https://doi.org/10.15255/KUI.2022.058
KUI-51/2023
Review
Received September 28, 2022
Accepted December 16, 2022

Recent Achievements in Photocatalytic Degradation of Organic Water Contaminants

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9th International Conference WATER FOR ALL 19–20 May 2022 Osijek-Croatia

Abstract

The chemical complexity of organic contaminants (drugs, agrochemicals, and dyes) requires new, more advanced ways to remove them from water compared to the conventional treatment methods used. One such method is photocatalytic degradation. In this paper, the mechanism of degradation of harmful organic compounds using semiconductor materials with photocatalytically active properties in the presence of UV or visible radiation will be explained. Methods and selection of components for the preparation of the latest developed photocatalysts, their stability, as well as the percentage of organic contaminant removal will be discussed. The discussion will also cover the advantages and drawbacks of photocatalytic methods, as well as future research in this area.

Keywords

Photocatalysis, organic water contaminants, plastics, dyes, drugs, pesticides

1 Introduction

Water pollution is a common problem all over the world. In most countries, microbiological water pollution is the principal risk to human health, although the importance of chemical contamination should not be underestimated. Large quantities of chemicals introduced from chemical industry and anthropogenic activities may cause potential harm to many ecosystems.

Intensive use and unrestricted access to drugs in everyday life has resulted in their increasing concentrations in water and environment. Emerging organic contaminants (EOCs) are heterogeneous groups of chemical compounds with negative influence on human health. Effluents of wastewater treatment plants (WWTPs) are the main source of EOCs. They appear in the concentration range from nanomolar to micromolar in both raw and treated wastewater. In order to for a clearer view of this problem, a few examples will be presented. The concentration of plasticizers as EOCs in urban wastewater was 5850 ng l^{-1} in influent, and after their removal at a conventional WWTP in effluent it was 1840 ng l^{-1} with a removal between 32–100 %. The next representative of EOCs are antibiotics considered in the same WWTP with the concentration of 303 500 ng l^{-1} in influent, and 37 000 ng l^{-1} in effluent with a removal range from 0–100 %.[1] A great concern is the presence of trace organic contaminants (TrOCs) such as pesticides, pharmaceutical and personal care products, as well as endocrine-disrupting chemicals in drinking water sources.[2]

Although they are present at trace levels, most TrOCs tend to bio-accumulate in living organisms inducing endocrine disruption, antibiotic resistance, and carcinogenicity.[3]

Mechanical (filtration, sedimentation, and flotation processes) and biological treatments (biodegradation using the conventional activated sludge) are usually used for conventional WWTPs. These methods are very often insufficiently effective to achieve removal of pollutants due to complex nature of wastewater matrix. Conventional treatment approaches have some drawbacks, such as incomplete pollutant removal and generation of new solid waste due to the transfer of EOCs from water to adsorbent, and does not involve degradation. Finally, the application of advanced oxidation processes (AOPs) can help overcome these problems.[4] AOPs are promising technologies for degrading refractory organic contaminants, removing toxic heavy metal ions and microorganisms from water and wastewater.[5]

According to available literature data, the required electrical energy expressed in unit (kWh m^{-3} $order^{-1}$) *per* Fenton-based AOP is 0.98, followed by photochemical 3.20, ozonation 3.34, electrochemical 29.5, photocatalysis 91, and ultrasound 971.45.[6]

Therefore, scientists today are focused on the development of new materials, such as adsorbents and photocatalysts for pollutant removal from both model aqueous solutions and real water samples.

