



Hybrid adsorption–photocatalysis composites: a sustainable route for efficient water purification

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Abstract

The convergence of adsorption and photocatalysis in hybrid composites offers a sustainable and energy-efficient strategy for the removal of persistent organic pollutants from water systems. This review presents a comprehensive analysis of recent advances in adsorption–photocatalysis hybrid materials, focusing on the synergistic mechanisms that enhance pollutant capture, photodegradation, and material regeneration. We classify and evaluate three major categories of composites: carbon-based, metal oxide, and polymeric materials, highlighting their physicochemical characteristics, surface morphologies, and functional architectures. Special attention is given to Z-scheme and type II heterojunctions, plasmonic enhancements, and nanoscale engineering that improve solar light harvesting and charge carrier dynamics. The influence of key environmental parameters such as pH, light intensity, and contaminant load is discussed, along with strategies for material optimization and recyclability. Unlike conventional reviews, this work offers a design-focused and environmentally integrated perspective, emphasizing scalable, low-waste, and sunlight-driven solutions for water purification. The insights provided here aim to guide future research on hybrid systems that contribute to the circular economy and renewable energy-based remediation technologies.

Keywords Adsorption · Photocatalysis · Synergetic effect · Organic pollutants

Abbreviations

CR	Congo red
EY	Eosin yellow
MB	Methylene blue
RB19	Reactive blue
MO	Methyl orange
PQ	Pesticide paraquat
h ⁺	Holes
e [−]	Electrons
ROS	Reactive oxygen species
•O ₂ [−]	Superoxide anion
•OOH	Hydroperoxide particles

•OH	Hydroxyl radicals
CB	Conduction band
VB	Valence band
NHE	Normal hydrogen electrode
E _g	Bandgap
SPR	Surface plasmon resonance
AC	Activated carbon
CNTs	Carbon Nanotubes
GO	Graphene Oxide
ACFs	Activated carbon fibers
CPs	Carbon polymers
UV	Ultraviolet radiation
RhB	Rhodamine B
CBZ	Carbamazepine
SUL	Sulfasalazine
MG	Malachite green
NPX	Naproxen
TC	Tetracycline
SMX	Sulfamethoxazole
RR2	Reactive red
LED	Light-emitting diode
LDH	Layered double hydroxide

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SSA	Specific surface area
q_m	Adsorption capacity
NAC	Nitrogen-doped activated carbon
PVP	Polyvinylpyrrolidone
CA	Cellulose acetate
PG	Geopolymers
DFB	Direct acid-resistant bordeaux
CTC	Hydrochloride
PFOS	Perfluorooctane sulphonate

Introduction

Water is the basis of life and is an irreplaceable resource that ensures human life and ecosystem stability. Its importance extends far beyond everyday consumption, and encompasses agriculture, industry, energy, and public health. Humanity faces an unprecedented water crisis [1, 2]. Forecasts indicate that the demand for water will far exceed the available supply by 2050, particularly in developing countries with growing populations and industries [3]. The pollution of aquatic ecosystems is one of the most alarming aspects of a crisis [4]. Chemicals such as pesticides, heavy metals, and organic dyes enter their way into rivers, lakes, and groundwater and threaten human health and ecological systems [5, 6]. Moreover, many of these substances are difficult to degrade in nature, which increases their long-term effects. As a result, water pollution is no longer a local problem but a global one [7, 8].

Organic pollutants are one of the key categories of pollutants, which are widely used in the textile, pharmaceutical, food, and other industries [5]. It is estimated that more than 50 thousand tonnes of these substances enter water bodies annually, with approximately 80% of them being discharged without treatment [9]. These compounds not only change the appearance of aquatic ecosystems but also interfere with photosynthesis, reducing the level of oxygen in water. Some dyes exhibit carcinogenic and mutagenic properties, posing serious risks to human health and biological systems [10]. Several methods have been developed to control water pollution using physical, chemical, and biological technologies [11]. Techniques such as, electrochemical oxidation [12], biofiltration [13], membrane filtration [14] and coagulation [15], are highly efficient in removing large particles and solids. However, their application is limited by their high operating costs and the need for secondary waste disposal [16, 17]. Chemical processes such as chlorination and ozonation also have limitations owing to the formation of byproducts, several of which are toxic [18]. Among the alternative technologies, adsorption and photocatalytic degradation are prominent. These methods have attracted attention owing to

their environmental friendliness, reproducibility, and ability to remove persistent organic pollutants [8].

Adsorption is widely used owing to its simplicity, low cost, and high efficiency [19]. Materials such as activated carbon [20], zeolites [21], PVA/CZnO₂ [22], chitosan [23], AC-Al [24], lignocellulosic compounds [25], PU/AC/CNW nanocomposite films [26], and SnS-C microplates [27] have shown impressive results in water treatment applications. Nevertheless, the main limitations of adsorption are related to the need for adsorbent regeneration, recycling of secondary waste, and a decrease in its efficiency after repeated use [13, 28]. In contrast to adsorption, photocatalytic degradation involves the decomposition of organic pollutants without generating secondary waste due to exposure to sunlight. Various photocatalysts have been actively investigated as promising tools for utilising solar energy in water purification [29]. Some of the most studied photocatalytic materials include ZnO [30], CdS [31], WO [32], g-C₃N₄ [33], and various TiO₂-based doped and modified semiconductors [34].

The combination of adsorption and photocatalysis, where the processes mutually reinforce each other, is an effective approach for the removal of organic pollutants. In the adsorption step, wastewater pollutants are effectively captured by the adsorbent, which prevents their accumulation on the surface of the photocatalyst and thus provides more stable conditions for subsequent photocatalytic processes. Subsequently, when exposed to light at ambient temperature, photocatalysis results in the complete mineralisation of these pollutants, converting them into harmless products, such as water and carbon dioxide. This not only restores the catalyst surface for the next adsorption cycle but also ensures its long-term efficiency and cost-effectiveness in purification processes [35, 36].

Recent advances in the synergistic effect of adsorption and photocatalysis are evidenced by an increasing number of reports published between 2006 and 2025. Of these, 263 were research articles and 12 were review articles. In addition, 140 publications were chemical research papers. These publications reflect progress in the development of technologies for the combined use of adsorption and photocatalysis, which show high efficiency in water treatment processes [37]. This review aims to analyse the current research and advances in the field of adsorption-photocatalytic composites, focusing on the mechanisms of adsorption and decomposition of pollutants that demonstrate high efficiency in removing pollutants from water. The main mechanisms of adsorption and photocatalysis, as well as key physicochemical characteristics such as structure, porosity, and surface area, are discussed. Factors such as temperature, pH, and contaminant composition directly determine the efficiency of these processes.

Principle of adsorption

Adsorption is a key process in purifying water from organic pollutants. This is based on the adhesion of adsorbate molecules to the surface of the adsorbent. The study of adsorption mechanisms is a priority because it provides an understanding of interactions at the molecular level. This enables the design of effective adsorbents for specific purposes [38]. Based on the nature of the interactions, the adsorption mechanisms are categorised into physical and chemical adsorption. In physical adsorption (physisorption), interactions between the adsorbate and the adsorbent occur because of weak intermolecular bonds. Therefore, the process is reversible, accompanied by low heat release (<20 kJ/mol) and is most efficient at low temperatures [39]. An example of such interactions is the adsorption of inert gases such as argon or methane onto zeolites, where the process proceeds without the formation of new chemical bonds [40]. In contrast to physical adsorption, chemical adsorption (chemisorption) is a process in which adsorbate molecules interact with active centres on the adsorbent surface to form strong chemical bonds, and is accompanied by significant heat generation (20–400 kJ/mol). This process is usually irreversible and requires significant desorption energy [41]. An example of chemical adsorption is the adsorption of CO_2 onto activated carbon functionalized with metal oxides. In this process, carbonate complexes or chemical bonds with oxygen are formed on the surface of the coal, which greatly enhances the adsorption efficiency compared with physical adsorption [42].

Basic mechanisms of adsorption of organic substances

Depending on the nature of the contaminant and characteristics of the sorbent, one or more interaction mechanisms are usually involved in the adsorption process [43]. The main mechanisms (Fig. 1) that determine the interaction of contaminants with the adsorbent surface include hydrophobic interactions, electrostatic forces, pore filling, deposition on the surface, hydrogen bonding and π - π interactions [44].

Hydrophobic interaction

Hydrophobic interactions are caused by the system's desire to minimise its free energy. When non-polar molecules are trapped in water, they disrupt the hydrogen bond structure, increasing the free energy of the system. In response, water pushes non-polar molecules out, resulting in their adsorption onto hydrophobic surfaces [45]. A key indicator of the hydrophobicity of a substance is the octanol-water distribution coefficient ($\log D_{ow}$). Adsorption processes depend

linearly on this coefficient, as confirmed by recent studies on bisphenol adsorption onto high-density polyethylene microplastics [46]. Furthermore, in a study conducted by the authors [47], using aerogels with different surface properties, it was shown that hydrophilic $\text{SiO}_2(\text{AG})$ aerogels had high efficiency for adsorption of soluble organic compounds such as phenol and methylene blue, with removal percentages of 84.6 and 78.0%, respectively.

Electrostatic interactions

Electrostatic interactions play a key role in the adsorption of charged or polar organic molecules by creating bonds between the contaminants and adsorbents. Based on Coulomb's law, these forces arise from the attraction between oppositely charged particles and functional groups on the adsorbent surface. The intensity of these interactions can be high, making the adsorption process particularly efficient. The efficiency of electrostatic interactions is influenced not only by the nature of the charge, but also by the chemical characteristics of the solution, such as ionic strength and pH. The pH is an important factor, as it regulates the ionisation of both contaminants and functional groups of the adsorbent. For example, COOH , $-\text{OH}$, and $-\text{NH}_2$ groups can be protonated or deprotonated depending on the pH level, changing the charge and hence the electrostatic attraction. By optimising the pH of the medium, the adsorption capacity can be maximised by increasing the attraction between charged particles [48].

