide, and tiny inorganic compounds. Photocatalytic degradation of organic dyes can result in the creation of several tiny intermediates due to their complicated structures.[89] Typically, the generation of intermediaries in photocatalytic treatment is not monitored.

The intermediates generated may be more toxic than the original dyes. Catechol can be produced as a byproduct during photocatalytic phenol degradation. Catechol is more harmful to animals than phenol. To further understand the nature and fate of intermediates produced during photocatalytic treatment, further research is necessary.[5]

Electron–hole recombination

Photocatalytic degradation of organic contaminants is affected by electron and positive hole production and recombination, as previously discussed. Photoluminescence analysis is often used to evaluate electron and positive hole recombination rates.[90] The photocatalyst emits light inversely proportional to the rate of electron and positive hole recombination. The photocatalyst emits radiations by transferring electrons from the conduction band to the valence band. If the photocatalyst contains components such as quantum dots or graphene oxide, the intensity of emitted radiation may not accurately reflect electron and positive hole recombination rates. Similarly, radical scavenging and open-circuit potentiometry are employed to assess electron and positive hole recombination rates. None of these methods produce unambiguous and accurate information. To accurately anticipate the rate of electron and positive hole recombination, new methodologies must be developed.[91]

Conclusions

It is concluded that as the textile business rises, so does the demand for diverse dyes. Only a small percentage of the produced wastewater is appropriately managed. The leftover trash is frequently collected or thrown directly into the sewer system, where it eventually finds up in rivers, lakes, or streams. Concentrated wastewater management and disposal, particularly dye-containing wastewater, create significant environmental challenges from generation to disposal. Conventional water treatment technologies such as filtration, flotation, and adsorption are physical separation processes that do not cause damage. Photocatalysis has proven to be a promising and effective method of dye degradation in wastewater treatment facilities. Under certain activation conditions, the process involves the generation and interaction of highly reactive hydroxyl radicals. These radicals effectively degrade and mineralize organic pollutants that are resistant to other treatments.

Conflicts of Interest

The authors declare no conflict of interests.

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