1.1 Organic contaminants

Pesticides, drugs, dyes, and agrochemicals contain very complex organic molecules in their structure that are toxic to human health, plant and animal life, and can cause endocrine disorders and cancer. Therefore, the photocatalyt-

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Note: The investigations in this paper were presented at the 9th International Conference WATER FOR ALL 2022, held on May 19–20, 2022, Osijek, Croatia.

ic degradation of antibiotics, dyes, plastics, and pesticides is discussed in this work. Many of these compounds appear in wastewater due to increasing sewage discharge generated from industrial and pharmaceutical manufacture.[7]

1.2 Water treatment

Chemical treatment, as a classic method of wastewater treatment, requires the use of aggressive chemicals, such as aluminium sulphate or iron chloride, which have a negative impact on the environment. This brought about the need to introduce a method such as photocatalytic degradation involving the use of sunlight for the activation of photocatalysts, which in reaction with the pollutants, leads to the formation of environmentally acceptable end products such as carbon dioxide (CO_2), water (H_2O), and mineral substances. In addition, photocatalytic processes take place at room temperature and pressure, as well as in the presence of oxygen from air, which represents advantages compared to classical processes.

Recently, increasing interest has been devoted to the development of new photocatalysts for the water and air purification process. For the production of photocatalysts, different types of semiconductor materials and their combinations are used, as well as different substrates for their heterogenisation. Among the most studied semiconductors for photocatalytic degradation of organic pollutants is titanium dioxide (TiO_2) due to its specific properties, such as strong oxidising ability, chemical stability, biocompatibility, non-toxicity, *etc.*[8] In addition to the advantages mentioned so far, photocatalytic processes take place in cycles, and the same photocatalyst in heterogeneous photocatalysis can be used several times, depending on its stability and photocatalytic activity.[9,10]

2 Photocatalytic degradation method

AOPs are characterised by *in-situ* generation of reactive species, primarily hydroxyl radicals (•OH), and have been recognized as one of the potential technologies for degradation of organic pollutants. The most studied AOPs include ultraviolet (UV) radiation in combination with: a) hydrogen peroxide (H_2O_2), b) ozone (O_3), and c) photocatalysts.[11] The major drawback of all extremely powerful AOP technologies is the high maintenance cost. However, AOPs can be widely used with the discovery of new photocatalysts that absorb in the visible region of the spectrum efficient light sources, and in more advanced reactor designs. However, further research is necessary to make this possible.

Semiconductors, such as zinc oxide (ZnO),[12] tungsten trioxide (WO_3),[13] titanium dioxide (TiO_2),[14] and cadmium sulfide (CdS)[15] have been used as catalysts in photocatalytic reactions. For example, WO_3 is not easily attainable, and CdS is easily inactivated and corroded by photons. However, the use of cadmium (Cd) is not recommended because it is a toxic metal. In addition, pure ZnO and TiO_2 do not perform well in the presence of visible light owing to their limited range of UV activity. In contrast, bismuth(III) oxyiodide (BiOI) has a narrow bandgap (1.7–1.9 eV) and is chemically stable. Although it is a relatively new material, BiOI has shown to be an excellent photocatalyst under visible light irradiation.[16,17]

Recently, Bratovčić in 2021, discussed heterogeneous photocatalysis with TiO_2 nanocomposites for the degradation of dyes and drugs, which were able to remove 80–99 % of organic pollutants in aqueous solution under UV and visible light.[18] Earlier, in 2019 Bratovčić discussed photocatalytic degradation of different contaminants present in textile wastewaters, refinery wastewaters, agricultural wastewaters, and pharmaceutical wastewaters with TiO_2 composites. In the same paper, he discussed in detail photocatalytic properties of TiO_2, its heterogenisation methods for improving the light absorption efficiency, and reduction of the recombination rate of generated electrons and holes.[19] Therefore, improved TiO_2-heterogenised photocatalysts can work under solar irradiation for environmental purifications without generating harmful by-products.[20]

2.1 Mechanism of photocatalytic degradation with TiO_2

The photocatalytic mechanism starts when a photon with energy $h\nu$ matches or exceeds the band gap energy, E_g, of the semiconductor. The whole mechanism is discussed in detail in the work of *Bratovčić*.[19] The lifetime of electron-hole pairs ($e^- - h^+$) is only a few nano-seconds, but it is long enough to initiate redox reactions with semiconductor material in solutions or gaseous phases. The formation of very strong oxidising OH radicals (Fig. 1) are a key factor for reaction with organic compounds resulting in the total mineralisation of most of these compounds.[21]