A typical example of electrostatic adsorption is the removal of organic pollutants using carbon nanotubes [49, 50]. These nanomaterials have unique properties that allow effective binding of cationic and anionic pollutants through a combination of electrostatic interactions and van der Waals forces.

Pore filling and surface deposition

Pore filling and surface deposition are important adsorption mechanisms that are actively used to remove organic pollutants effectively. The former is a physical process, whereas the latter involves chemical interactions. Pore filling is a physical process in which contaminant molecules penetrate the micropores (<2 nm) and mesopores (2–50 nm) of an adsorbent. This mechanism is based on adhesion forces and capillary effects, which reliably hold molecules inside pores [51]. The success of this process depends largely on matching the size of the pollutant molecules with the pore structure of the material. For example, activated carbon from plant residues has micro- and mesoporous structures that favour the entrapment of organic pollutant molecules in the pores [52]. Increasing the specific surface area and

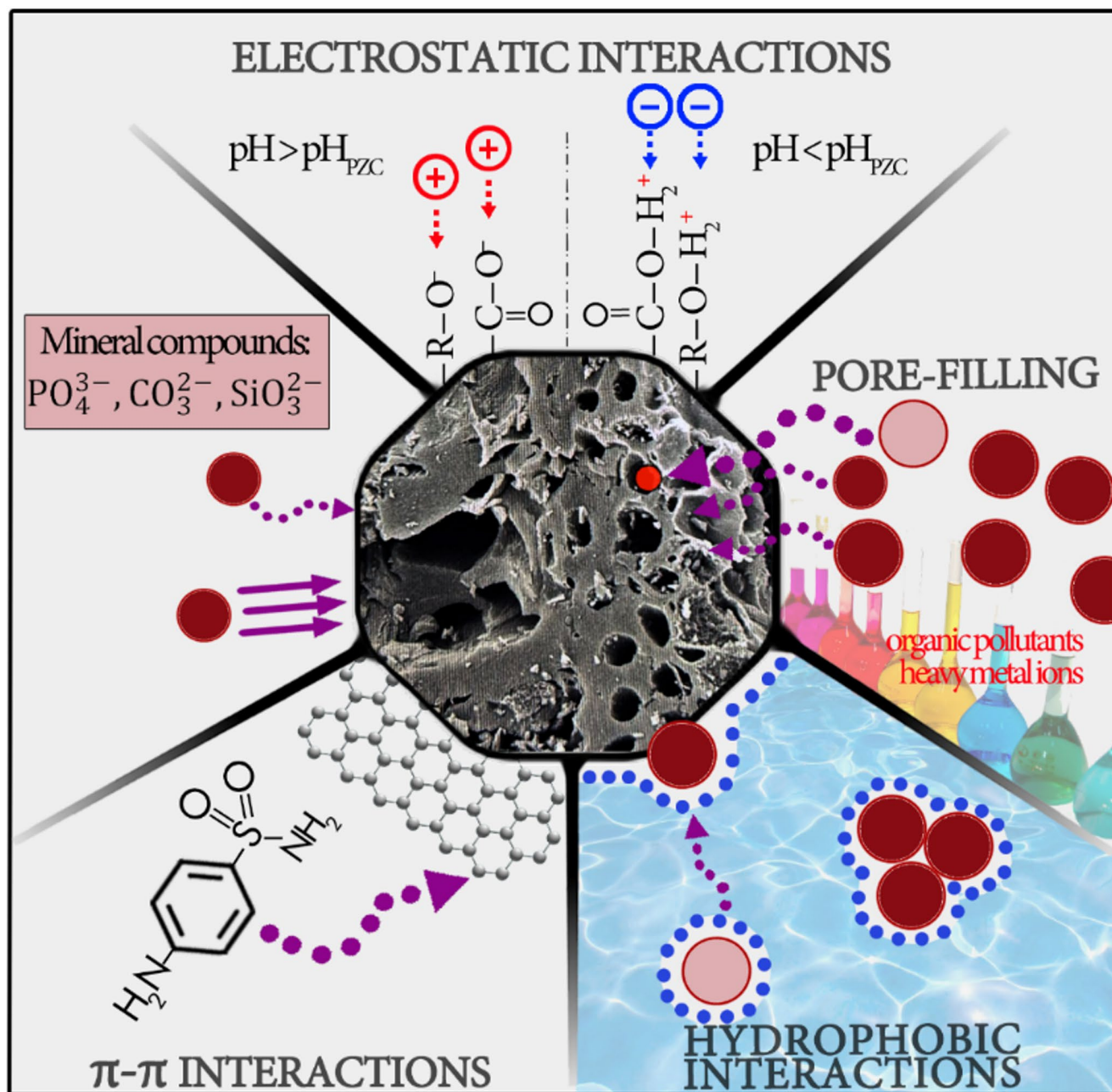


Fig. 1 Main mechanisms of organic substances

pore volume increases the efficiency of this approach. However, this mechanism has limitations; large molecules or their agglomerates can block the entrance to the pores, thereby reducing the accessibility of the inner surface of the material.

In contrast, surface deposition is a chemical process in which contaminants interact with the active centres of the adsorbent to form insoluble compounds. This mechanism is often triggered by changes in solution pH or the presence of functional groups on the adsorbent surface. An example is the deposition of heavy metals such as Cd²⁺ on the surface

of biochar, where they form carbonate precipitates (CdCO₃) due to interaction with carbonates released by the biochar [49]. This mechanism has the advantage of being able to efficiently remove metals and chemical compounds that are difficult to capture by physical adsorption. Density of states (DOS) calculations performed by the authors of [53], who studied the interaction of heavy metals such as Ag, Cd, Pd, Hg, Zn, with the surface of graphite (111), showed that the interactions occur exclusively due to chemisorption. They found that during adsorption of metals, there is a shift of carbon orbitals, which is particularly pronounced

near the Fermi level. In addition, the authors found that the adsorption of metals in acidic, neutral and alkaline media equally occurs with energy absorption, which once again proves that the interactions are chemical. However, a favorable environment for adsorption is exactly in neutral and weakly acidic media. This is due to the reduced competition of metals with H_3O^+ ions. Although most organic dyes interact with most adsorbents through non-chemical bonds. In a study of [53] using a DFT approach, we show that methylene blue (MB) cation is chemisorbed on Fe(110) and $Fe_3C(001)$ surfaces with high exothermic adsorption energies (-648 and -494 kJ/mol, respectively), causing significant structural distortion of the molecule. In contrast, weak physical adsorption is observed on graphene and hydroxylated Fe_3O_4 surface with preservation of planar MB geometry. This emphasizes the key role of active metal surfaces in the chemisorption mechanism, the results of which are in agreement with the experimental data. Depending on the characteristics of the contaminant and the environmental conditions, these two adsorption mechanisms can be used either separately or together [54, 55].

Other non-covalent interactions

Hydrogen bond is a type of non-covalent interaction that occurs between a hydrogen atom bonded to an electronegative atom (such as oxygen or nitrogen) and another electronegative atom. Although this interaction is electrostatic, it is characterised by strict directionality and the need for a precise spatial arrangement of the atoms involved. The chemical structure and functional groups of organic pollutants such as -OH, -NH₂ or -COOH play a crucial role in the ability of these compounds to form hydrogen bonds. For example, the donor and acceptor groups of pollutants form strong hydrogen bonds with the carboxyl sites of microplastics such as polyethylene terephthalate [56]. Similarly, hydroxyl radicals adsorbed on transition metal flakes actively interact with organic pollutants, facilitating their removal from solutions [57]. Recent studies show that adsorption mechanisms based on π - π interactions such as π - π stacking, π -cationic, and π -anionic interactions can be effectively combined with each other, which significantly enhances the sorption capacity of materials [58, 59]. In addition, the synergistic effect between hydrogen bonds and π - π interactions can significantly enhance the efficiency of adsorbents [60, 61]. Hydrogen bonding and π - π interactions are reversible processes that make these interactions suitable for reusable adsorbents [62].

Parameters affecting the adsorption process

The adsorption process is directly dependent on parameters such as the adsorbent dosage, temperature, contact time, and pH of the medium. These factors play an important role not only in achieving high adsorption efficiency but also in ensuring the selectivity of the process, allowing the selective removal of certain pollutants from complex multicomponent systems.

The pH of the medium is a key parameter determining the adsorbent surface charge and the ionisation state of organic pollutants. At different pH levels, the surfaces of the same adsorbent can be charged differently. For example, activated carbon under acidic conditions ($pH < PZC$) has a positively charged surface that favours effective interactions with anionic pollutants, whereas (at $pH > PZC$) the surface becomes negatively charged, which favours cations [63]. The ionisation states of organic pollutants are also pH-dependent. In [64], the adsorption of anionic dyes such as Congo red (CR) and eosin yellow (EY) reached a maximum at pH 3. In contrast, the adsorption of the cationic dye MB increases with increasing pH, reaching a maximum efficiency at pH 7 [65]. This is due to the competition of H^+ ions with cationic pollutants for active adsorption centres, thereby reducing the efficiency of the process [66, 67]. For neutral pollutants, slightly acidic or neutral pH levels (around pH 6–7) are optimal [68].

Temperature has a significant effect on adsorption. Generally, an increase in temperature increases the adsorption capacity of the adsorbent. The adsorption of MB by different adsorbents increases in the temperature range of 25–60 °C [69–71]. This increase may be due to the increase in pore size, number of functional groups on the surface, and the improved solubility of the organic pollutants. However, the effect of the temperature is not always linear. In a study by Zein et al. [72], the maximum adsorption of MB was reached at 75 °C, after which the adsorption efficiency decreased. This was attributed to the destruction of functional groups on the surface or enhancement of the desorption process [73].

The adsorbent dosage is one of the most significant parameters. In most cases, increasing the dosage leads to an increase in the adsorption efficiency by increasing the available surface area and number of active centres [74, 75]. For example, in a previous study [76], increasing the dosage of the ZIF-8/MAA aerogel from 200 to 1000 mg/ml increased the adsorption of MB from 44.8 to 90.9%. Nevertheless, there is an optimal dosage that does not further increase the efficiency. In addition, excessive dosage can cause particle agglomeration, thereby reducing the available surface area and decreasing the overall process efficiency [77, 78].

The contact time between the adsorbent and the adsorbate directly affects the efficiency of the process. In the initial stage, adsorption proceeds rapidly owing to the numerous active sites and the high concentration of pollutants. However, as the active centres become saturated, the process slows. In a previous study [76], the maximum adsorption capacity of ZIF-8/MAA relative to that of MB was reached after 12 h. At this stage, equilibrium is established, and the rates of adsorption and desorption are equalised [26].

Factors such as the adsorbent dosage, temperature, contact time, and pH of the medium can be altered to increase the adsorption activity. However, for each system, optimal conditions exist under which the highest efficiency is achieved.

Table 1 lists the adsorption results of various adsorbents and pollutants. The analysis shows that the adsorption efficiency depends on the environmental conditions as well as on the properties of the adsorbate and adsorbent. Adsorbents exhibit different adsorption capacities depending on the

nature of the organic pollutants. In addition, the same contaminant can interact with different adsorbents via different mechanisms. This underlines the importance of careful selection of the adsorbent, considering the environmental conditions and characteristics of the adsorbate, to achieve optimal results.

Photocatalytic degradation

Principles of the photocatalytic process

Photocatalytic decomposition of pollutants in aquatic environments is becoming increasingly popular owing to its ability to efficiently use sunlight as an affordable, clean, and renewable energy source. In contrast to adsorption methods that only transfer pollutants from the aqueous phase to the solid phase, photocatalytic processes ensure complete destruction. This is achieved through photocatalytic

Table 1 Comparative data on adsorption of pollutants on different adsorbents

No	Adsorbent	Adsorbate	Adsorption capacity, mg/g	Surface area, m ² /g	Adsorption conditions	Adsorption mechanisms	Ref.
1	HCM	Eu(III) ion	176.31	411	pH=5	chemisorption	[79]
2	CS-G/ZnO/Fe ₃ O ₄ NP	(RB19)	363.3	7.375	pH=4, T=60 °C	chemisorption, electrostatic attractors, H-bonding, π -interaction	[80]
3	MPPMC	MB	585	-	pH=7, T=25 °C	electrostatic attractors	[81]
4	Pistachio shell bio-char (PSB-900)	CR	614.7	467.8	pH=6, T=30 °C	chemisorption, electrostatic attractors, H-bonding, π -interaction, complexation, and van der waals forces	[82]
5	Pistachio shell bio-char (PSB-900)	MB	384.2	467.8	pH=1, T=30 °C	chemisorption, electrostatic attractors, H-bonding, π -interaction, complexation, and van der waals forces	[82]
6	MGCN	CR	303	84.37	pH=5	H-bonding	[83]
7	Fe ₃ O ₄ @UiO-66	Methyl orange (MO)	244	348	pH=4 T=25 °C	electrostatic interaction, π - π -stacking interactions, H-bonding and pore filling	[84]
8	NTA- β -CD-CS	MO	132.5	1.02	pH=4	ion exchange and H-bonding	[85]
9	Ti ₃ C ₂ -MoS ₂	pesticide paraquat (PQ)	105.53	22.078	pH=7 T=25 °C	physisorption and chemisorption	[86]
10	CWB	2,4-dichlorophenylacetic acid	276.3	422.4	pH=6	electrostatic interaction, π - π -stacking interactions, H-bonding, pore filling	[87]
11	FeNi-RSN-OH	Pb(II)	242.15	-	pH=5, T=25 °C	electrostatic interaction	[88]
12	AOSA3	Pb(II)	598.05	398.91	pH=5, T=25 °C	chemisorption and pore-filling	[89]
13	RSBC700	Cd ²⁺	62.45	155	pH=5, T=25 °C	complexation and cation- π interactions	[90]
14	MXene (Ti ₃ C ₂ Tx)	Cd ²⁺	475.6	-	pH=10, T=25 °C	electrostatic interaction, ion exchange	[91]
15	BVO	MB	52.065	-	pH=8.24, T=25 °C	electrostatic interaction, surface and pore diffusion	[92]
16	BVO	CR	57.971	-	pH=5, T=25 °C	electrostatic interaction, surface and pore diffusion	[92]

reactions occurring on the surface of the catalyst, which eliminates the formation of secondary contaminants and makes this approach promising for sustainable water purification. The main operating mechanisms of photocatalysts for the photocatalytic degradation of pollutants can be summarised as follows: photon absorption, excitation, and reaction [93]. The photocatalytic process begins with the absorption of light by the material when the photon energy corresponds to the bandgap of the semiconductor (Eq. 1) [94]. This causes the transition of electrons (e^-) from the valence band to the conduction band, forming holes (h^+). Electrons and holes participate in redox reactions, become trapped by material defects, or recombine, thereby losing energy (Eq. 2). Only successful separation and transportation to the surface ensures photocatalytic activity.

The photogenerated holes in the valence band interact with water molecules adsorbed on the surface of the irradiated material (Eq. 3) [95]. This leads to the formation of hydroxyl radicals ($\text{OH}\cdot$), which have high oxidising ability and play a key role in the degradation of organic pollutants. Simultaneously, oxygen molecules in the conduction band capture electrons, leading to the formation of anionic

superoxide radicals (Eq. 4)). In the next step, the superoxide anions undergo a reduction process, which makes oxygen an important participant in alternative ways of producing hydrogen. Electrons from the conduction band interact with dissolved oxygen to form superoxide anions, which in turn interact with the intermediate products of oxidative reactions. The duration of illumination plays a key role in the photocatalytic degradation of organic pollutants; with short exposure, partial destruction is achieved, whereas prolonged illumination promotes complete mineralization (Eqs. 8–9) [96]. The Fig. 2 shows the redox potentials of ROS (E vs. NHE) and their photogeneration in oxidation and reduction processes.

Reactive oxygen species (ROS) formed by complex oxidative and reducing reactions interact with molecules of organic dyes and antibiotics, initiating their decomposition in various ways, making this mechanism universal for cleaning aquatic environments from a wide range of pollutants [97–99]. For example, for MB, the process begins with demethylation, in which the $\text{N}-\text{CH}_3$ bond is destroyed, after which radical particles attack the aromatic ring [97]. In the case of other dyes and organic compounds, similar radicals

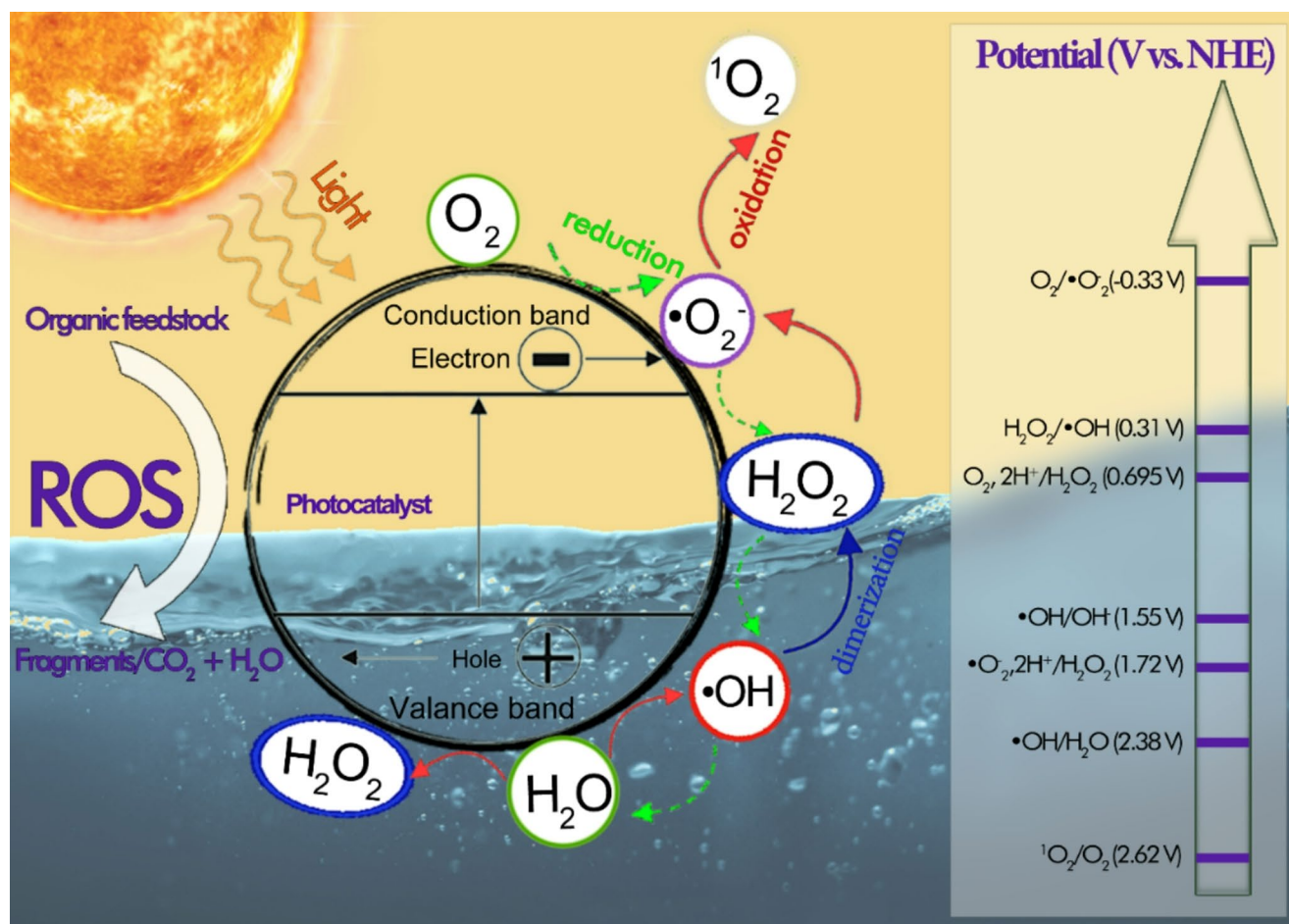


Fig. 2 Schematic illustration of photocatalytic advanced oxidation and reduction processes for water treatment

initiate similar reactions, including the rupture of functional groups and destruction of basic molecular structures [100]. The intermediate products of the reaction usually include fragments of aromatic rings, aldehydes, carboxylic compounds, phenols, and amines, which are sequentially degraded to environmentally friendly compounds such as HO, Co, ammonium, and sulfate ions (Eqs. 8–9) [98]. The photocatalytic degradation of antibiotics includes the oxidation of amino groups, hydroxylation, decarboxylation, deamination, as well as destruction of ring structures such as piperazine or β -lactam rings, depending on the type of antibiotic [101–103]. These processes are initiated by ROS, including $\bullet\text{OH}$ radicals, which play key roles in the destruction of chemical structures [104].