Photocatalytic degradation is an optical degradation process that is very effective for the degradation of recalcitrant pollutants that resist ordinary oxidation processes. In this process, the pollutant molecules are oxidised over a catalyst comprised of metal oxide semiconductor (photocatalyst) particles exposed to UV or visible light.[22]

Specifically, the photocatalytic degradation process involves the irradiation of photocatalyst particles with light in the photocatalytic reactor, which excites electrons from the valence energy band to the conduction energy band, followed by the production of •OH that have high oxidation ability.[23,24] These radicals can quickly mineralise organic pollutants such as antibiotic molecules into CO_2 and minerals.[25]

2.2 Physicochemical parameters that affect photocatalytic activity

The pH value, photocatalyst dose, initial concentration of contaminant, and photocatalytic reaction time are main physicochemical parameters that affect photocatalytic activity (Fig. 2).

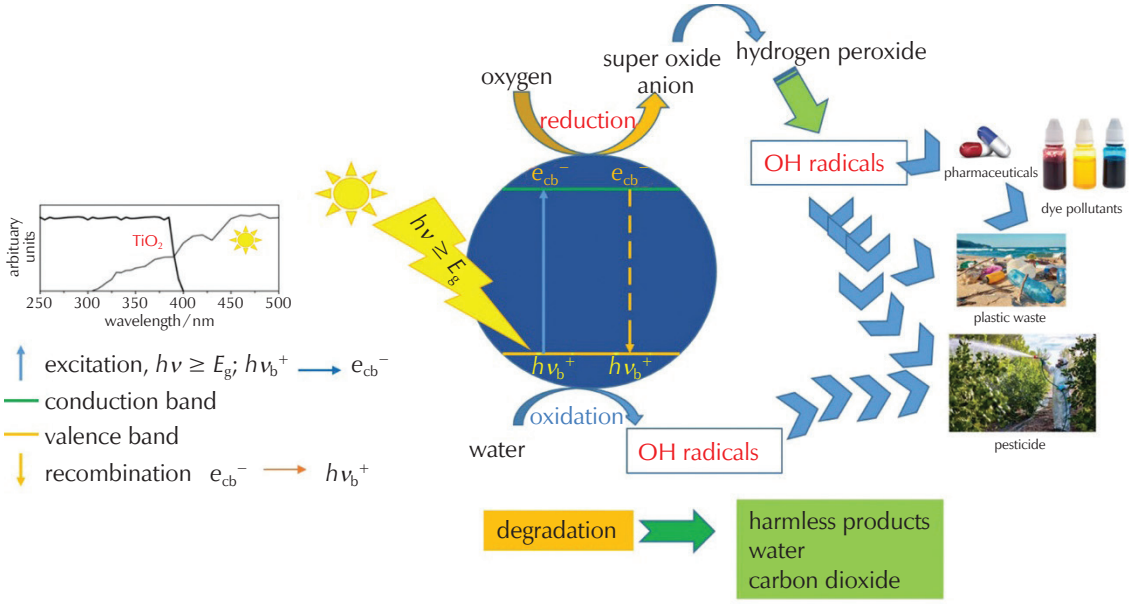


Fig. 1 – Mechanism of photocatalytic degradation with TiO_2
Slika 1 – Mehanizam fotokatalitičke degradacije s TiO_2

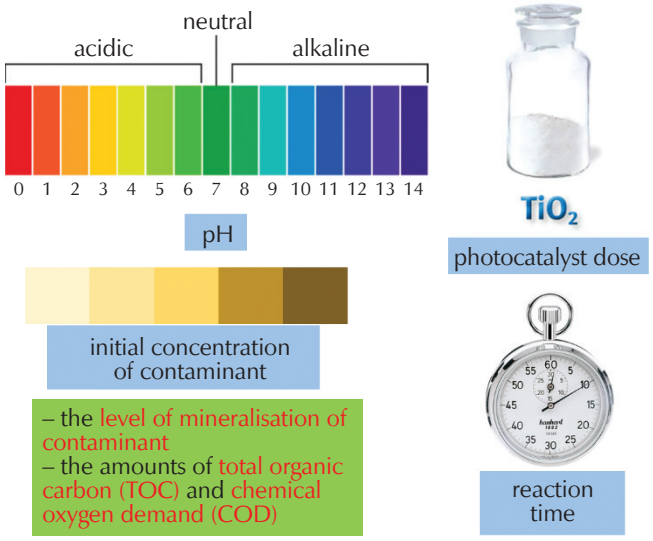


Fig. 2 – Physicochemical parameters that affect photocatalytic activity
Slika 2 – Fizikalno-kemijski parametri koji utječu na fotokatalitičku aktivnost