Some studies emphasise the importance of the formation of hydroperoxide particles ($\bullet\text{OOH}$) through the protonation of the superoxide anion ($\bullet\text{O}_2^-$), which promotes the formation of hydrogen peroxide (H_2O_2) in the reaction medium (Eqs. 5–7) [93, 105]. H_2O_2 is involved in the further formation of hydroxyl radicals ($\bullet\text{OH}$), which have a high oxidising ability and play a key role in the mineralisation of pollutants. ROS, such as $\bullet\text{OH}$ and $\bullet\text{O}_2^-$, prevent the recombination of electron hole pairs, acting as effective traps for electrons [106]. This significantly increases the redox potential and ensures a high efficiency of the photocatalytic processes.

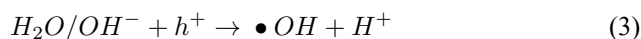
Photoexcitation



Recombination



Oxidation



Reduction



Formation of H_2O_2



Photodegradation



Requirements of the zone structure of photocatalysts for ROS generation

From the perspective of the zone theory of photocatalysis, to generate ROS, the zone structure of the photocatalyst must meet the following requirements:

The energy level of the conduction band (CB) of the photocatalyst should be more negative than the oxygen reduction potential of superoxide anions. The standard redox potential of $\text{O}_2/\text{O}_2\bullet$ is approximately -0.33 V relative to NHE at pH 7 [104]. This implies that the CB of the photocatalyst must be above -0.33 V such that the electrons can efficiently restore oxygen.

The energy level of the valence band (VB) of the photocatalyst should be more positive (lower potential) than the potential for the oxidation of water to hydroxyl radicals. The standard redox potential for $\bullet\text{OH}/\text{OH}^-$ is approximately $+1.55$ V relative to NHE at pH 7. This requires the VB energy level of the photocatalyst to be higher than this potential to ensure the oxidation of water to hydroxyl radicals [94, 107, 108].

The ability of the photocatalyst to absorb the solar spectrum over a wide range of wavelengths generates the maximum charge flow [109]. The width of the photocatalyst bandgap (E_g) significantly determines the light absorption limit. Therefore, photocatalytic materials with high E_g values, despite the presence of suitable potentials at the edges of the zones, are not suitable in their original form for effective absorption of sunlight and require further modification. Compliance with the criteria for the photocatalyst band structure is the basis for efficient ROS generation. However, to further increase the photocatalytic activity, it is necessary to enhance the generation of charge carriers, which can be achieved by optimising light absorption and developing new materials such as doped semiconductors and nanocomposites with plasmonic metals.

Generation and transfer of charge carriers

Improving the generation of charge carriers in semiconductor photocatalysts is a key factor in improving their photocatalytic efficiency. One approach is to expand the light absorption spectrum of wideband semiconductors such as TiO_2 , SrTiO_3 , and ZnO , which enables the conversion of more photons into excited electrons and holes [110]. An effective way to extend the range of light absorption by wideband semiconductors is by doping with metals or non-metals that create energy levels in the bandgap. For example, the alloying of TiO_2 with sulfur using the MOCVD method leads to the replacement of Ti^{4+} with S^{6+} , which narrows the

band gap, improves optical absorption, and forms oxygen vacancies [111]. This, in turn, slows the recombination of charge carriers and enhances the photocatalytic degradation of the MO dye under visible light. Another proven approach to enhance charge generation is the addition of plasmonic metals such as Au or Ag, which are capable of generating surface plasmonic resonances in the visible range. Nanostructured photocatalysts with plasmonic nanoparticles such as Au, Ag, and Co on wideband semiconductors have demonstrated improved efficiency through the use of surface plasmon resonance (SPR) and structural optimisation [112, 113]. For example, Au nanoparticles decorated on the surface of SrTiO_3-x increase the current density and extend the optical absorption range due to SPR to the near-infrared spectrum [114]. Plasmonic nanoparticles also contribute to energy transfer, increasing the lifetime of charge carriers, which in turn increases photocatalytic activity [113, 115]. These approaches are combined to enhance charge-carrier generation and increase the efficiency of solar energy conversion.

The efficient use of solar energy can be significantly improved by optimising the charge carrier transfer in semiconductor photocatalysts, which often suffer from low conductivity [116]. A promising approach is to reduce the size of the photocatalyst to the nanoscale, which reduces the path for charge diffusion to the surface. Nanoscale particles have a large surface area, small migration path, and high density of active sites, which improve the separation of electron-hole pairs. However, the small particles facilitate charge recombination because of the need for an appropriate concentration gradient or internal electric field to ensure carrier transport from the particle volume to the surface [117]. The internal electric field in smaller nanoparticles may not be sufficient for effective carrier separation, leading to increased recombination. To eliminate such limitations, it is necessary to develop photocatalysts that not only take advantage of nanoscale structures but also minimise their disadvantages. One promising solution is to use structures that combine micro- and nanoscale elements. Photocatalyst particles with complex nanoarchitectures such as hollow spheres, nanospheres, nanorods, and mesoporous materials are particularly effective [118–120]. In particular, mesoporous photocatalysts with nanometre channel walls provide accelerated electron migration from the volume to the surface, which contributes to a more efficient decomposition of organic pollutants adsorbed on their surface [121, 122]. This combination of morphological features makes it possible to achieve a high photocatalytic activity while eliminating the limitations associated with charge recombination.

Despite the significant advantages of nanomaterials, the efficient migration of charged particles remains a key task for increasing photocatalytic activity. Increasing the

conductivity of semiconductor materials is a strategy aimed at accelerating charge transfer to reaction sites [123]. Carbon-containing materials are actively used to implement this strategy, demonstrating a significant increase in conductivity, and consequently, photocatalytic efficiency. Unique conjugated structures, such as activated carbon (AC), CNTs, reduced GO, carbon fibres (ACFs), and carbon polymers (CPs), can efficiently transport electrons [124–127]. These materials act as a kind of “reservoirs”, contributing to the removal of photoexcited charges. Owing to their long coupling lengths, the electrons trapped in such structures acquire high mobility, which reduces the likelihood of their recombination. Simultaneously, the effect of the quantum charge limitation is minimised [128]. An example of the application of this concept is the $\text{Sm}_2\text{Ti}_2\text{O}_5\text{S}_2/\text{CNTs}/\text{BiVO}_4$ composite, in which $\text{Sm}_2\text{Ti}_2\text{O}_5\text{S}_2/\text{BiVO}_4$ acts as a photocatalytically active component and CNTs improve the conductivity and mobility of charges, effectively reducing the likelihood of their recombination [129].

Compared with the rapid generation and transfer of charge carriers, which occur in femtoseconds and picoseconds, surface reduction and oxidation reactions have longer timescales, ranging from hundreds of picoseconds to microseconds. This creates an energy barrier, which is the defining stage of the photocatalytic process. Slow surface reactions are a major problem in most semiconductor photocatalysts. Therefore, it is necessary to accelerate these reactions to increase the solar energy efficiency. The integration of co-catalysts helps separate charge carriers and reduce the activation energy, ensuring efficient reactions. In particular, the dual $\text{Rh}/\text{Cr}_2\text{O}_3$ and CoOOH -based cocatalysts applied by selective photodeposition to the surface of SrTiO_3/Al effectively improved the kinetics of the surface reactions and photocatalytic efficiency with respect to dye degradation by a factor of 4.5, compared with SrTiO_3/Al . The reduction ($\text{Rh}/\text{Cr}_2\text{O}_3$) and oxidative CoOOH co-catalysts deposited on various faces effectively suppress the recombination of photogenerated electrons and holes owing to the increased separation and transport of charge carriers. Similar studies using dual cocatalysts report the effective generation of both types of ROS ($\cdot\text{O}_2^-$ and $\cdot\text{OH}$) on the photocatalyst surface [130–132].

Factor influence photocatalytic degradation

For the effective degradation of organic pollutants in aquatic environments, several controlled parameters should be considered during the experiment, such as light intensity, pH of the solution, dosage, and initial concentration of the pollutant in the solution.

The intensity of irradiation directly affects the rate of photocatalytic decomposition [133]. An increase in light

intensity increases the probability of photocatalyst excitation, which promotes the separation of electron-hole pairs and reduces their recombination, which is a key problem in photocatalysis. At low light intensities, the degradation of organic molecules slows because of the lack of free radicals [134]. Studies have shown that at low intensity, the reaction rate is linear, at medium intensity, it depends on the square root of the intensity, and at high intensity, saturation is achieved [133]. Thus, an increase in light intensity enhances the photocatalytic activity.

The pH value of the solution plays a key role in the photocatalytic degradation of organic pollutants [135]. It affects the charge of the photocatalyst surface, structure of pollutants, and decomposition of oxidising agents such as persulfates, ozone, and hydrogen peroxide. These effects are directly related to the adsorption of molecules on the surface of the photocatalyst, which is regulated by the surface charge depending on the zero-charge point (pHPZC). For example, SrTiO₃ at pHPZC = 8.4 is neutral, which minimises adsorption [136]. In an acidic environment (pH < pHPZC), the surface becomes positively charged, promoting the adsorption of anionic molecules, whereas in alkaline environments (pH > pHPZC), the negative charge increases the adsorption of cationic compounds. In addition, studies have emphasised that the optimal pH of the reaction mixture varies depending on the nature of the contaminant. In particular, for SrTiO₃ at pH 9–11 (in an alkaline medium), the surface is negatively charged and the degradation rate of the cationic dye MB is higher [137], whereas for the anionic dye Rhodamine B (RhB), a high degradation rate is observed in an acidic medium at pH 1–4 [138]. These results can be explained by the fact that at low pH, there is a lack of hydroxyl radicals (•OH) and improved adsorption of anionic molecules. In contrast, alkaline conditions promote the formation of active •OH particles, which significantly increases the efficiency of cationic molecule degradation [139, 140]. These aspects are important when studying industrial wastewater with a wide range of pH values, which requires a detailed analysis and optimisation of each system [141].

Effect of the initial concentration of the pollutant. According to the Beer–Lambert law, an increase in the initial concentration of an organic pollutant reduces the penetration of light into the solution, thereby reducing the adsorption of photons on the surface of the photocatalyst and, accordingly, decreases the rate of photocatalytic degradation [94]. An increase in the initial concentration of the contaminant leads to an increase in the rate of photodegradation up to a certain limit, after which this rate stabilises and finally decreases with a further increase in concentration beyond the optimal value [142]. For example, in a study on MB decomposition using SrTiO₃, the degradation efficiency decreased with an increase in concentration from 5

to 15 mg/l. This is due to the adsorption of dye molecules on the surface, which prevents the reaction with radicals, as well as the “UV screening” effect, which blocks the penetration of light to the photocatalyst [143]. In addition, inhibition of the reactions of radicals generated by adsorbed dye molecules is important for porous photocatalysts and can cause their deactivation [144–146].

The concentration of the photocatalyst is a key parameter that determines its photocatalytic efficiency. It is important to optimise the amount to avoid overdosing, which contributes to the cost-effectiveness of the reaction [94]. Increasing the concentration of the photocatalyst enhances its activity owing to an increase in the number of active sites, which leads to more hydroxyl radicals and other reactive oxygen species required to destroy pollutants. However, if the dosage is too high, the photocatalyst can cause turbidity in the solution, thereby reducing light penetration and limiting degradation efficiency [97]. In particular, in one study [34], the effect of cocatalyst-loaded SrTiO₃@Al photocatalyst loading on MB degradation showed that the removal efficiency increased with increasing dosage from 10 to 20 mg but decreased at 30 mg because of solution turbidity and light scattering. Thus, selecting the optimal photocatalyst concentration is an important step for maximising the photodegradation efficiency of organic pollutants.

Table 2 summarises the results of recent studies on photodegradation of various pollutants using photocatalysts. The data demonstrate that the efficiency and rate of the process are significantly affected by parameters such as the width and position of the bandgap, wavelength and power of the light source, concentration of the pollutant, pH of the medium, and type of pollutant. Photocatalysts with a narrow bandgap generally demonstrate higher activity; however, the positions of the VB and CB, which affect ROS generation, also play a key role. These factors determine the efficiencies of pollutant oxidation and degradation. In addition, the optimal activity of each photocatalyst varies depending on the type of pollutant and pH of the solution. This emphasises the need to tune the reaction conditions to achieve maximum efficiency and further study the structural features of photocatalysts.

Synergistic effect of adsorption and photocatalysis

The combination of adsorption and photocatalysis is considered an effective technology for pollutant removal. The synergy of these methods eliminates their individual drawbacks and combines their advantages, such as high efficiency, cost-effectiveness, versatility, catalyst reusability, and complete mineralisation [151]. During the adsorption stage,

Table 2 Results of recent work on photocatalytic degradation of organic pollutants

No	Photocatalyst	Eg, eV	Light source	Organic Pollutant, (concentration)	pH value	Irradiation time	Efficiency; k_1 , (min^{-1})	Ref.
1	SrTiO ₃ /g-C ₃ N ₄ /Ag	2.87	OSRAM lamp (400 W; $\lambda=400\text{--}700$ nm)	MB, (11.2 mg/L)	-	47 min	99%; 0.057; $R^2>0.98$	[113]
2	Pt/BiVO ₄ /Co ₃ O ₄	~2.31	Xe lamp (300 W; $\lambda>420$ nm)	Carbamazepine (CBZ), (10 mg L ⁻¹)	-	120 min	56%; 0,00698	[130]
3	Ag/BaTiO ₃ /MnOx	3.14	Xe lamp (300 W; 100 mW/cm ²)	Rhodamine B (RhB), (10 mg L ⁻¹)	5.5	120 min	98.1%; 0,03521	[131]
4	g-C ₃ N ₄ /MoS ₂	2.75/1.65	Xe lamp (600 mW/cm ² ; $\lambda>420$ nm)	Sulfasalazine (SUL), (20 mg L ⁻¹)	6	90 min	97%; 0,039	[104]
5	SrTiO ₃	3.05	LED (150 W; solar light)	Malachite green (MG), (5 mg L ⁻¹)	7	60 min	93.8%; 0,0249	[136]
6	Bi ₂ S ₃ /CoS ₂	1.6/0.6	Xe lamp (500 W; $\lambda=400\text{--}800$ nm)	Naproxen (NPX), (10 mg L ⁻¹)	7	90 min	96.46%; 0,2847	[147]
7	SrTiO ₃ /CZTS/Ag	2.86	UV-filtered OSRAM lamp (150 W)	MB, (5 mg L ⁻¹)	7	90 min	99%; 0,0465; $R=0.99$	[137]
8	BiOI/BiOBr	1.67/1.85	Xe lamp (300 W)	Tetracycline (TC), (10 mg L ⁻¹)	8.5	90 min	91.92%; 1,4472	[139]
9	ZnO nanorods	3.2	Visible light (1000 W/m ²)	Phenol, (10 mg L ⁻¹)	5	300 min	84%; 0,00571; $R^2=0.9921$	[140]
10	Rh/Cr ₂ O ₃ /SrTiO ₃ @Al/CoOOH	3.07	Mercury lamp (10 W; $\lambda\leq 400$ nm)	MB, (5 mg L ⁻¹)	7	45 min	100%; 0,141; $R^2=0.9731$	[34]
11	PAN/SrTiO ₃ nanofibers	-	Mercury lamp (10 W)	Sulfamethoxazole (SMX), (5 mg L ⁻¹)	2	40 min	100%; 0,02; $R^2=0.9731$	[126]
12	Aux-Pdy/rGO	1.89	Solar light (773.2 mWh/cm ²)	RhB, (10 mg L ⁻¹)	3	60 min	98.5%; $R^2=0.9958$	[148]
13	SrTiO ₃	3.12	Mercury lamp (10 W; $\lambda\leq 400$ nm)	MB, (10 mg L ⁻¹)	7	60 min	51.7%; 0,0092	[143]
14	BiOCl nanosheets	2.22	Xe lamp (300 W; $\lambda>420$ nm)	RhB, (10 mg L ⁻¹)	3	15 min	99.8%; 0,181	[149]
15	Ni/CdS NWs	1.8	Xe lamp (300 W; $\lambda>420$ nm)	Reactive red (RR2), (20 mg L ⁻¹)	1	30 min	99.8%	[150]

pollutants from wastewater are reliably captured, preventing their accumulation on the catalyst surface and increasing the efficiency of the subsequent photocatalytic degradation. Upon light exposure, the photocatalyst decomposes pollutants into non-toxic products such as H₂O and CO₂, restoring the catalyst for reuse. This combination effectively copes with microorganisms, volatile organic compounds, dyes, and gases. High-quality adsorption is important for enhancing photodegradation, because these processes occur on the catalyst surface or in its vicinity [35]. Photocatalytic degradation is environmentally friendly as it converts organic pollutants into nontoxic products without generating waste. Thus, this technology is a versatile and sustainable solution for water purification and environmental risk reduction [152]. Table 3 shows the advantages and disadvantages of the two water purification methods, adsorption, photocatalysis, and the synergistic interactions between the two methods. Adsorption is characterised by high speed, cost-effectiveness, and efficiency in removing a wide range of pollutants; however, it is limited by capacity and stability and depends on environmental parameters. Photocatalysis ensures the complete decomposition of pollutants and is

environmentally friendly and versatile. However, the efficiency of the process depends on illumination, and there is a risk of catalyst deactivation and scaling difficulties. Figure 3 shows the interaction process of adsorption and photocatalytic decomposition of aqueous pollutants.