2.2.1 The pH value

The pH value is a key factor affecting the degradation and elimination of pollutants, especially pharmaceutical compounds. Specifically, the pH can considerably affect the sorption capacity and distribution of electric charge on the nanocomposite surface. Thus, the determination of point of zero charge (pzc) is necessary to determine the pH range at which the composite surface is positive or negative.[26]

2.2.2 Optimal photocatalyst dose

Optimal photocatalyst dose should provide improvement in degradation efficiency of contaminant due to increased number of reaction sites, and the higher probability of collision between the photocatalyst particles and pollutant molecules. However, at higher than optimal doses, a decrease in degradation efficiency may occur, probably as a result of reduced UV or visible or solar light penetration.[27]

2.2.3 Optimal initial contaminant concentration

In order to determine the optimal initial contaminant concentration, a number of different contaminant concentrations should be prepared. Each of the prepared concentrations must be exposed to radiation at a specific time and with a certain amount of photocatalyst. After photocatalytic reaction, the highest yield of the desired product obtained with the certain amount of the catalyst determine the optimal dose of the photocatalyst.[28] In order to study the effect of substrate concentration on the degradation of gentian violet, four different concentrations of gentian violet in the range (0.18–0.5 mM) were prepared. The optimal concentration of pollutant was 0.25 mM, because the degradation rate increased with increasing the substrate concentration up to this value, and then declined.[29] Similar results were obtained by other researchers working with Acid Orange 7 (AO7). They prepared different solutions of AO7 in concentration range from 25 to 600 mg l^{-1}.[30] They found that the time required for total degradation of AO7 was strongly dependent on initial dye concentration. For concentrations up to 100 mg l^{-1}, the photocatalytic reactions occur in less than 60 min, and complete decolourisation was achieved, while this was not the case for the higher concentrations.

The degradation efficiencies of methylene blue (MB) and indigo carmine (IC) were studied at 10, 30, and 50 ppm by composite nanofibers systems containing cellulose acetate (CA), multiwall carbon nanotubes (CNT), and TiO_2 nanoparticles under UV light. The result indicated that the degradation efficiencies were, respectively, 100, 80, and 70 % for MB, and 100, 90, and 80 % for IC. High concentration of the dye activated the photocatalytic process, but reduced the degradation rate.[31]

2.2.4 Mineralisation of contaminant

Finally, in order to investigate the level of mineralisation of contaminant through the photocatalytic process, the amounts of total organic carbon (TOC) and chemical oxygen demand (COD) need to be determined.

A mixture of eight antibiotics containing isoniazid, metronidazole, sulfadiazine, sulfamethoxazole, trimethoprim, norfloxacin, moxifloxacin, and lincomycin was degraded by copper (Cu)-modified TiO_2 photocatalysts. They achieved complete mineralisation within 6 h of reaction with the most efficient catalyst (0.8 wt% Cu loading on TiO_2) with 75 % reduction of TOC.[32]

Visible light photodegradation of tetracycline (TC) has been done with black anatase-TiO_2 with 66.2 % removal efficiency of TC, while white TiO_2 and N-doped TiO_2 exhibited 43.4 % and 59.6 % removal efficiencies within 4 h, respectively. The mineralisation products were CO_2, H_2O, and inorganic ions were confirmed by 29.6 % of TOC removal in TC photodegradation catalysed with black-TiO_2 under visible light. In contrast, with white TiO_2, no mineralisation of TC occurred and no changes of TOC were observed.[33]

2.3 Photocatalytic degradation of organic compounds

Fig. 3 presents the research trend on *ScienceDirect* in the last 10 years in the search terms "photocatalytic degradation of dyes", "photocatalytic degradation of pesticides", "photocatalytic degradation of drugs", and "photocatalytic degradation of plastics". Exponential growth of publications is seen for each contaminant per year. Photocatalytic degradation of dyes is the most studied, followed by drugs, pesticides, and the least, plastic.