Mechanisms associated with photocatalysis and adsorption

Photodegradation can occur on or near the catalyst surface, whereas adsorption is mainly observed on the surface. In turn, adsorption improves the interfacial interactions between the photocatalyst and pollutants. Adsorption is an important prerequisite for efficient initiation of photocatalytic reactions [153]. In addition, compared with adsorption, the photocatalytic reaction rate in the system is relatively low. The combination of adsorption and photocatalysis contributes to more efficient practical applications of photocatalytic technologies [154]. Adsorption is a scalable and cost-effective method for the removal of organic pollutants; however, it is accompanied by the formation of secondary waste after the adsorbent is saturated [155]. Moreover,

Table 3 Comparative analysis of advantages and disadvantages of adsorption, photocatalysis and their interaction

	Advantages	Restrictions
Adsorption	<i>High efficiency:</i> Due to the high specific surface area of the adsorbents, the process effectively removes a wide range of organic pollutants, including difficult-to-decompose organic compounds. <i>Fast process kinetics:</i> Under optimal conditions, adsorption occurs at a high rate, reducing the processing time. <i>Cost-effectiveness:</i> Several adsorbents can be obtained from cheap raw materials, and the adsorption process is easy to operate, which reduces costs. <i>Adaptability:</i> Combines well with other cleaning methods, including photocatalysis.	<i>Limited adsorption capacity:</i> Adsorbents can quickly become saturated, particularly at high pollutant concentrations. <i>Dependence on environmental parameters:</i> Adsorption efficiency is strongly influenced by parameters such as pH and temperature. <i>Limited stability:</i> Several adsorbents have low mechanical strength, which leads to the degradation of the adsorbent structure during regeneration. <i>Waste generation:</i> Improper disposal and regeneration of saturated adsorbents can lead to secondary environmental pollution. <i>Regeneration costs:</i> despite the low cost of starting materials, regular regeneration or replacement of saturated adsorbents can increase operating costs, especially at high pollutant loads.
Photocatalysis	<i>Complete mineralization:</i> Breaks down pollutants into harmless compounds without producing toxic byproducts. <i>Energy efficient:</i> Uses sunlight and visible light (e.g., fluorescent and LED lights) as a cheap energy source. <i>Versatility:</i> Applicable to a wide range of pollutants, including dyes, pesticides, antibiotics and other organics. <i>Environmentally friendly:</i> Operates at normal pressure and temperature, thereby minimizing carbon footprint. <i>Cost-efficient:</i> Reduces water treatment costs due to the simplicity of the process.	<i>Light dependence:</i> Ineffective in low light conditions. <i>Catalyst deactivation:</i> Catalysts may lose activity over time. <i>Scaling issues:</i> Difficult to scale from lab scale to industrial scale. <i>Incomplete decomposition:</i> May form intermediates that require further processing. <i>Resource intensive:</i> Some catalysts are expensive to manufacture and operate. <i>Scaling of systems:</i> there are no mature industrial schemes for process integration, and most data are limited to laboratory tests.
Synergy of adsorption and photocatalysis	<i>Material regeneration:</i> Photocatalysis breaks down adsorbed molecules, restoring the adsorption properties of the material. <i>Stability in repeated cycles:</i> Several materials retain their effectiveness after several cycles of use. <i>Increasing the concentration of the pollutant on the surface of the catalyst:</i> Adsorption collects the pollutant on the surface of the material, enhancing its photocatalytic decomposition.	<i>Risk of secondary pollution:</i> Particles of materials such as nanophotocatalysts may be released into the environment, creating additional environmental risks. <i>Complexity of synthesis:</i> Combined materials such as those based on the Z-scheme require complex synthesis methods for optimal structure and distribution of active components. <i>Scale-up:</i> Despite the high potential, the practical realisation of such hybrid systems in large-scale plants still requires further development, especially in terms of scale-up and integration into real water treatment processes.

problems arise with the recycling and reuse of adsorbents and leaching or desorption of pollutants, which is an environmental issue [156]. In addition, the elimination of pollutants does not imply the complete removal of all impurities from the system. After degradation of the nanocomposites, the adsorption sites become conditionally available for the absorption of additional reactive chemicals. Therefore, continuous adsorption and photocatalysis is essential [157]. In contrast to absorption, photocatalytic degradation allows the conversion of organic pollutants into less toxic intermediates, which are mineralised over time into safe compounds [158].

The role of adsorption in increasing the efficiency of photocatalysts

The combination of the synergistic effects of adsorption and photocatalysis, where both processes mutually enhance each other, represents an effective strategy for the removal of organic pollutants. Adsorption improves photocatalytic performance by increasing light absorption, facilitating catalyst

excitation, and promoting charge separation during the catalytic process. A high adsorption capacity can significantly enhance photocatalytic activity due to improved light harvesting and catalyst activation [159]. For example, $\text{NiFe}_2\text{O}_4/\text{ZnO}$ synthesized via the hydrothermal method demonstrates a high adsorption capacity and excellent photostability. During the adsorption–photocatalysis process, CR molecules are adsorbed onto the $\text{NiFe}_2\text{O}_4/\text{ZnO}$ hybrid material, leading to ZnO sensitization by the dye and an enhanced ability to absorb sunlight. This improved light absorption notably increases the photocatalytic performance [160].

Additionally, adsorption facilitates the dissociation and migration of photogenerated electrons and holes, thereby improving photocatalytic efficiency [161]. Studies have shown that the adsorbed pollutants promote the separation of photogenerated charge carriers by continuously freeing voids in the valence band of the component. A composite material consisting of spongy $\text{g-C}_3\text{N}_4$ and calcined layered double hydroxide (LDH) exhibits high efficiency due to the formation of a type II heterojunction. This heterojunction is formed by matching the energy bands between calcined

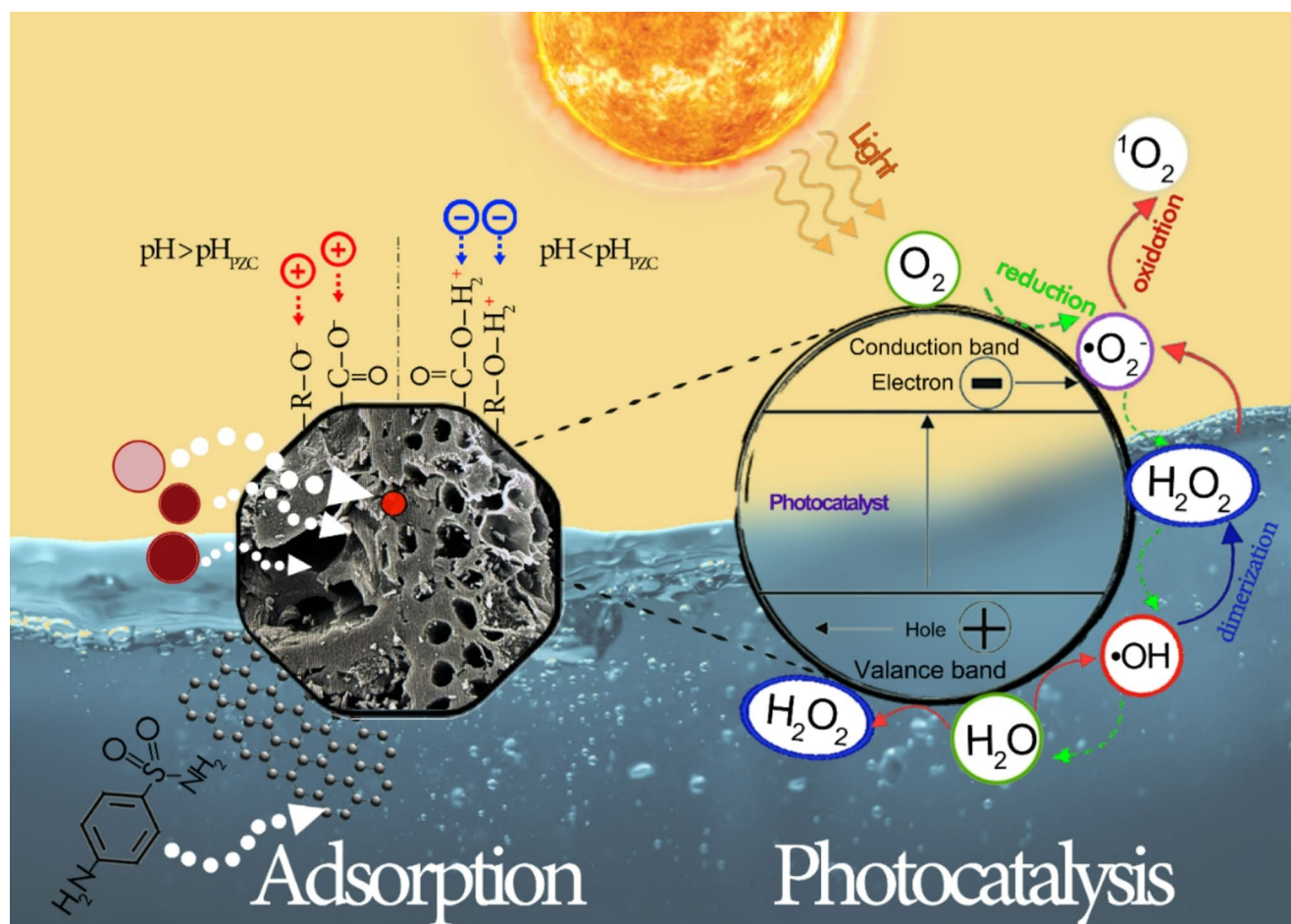


Fig. 3 Schematic illustration of the effective synergy of photocatalysis and adsorption process for the removal of aqueous pollutants

LDH and g-C₃N₄. When irradiated with visible light, the calcined LDH/g-C₃N₄ composite generates photoinduced electrons and holes. Electrons from the CB of calcined LDH move to the conduction band of g-C₃N₄, which has a lower energy potential. Simultaneously, holes from the VB of g-C₃N₄ migrate to the valence band of calcined LDH. Consequently, numerous electrons accumulate in CB g-C₃N₄, and holes in VB of calcined LDH. Importantly, studies have confirmed the high efficiency of calcined LDH for the adsorption of tetracyclines. The photoinduced holes concentrated on the surface of the calcined LDH effectively oxidise TC. Moreover, voids contribute to an increase in the separation of electrons and holes, significantly enhancing the photocatalytic activity and ensuring the effective destruction of tetracyclines [162].

The adsorption capacity can also significantly improve photocatalytic efficiency by enhancing surface reactions. The adsorption of reactants on the surface of the photocatalyst improves the subsequent processes. The contact between the catalyst and pollutants enhances the chemical reaction, increasing the utilisation of radicals, and

preventing a decrease in efficiency near the surface caused by their limited lifespan [163].