2.3.1 Photocatalytic degradation of plastics

Excessive amounts of plastic waste, and especially the presence of micro and nanoplastics, is a concern because of their harmful effects on plant and animal life, as well as human health. For the time being, more than 90 % of microplastics waste can be removed with the conventional method of wastewater treatment. However, the remainder of less than 10 % remains in the sludge. Actually, the removal efficiency of microplastic depends on the stage of treatment used. Therefore, with primary treatment at WWTP it is possible to remove from 16.5 to 98.4 % of microplastics, while with secondary from 78.1 to 100 %, and

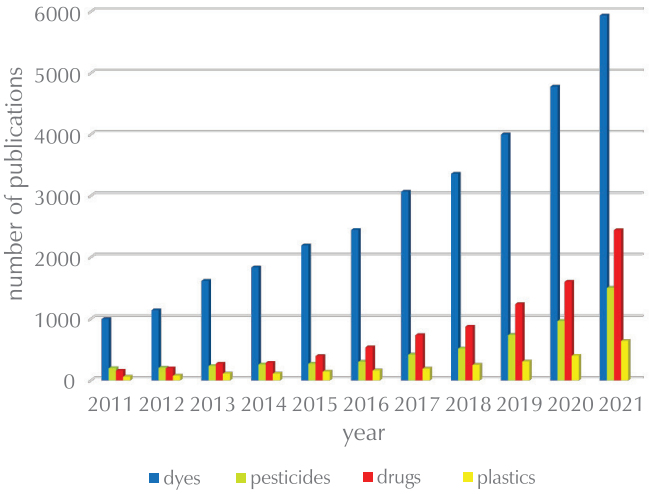


Fig. 3 – Number of publications in last 10 years on photocatalytic degradation of dyes, pesticides, drugs, and plastics on *ScienceDirect*

Slika 3 – Broj publikacija u posljednjih 10 godina vezanih uz fotokatalitičku degradaciju bojila, pesticida, lijekova i plastike prema *ScienceDirect* bazi podataka

tertiary from 87.3 to 99.9 %, respectively. The largest fraction of microplastics removed conventionally is trapped in sludge.[34] For this reason, it is necessary to develop new methods as soon as possible that will be able to remove all pollution, and one of them is the promising highly efficient photocatalytic decomposition. In this perspective,[35] explained that the photocatalytic degradation of microplastics creates organic molecules with a number of carbon atoms smaller than 8, carbon dioxide, and water. When a photon is absorbed by a macromolecule, an excited state is created and the C−C bond breaks, and an oxidation reaction occurs. Therefore, the development of photocatalytic process using renewable energy sources, such as solar energy, is an increasingly attractive option from the economic, energy, and environmental perspective.

Multifunctional composites with metal or non-metal dopants for photocatalytic degradation of (micro)plastics have been prepared.[36] They reveal that superoxide ions and hydroxyl radicals participate in the photocatalytic degradation, leading to the breaking of the polymer chain and the production of some intermediates. The complete mineralisation of (micro)plastics by photodegradation has not been achieved to date.

In research carried out by *Acuña-Bedoya et al.*[37], the photocatalytic degradation with visible light irradiation of polystyrene (PS) has been done. PS particles, the size of ≈ 350 nm, were degraded using immobilised copper (I) oxide/copper (II) oxide (Cu_2O/CuO) semiconductors grown in ammonium fluoride (NH_4F) and sodium hydroxide (NaOH) media by the anodising process. The result of photocatalytic experiments with photocatalysts (a band gap between 1.6 and 2 eV) in visible light promotes polymer chain scissions, and reduces the concentration of polystyrene nanoparticles (PS-NPs) up to 23 %, representing six times more than the reductions achieved by photolysis. In addition, mineralisation of up to 15 % was achieved.