Optimization of adsorption through photocatalytic activation

Adsorption is a highly effective method for environmental applications as mentioned earlier. However, the complexity and high cost of the desorption process limit its applications [164]. This problem can be solved using bifunctional catalysts that combine adsorption and photocatalysis. Photocatalytic reactions can effectively degrade pollutants by releasing the occupied sites on the adsorbent surface. Hybrid materials that integrate LDH and TiO₂ for wastewater treatment have been developed. The combination of the photocatalyst and adsorbent allows the use of light to oxidise the adsorbed pollutants, which helps release the adsorption sites. After regeneration through a photocatalytic process, the composite recovered 92% of its adsorption capacity for the target pollutants [165]. Moreover, an Au NP/TiO₂/LDH ternary heterojunction was presented, which showed

improved efficiency for the degradation of pollutants in water through adsorption-photocatalytic regeneration. The introduction of light-responsive plasmonic Au NPs into the system significantly improved the photocatalytic performance [166].

The combination of these processes not only accelerates the removal of organic pollutants but also ensures the continuity of treatment by effectively combining the accumulation and decomposition of pollutants, which contributes to the improvement of system performance. Therefore, the integration of photocatalysis and adsorption is a promising and effective approach for environmental rehabilitation [167].

Modern adsorption-photocatalytic composites

This chapter reviews recent advancements in hybrid materials that combine adsorption and photocatalysis for efficient pollutant removal. The materials are grouped into three categories: carbon-based, metal oxide-based, and polymer-based composites.

Carbon-based composites

Synergistic removal of pollutants using adsorption and photocatalysis on carbon materials is a sustainable and environmentally friendly technology. Carbon materials exhibit different efficiencies for adsorption and photodegradation of organic pollutants because of their unique structures and surface characteristics [151]. They provide high photocatalytic activity, have significant adsorption capacity, and are resistant to chemical attacks, making them ideal components for adsorption-photocatalytic purification systems [168]. For example, 3D g-C₃N₄/agar aerogels demonstrated improved adsorption and photocatalytic degradation of dyes and antibiotics under simulated sunlight, owing to enhanced light absorption and recyclability [169]. Similarly, biochar-supported ZIS/WO₃ composites exhibited efficient charge separation and high removal efficiencies for model dyes. As shown in Fig. 4, the activated biochar (BC) exhibits a well-developed porous structure with numerous defects favouring adsorption. WO₃ is characterised by a dense rectangular shape, whereas ZIS forms flower-shaped microspheres of interwoven nanosheets. In the ZIS/WO₃ sample, the WO₃ nanosheets are uniformly distributed on the surface of ZIS, forming a 3D structure. In the BC/2ZIS/WO₃ composite, the ZIS/WO₃ heterostructure is homogeneously deposited on the biochar, which confirms the successful integration of the components and explains the high efficiency of the combined contaminant removal mechanism [170]. Studies on

GO–CeO₂ nanocomposites also confirmed strong synergistic effects, with multilayer adsorption and nearly complete degradation of pharmaceutical pollutants [171]. Activated carbon derived from biomass sources has shown strong performance in both adsorption and photocatalysis, though often requiring modification with photocatalytically active species [172–174]. Despite their advantages, carbon materials can suffer from low intrinsic photocatalytic activity and reduced efficiency after reuse [171, 173, 174].

Metal oxide composites

This study examined various materials that can effectively remove organic pollutants using adsorption and photocatalytic degradation methods. Metal oxide nanoparticles such as iron, cobalt, copper, zinc, titanium, magnesium, cerium, aluminum oxides, and other composite materials, demonstrate high efficiency in removing and decomposing pollutants, including heavy metals and persistent organic compounds [175].

These materials have wide applications as nanoadsorbents and photocatalysts, particularly for the restoration of pesticide-polluted ecosystems. The unique physicochemical properties of nanoparticles, caused by their nanometre size (1–100 nm), distinguish them from those of traditional bulk materials. Among the key characteristics are a large specific surface area, high number of active sites, porous structure, chemical stability, possibility of reduction, and low toxicity. These properties make nanoparticles a valuable and promising tool for environmental clean-up [176]. ZIF-67/V-BiOIO₃ composites, for instance, effectively removed antibiotics due to the coupling of high adsorption and strong visible-light photocatalysis [177].

ZnO and Ag-ZnO nanoparticles embedded in polymer membranes (polyvinylpyrrolidone (PVP) nanofibre) also demonstrated high removal efficiency for dyes and emulsions [178]. In addition to membrane materials, the use of photocatalytic aerogels with magnetic properties is another promising strategy for wastewater treatment. ZnO/ZnFe₂O₄/carbon cellulose magnetic photocatalyst was synthesised by impregnation and calcination. In the ZnO/ZnFe₂O₄/CCA-400 sample, ZnO/ZnFe₂O₄ particles (1–2 µm) were uniformly distributed on the carbon matrix, providing a specific area of 33.65 m²/g and narrow band gap of 1.66 eV. The composite achieved 98.1% MB removal within 2.5 h of visible light irradiation and maintained an efficiency of 85.5% after five cycles of magnetic reduction, making it a promising candidate for wastewater treatment [179].

Similar to aerogel magnetic photocatalysts, the BVO/Vt composite material synthesised using the hydrothermal method demonstrated high efficiency in wastewater treatment. Its adsorption capacity reached 41.12 mg/g, which

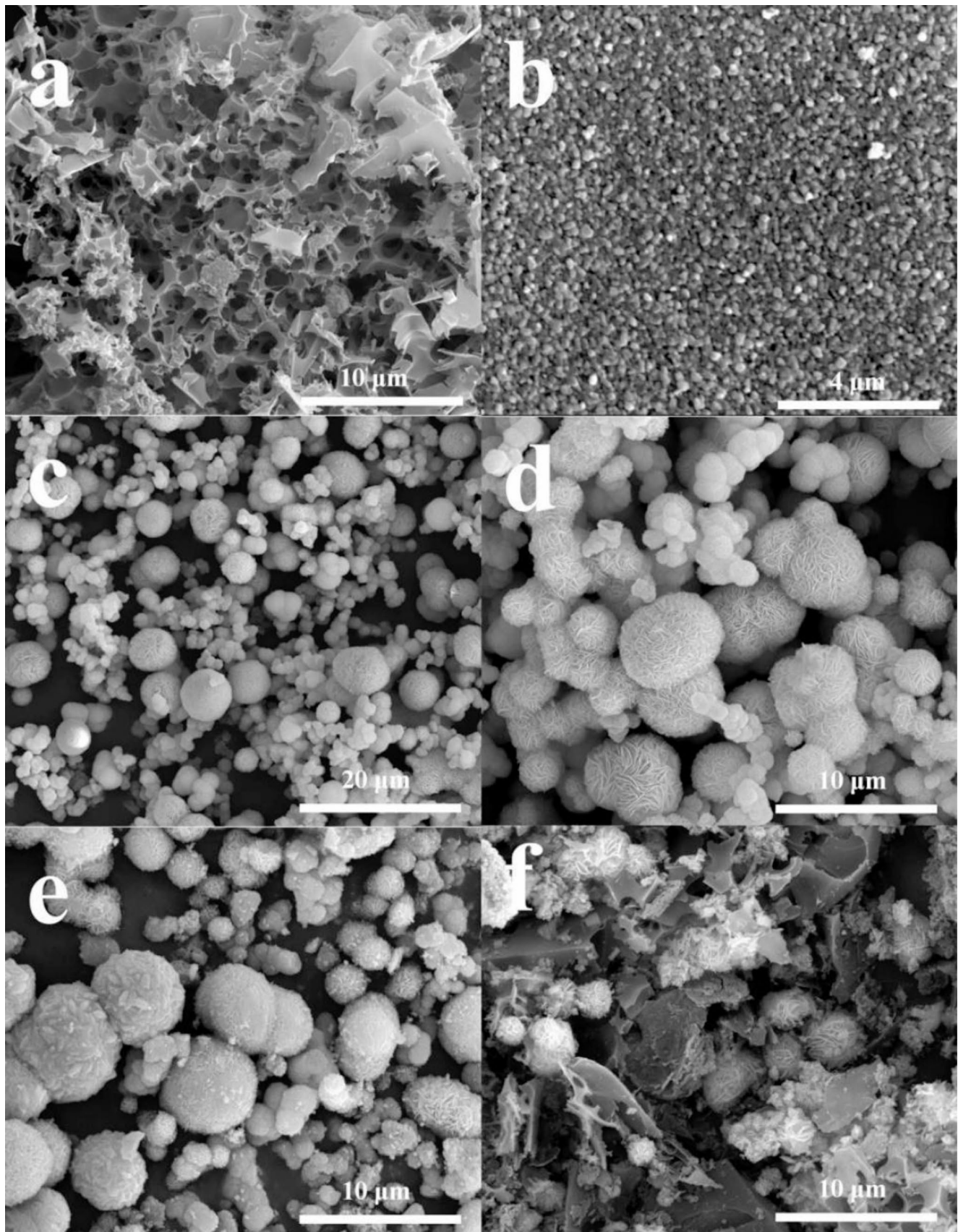


Fig. 4 SEM images of (a) BC, (b) WO_3 , (c, d) $\text{Zn}_3\text{In}_2\text{S}_6$ microspheres, (e) ZIS/WO_3 -6 composite and (f) $\text{BC}/2\text{ZIS}/\text{WO}_3$ composite. Revised/reproduced with permission from Ref [170]

was 1.64 times higher than that of Vt, owing to the chemisorption and multilayer distribution of MB molecules. The maximum photocatalytic rate was 5.77 min^{-1} , which was 6.4 times higher than that of pure BVO. The material retained 76% efficiency after five cycles and successfully operated at MB concentrations of up to 300 mg/L owing to the Z-scheme heterojunction, which improved charge separation and light absorption [180]. Metal-oxide adsorption catalytic materials are a promising solution for efficient and environmentally friendly wastewater treatment of organic pollutants [181]. In summary, metal oxides are promising materials for water purification due to their chemical stability, ability to generate active radicals and purifying effect through the release of metal ions [175]. However, despite these advantages, they are characterised by a number of limitations - low activity under visible light, rapid charge recombination, poor adsorption capacity and reduced efficiency when reused. These factors make it necessary to modify or create composite structures to increase their photocatalytic activity and operational reliability [182].