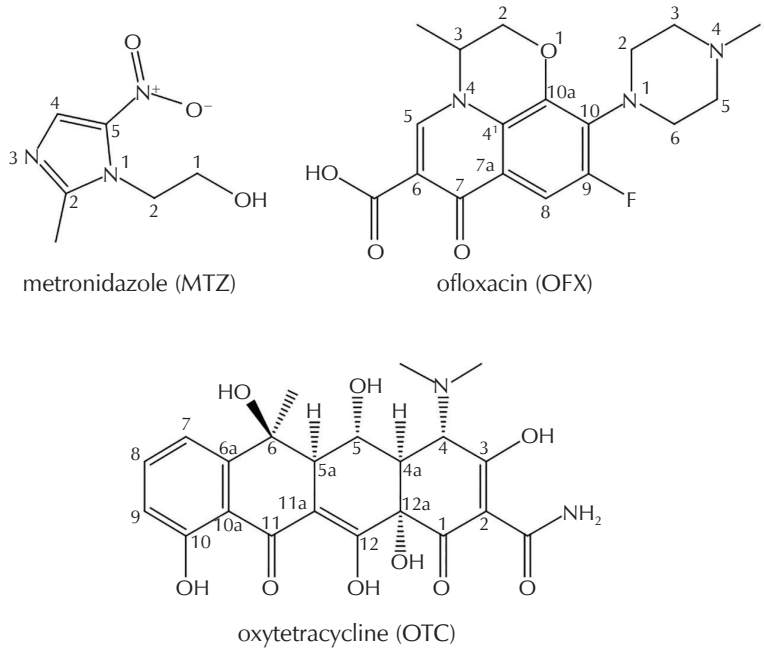


Fig. 4 – Chemical structures of metronidazole, ofloxacin and oxytetracycline
Slika 4 – Kemijske strukture metronidazole, ofloksacina i oksitetraciklina

The research studies have shown that the presence of the micro- and nanoplastics are ubiquitous in the environment. By photocatalytic process, it is possible to degrade micro- and nanoplastics into a useful lower molecular weight of organic species, such as carboxylic acids and aromatic compounds (formate, acetate, benzene, phenol, benzaldehyde, benzoquinone, acetophenone, benzoate, dibenzoylmethane, benzoic anchidride), which can be used further in organic synthesis production of new chemical products or plastics.[38] Therefore, photocatalytic degradation is a promising alternative to minimise microplastics pollution from continental sources with reduced by-products.[39]

2.3.2 Photocatalytic degradation of antibiotics

Antibiotic pollutants discharged from municipal and pharmaceutical wastewater are often present in the aquatic environment due to ineffective treatment of wastewater. In reality, pollution of water resources with antibiotics or their degradation by-products can pose serious risks to human health because of the high toxicity and carcinogenic properties of these compounds. For example, the presence of antibiotics in the environment, even at trace levels, can induce the development of antibiotic-resistant pathogens, which potentially endanger human health as well as the ecosystems.[40]

Metronidazole (MTZ), also known as flagyl, is an antibiotic and antiprotozoal medication prescribed as a remedy for anaerobic infections.[41,42] Photocatalytic degradation of MTZ has been carried out in a continuous flow-loop photoreactor by titanium dioxide/silver phosphate/graphitic carbon nitride ($TiO_2/Ag_3PO_4/g–C_3N_4$) composite under irradiation with blue light-emitting diodes. The successful degradation was achieved thanks to the formation of hydroxyl radicals with an efficiency of MNZ 97.18 %. During this process, several reactions (hydroxyethyl cleavage, N-denitration, nitro-reduction, and ring-opening) occurred and formed 13 types of intermediate products. A part of the by-products had oxidised and mineralised into low toxicity substances, including carboxylic acid, CO_2, H_2O, and nitrate (NO_3^-).[43]

Pharmaceutical waste is a source of dangerous pollutants that can be carcinogenic to humans. Therefore, the removal of these residues from wastewater is a priority in environmental engineering.