Metal–organic framework composites (MOFs)

Metal-organic framework structures (MOFs) are porous crystalline materials with high specific surface area, tunable porosity and chemical variability [183]. These properties make them promising non-carbon support components for hybrid photocatalytic systems. The integration of MOFs with other functional materials allows synergy between adsorption and photocatalysis. For example, the MOF@COF composite with a nuclear-shell structure provides fast binding of contaminants on the MOF component and efficient charge separation in the COF shell, which enables almost complete removal of dyes [184]. The BiOX/GaMOF heterostructure shows a similar effect in the removal of ciprofloxacin: the MOF is responsible for the pre-sorption and the semiconductor component for the photocatalytic decomposition [184]. Hierarchically porous MOF composites with alginate and tannic acid were also obtained, where high efficiency is achieved due to complexation and developed pore structure [185]. Such hybrid materials have high potential for sustainable water purification. However, their performance depends on structural stability, energy level matching and interfacial contact engineering. Meanwhile, limitations identified in a number of papers [184, 185], include the instability of MOFs in aqueous media, the possible blocking of active centres by high adsorption, and the need to optimise photosensitivity and charge transfer in heterostructures.

Composites based on polymeric materials

Polymers, known for their unique properties, such as high mechanical strength, elasticity, large surface area, and chemical resistance [186], play a key role in the synthesis of both organic and inorganic materials. In recent years, hybrid materials that combine the advantages of organic and inorganic components have attracted considerable attention. This combination allows the production of materials with new properties, including a synergistic combination of strength, ease of processing, high adsorption capacity, and chemical resistance, that is unattainable for their individual components [186]. Cu₇S₄-TiO₂-CPP composites, for example, exhibited rapid degradation of bisphenol A (BPA), enabled by hydrogen bonding and π - π interactions facilitated by the porous polymer matrix [187]. In addition to Cu₇S₄-TiO₂-CPP, hierarchical porous geopolymers (PG) synthesised using the dealumination method with hydrochloric acid have attracted considerable interest and have demonstrated high efficiency in wastewater treatment. Their specific surface area reached 265.46 m²/g, which was three times higher than that of the original material. PG effectively adsorbed 100 mg/L of DFB dye at pH 2, and Co₃O₄/3PG composites decomposed DFB (20–100 mg/L) at pH 4, reaching equilibrium 20 min faster than adsorption. These materials show high potential for removing dyes from wastewater [188]. Table 4 presents the data on the materials, their characteristics, and their efficiency in removing organic pollutants using the synergy of adsorption and photocatalysis.

Stability considerations and simulation approaches for hybrid adsorption–photocatalytic composites

An essential factor in the practical deployment of adsorption–photocatalytic materials is their long-term stability under operating conditions, especially when exposed to light, oxygen, and various reactive species. A common challenge for semiconductor-based photocatalysts, such as ZnO, BiOCl, and CdS, is photocorrosion, which leads to structural degradation and loss of activity over time [200, 201]. Similarly, metal ion leaching from composites containing Co²⁺, Ag⁺, or Cu³⁺ poses not only an environmental risk but also reduces the efficiency and reusability of the catalyst [202–204]. These issues highlight the need for both experimental durability testing and theoretical modeling. Recent studies have demonstrated that material modifications, such as surface passivation, cocatalyst loading, or integration with stable supports, can significantly enhance stability. For example, Bi₂S₃/CoS₂ composites demonstrated outstanding structural and photocatalytic stability, maintaining high degradation efficiency of NPX over six

Table 4 Effectiveness of hybrid materials for water treatment

No	Hybrid materials	Pollutants	Adsorption capacity	% photocatalysis efficiency	Ref.
1	TiO ₂ /C/MnO ₂	formaldehyde and toluene	13.7 mg/g formaldehyde and 3.9 mg/g toluene	almost complete mineralisation within 60 min	[189]
2	Co ₃ O ₄ -TiO ₂ /N-MCMs	RhB и MO	-	99,0% and 99,2%	[190]
3	GO-chitosan @Cu ₃ (BTC) ₂	MB	357 mg/g	98%	[191]
4	Fe ₃ O ₄ /MOGs	hydrochloride (CTC)	355,87 mg/g	94,34%	[192]
5	2%Ga/ titanium nano-tubes@AC	Perfluorooctane sulphonate (PFOS)	49,8 mg/g	75.0% for 4 h of UV irradiation	[168]
6	ZIF-8@TA/CaAlg@TA	MB	1277 mg/g	95,5%	[185]
7	Ag1.0/ZnO/nBC	formaldehyde, methyl alcohol, phenol and acetone	-	decomposing formaldehyde, methyl alcohol, phenol and acetone by 89%, 92%, 90% and 81%	[193]
8	nanoscale TiO ₂ /ZSM-5	toluene	58.2 mg/g in 60% wet condition; 84.6 mg/g in dry conditions	10–70%	[194]
9	TiO ₂ /SiO ₂	ethyl acetate	22,53 mg/g	85.7% after 4 h	[195]
10	BC/2ZIS/WO ₃	MB и RhB	120,04 and 466,55 mg/g	80,5% and 99%	[170]
11	Bi ₂ MoO ₆ /BC	MB	160,6 mg/g	99,7%	[196]
12	NiFe-LDH/BC	RR120	103,4 mg/g	88,5%	[197]
13	Bi ₂ O ₂ CO ₃ /BC	TC	173 mg/g	84,7%	[198]
14	MIL-101(Fe)@TPPE	TC	573 mg/g	95%	[199]

consecutive photocatalytic cycles without significant loss in performance. Characterization of the recovered materials (SEM, XRD, FTIR) revealed no detectable changes in morphology, crystallinity, or functional groups, confirming their excellent physicochemical robustness under visible-light irradiation [147]. Similarly, 28% Ni/CdS nanowire composites exhibited notable durability in the photodegradation of RR2 and TC, retaining catalytic activity over five reuse cycles [150]. The enhanced stability was attributed to the uniform deposition of Ni nanoparticles, which acted as active sites and suppressed charge recombination, thereby improving both photocatalytic performance and resistance to photodegradation. Post-cycle XRD analysis confirmed the structural integrity of the catalyst, indicating that the Ni/CdS nanocomposite is well-suited for repeated application in solar-driven water purification.

In parallel, advanced computational simulations—notably real-time time-dependent density functional theory (rt-TDDFT)—have been used to reveal charge separation dynamics and orbital-level interactions in doped photocatalysts. For example, in N-doped ZnIn₂S₄ systems, rt-TDDFT analysis confirmed enhanced carrier separation and identified O₂ as the primary electron acceptor and OH⁻ as the hole acceptor, clarifying photocatalytic pathways and efficiency determinants [205].

Overall, combining empirical durability data with theoretical modeling provides a more comprehensive understanding of material performance and guides the rational design of stable, high-efficiency hybrid photocatalysts suitable for real-world applications.

Conclusions and future prospects

This review analyzes the current research and achievements in the field of adsorption-photocatalytic composites that demonstrate high efficiency in water purification, allowing for the effective removal of a wide range of organic pollutants. The key mechanisms of adsorption and photocatalysis, as well as the physicochemical characteristics of the materials, such as structure, porosity, and surface area, which determine their efficiency, are considered. Additionally, the influence of environmental factors, including irradiation intensity, temperature, pH, and composition of the pollutant medium, on these processes is discussed. For the adsorption of organic dyes, an important factor is electrostatic attraction, and for pharmaceutical pollutants, hydrophobic interactions and π interactions are important. In photocatalytic processes, the efficient generation of reactive oxygen species and their interaction with materials play a key role. For successful water purification from pollutants, precise engineering of the band gap of photocatalysts and optimisation of the generation and transport of charge carriers are important. Combining adsorption processes, which provide the initial accumulation of pollutants on the surface of the material, with photocatalytic reactions leading to their destruction, significantly increases the efficiency of purification. Micro- and mesoporous materials, owing to their high sorption capacity, provide access to active centres and facilitate the transport of pollutants to photocatalytic zones. In addition, the structure and morphology of the materials determine the migration path of the charged carriers, thereby minimising the recombination of electron-hole pairs. Environmental

factors, including temperature, pH, and the composition of the polluting environment, have a significant impact on the efficiency of combined processes. For example, a change in pH can affect both the charge on the adsorbent surface and the ionisation state of the organic molecules, determining their interaction with the photocatalyst.

In addition to water purification, the synergy between adsorption and photocatalysis can also be applied to remove volatile organic compounds from air. Hierarchical porous structures increase the number of active chemical sites, reduce charge-transfer distance, promote mass diffusion, and improve light transmission.

1. *Development and modification of materials*: It is necessary to focus on the development of photocatalytic systems that operate under a wide spectrum of sunlight while simultaneously effectively purifying water resources from various types of pollutants. In addition, modification of the surfaces of highly porous adsorbents with various functional groups is an important aspect that allows the selective and simultaneous effective capture of various pollutants in aquatic environments.
2. *Optimization of the synthesis of composites*: Creating close contact between the adsorbent and photocatalyst remains a complex task that affects the efficiency of the composite and requires the development of more efficient and simple synthesis methods.
3. *Synergistic mechanism of adsorption and photocatalysis*: To achieve maximum efficiency, it is necessary to study the balance between the adsorption and photocatalysis processes in more detail. The development of theoretical models and computational approaches can help predict the behaviour of materials and optimise their properties. A deeper understanding of the kinetics and mechanisms of the reactions in such systems will allow the creation of materials that simultaneously provide fast adsorption and efficient photocatalysis.
4. *Environmental safety and reuse*: To implement combined technologies under realistic conditions, their environmental safety must be considered. Therefore, it is important to study the toxicity of photocatalytic materials to aquatic organisms and the impact of reaction intermediates on the environment. Attention should be paid to the development of materials that can be reused without significantly reducing their activity. This reduces costs and minimises environmental impacts.

Therefore, future research in the field of adsorption and photocatalysis synergy should aim to eliminate the existing limitations and develop sustainable technologies that can meet the growing demand for clean water with minimal impact on the environment.

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