The presence of oxytetracycline (OTC) is one of the most frequently detected antibiotics in water and sediment, and is a serious problem for the environment due to its high toxicity, while its removal by conventional treatment processes is difficult because of stable naphthol ring structure, and high toxicity to the microorganisms used in biological treatment.[44]

By photolytic degradation of 20 mg l^{-1} of OTC solution after 4 h of irradiation by a 500 W medium mercury lamp, the degradation rate was 90 %, but only 13.5 % of TOC was reduced. During the photolytic degradation, by-products containing the naphthol ring were proved to be even more toxic than the parent, when tested with luminescent bacterium *P. phosphoreum*.[45]

Fig. 4 presents the chemical structures of antibiotics discussed in this paper.

Bionanocomposites are known as a novel class of advanced materials. Bionanocomposites consist of biopolymers and

inorganic solids. Actually, they can be defined in two ways: i) as materials made from renewable nanoparticles such as cellulose and petroleum-derived polymers such as polypropylene (PP), polyethylene (PE) and epoxies, and ii) bionanocomposites derived from biopolymers such as polylactide (PLA) and polyhydroxyalkanoates (PHA), and synthetic or inorganic nanofillers like carbon nanotubes and nanoclay.[46] The properties of a composite vary considerably from point to point in the material, depending on in which material phase the point is located. Polymers are relatively weak, low-stiffness materials, but in combination reinforcement materials, it is possible to improve their mechanical and physical properties.[47]

For the preparation of composite materials, chitosan is mainly used. Chitosan is a second most abundant natural polymer obtained by the deacetylation of chitin, a structural macromolecule found in the exoskeletons of crustaceans, as well as fungal cell walls. This polymer possesses desirable properties, such as non-toxicity, antibacterial activity, biodegradability, low price, high natural abundance, and excellent chelating properties, that make it suitable as a purification agent for removing contaminants.[48]

In 2021, *Arghavan et al*.[49] synthetised a photocatalyst composed of $FeNi_3$/chitosan/BiOI and used for MTZ degradation. At the optimal conditions (pH = 7; $FeNi_3$/chitosan/BiOI dose = 0.04 g l^{-1}, MTZ concentration = 20 mg l^{-1}, and reaction time = 200 min), the degradation of MTZ was 100 %. The prepared photocatalyst was very stable and could be reused six times with only slight losses in its activity. The mineralised products were final by-products of MTZ degradation.

In the study of *Shang et al.*,[50] the heterogeneous photocatalyst composed of titanium silica-carbon nitride (TS-1/C_3N_4) was prepared and used for photocatalytic treatment of wastewater polluted with ofloxacin (OFX). The prepared photocatalyst was very efficient and able to remove 82.92 % of OFX.

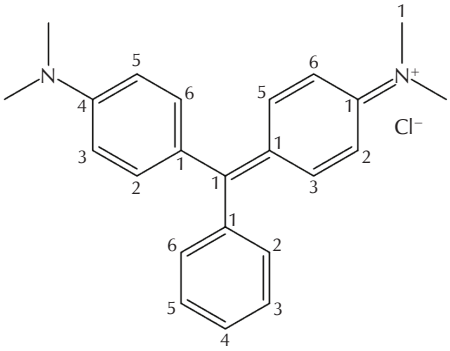
Wu et al. chose bismuth sulphide, Bi_2S_3 (BS) and 2D g-C_3N_4 nanosheets (CN) for hydrothermal preparation of the photocatalyst Bi_2S_3/g-C_3N_4 (BSCN) with different mass ratios of CN to BS.[51] The structure of the CN was not changed by the introduction of Bi_2S_3. The best photocatalytic activity of BSCN (98.98 %) was achieved with the mass ratio of CN/BS 8 : 1. The stability of prepared photocatalyst was confirmed with 5 cycles of high degradation efficiency of tetracycline. They explained that the h^+ and O_2^- played a major role in the mechanism of the photocatalytic reaction, while •OH species played a secondary role.

2.3.3 Photocatalytic degradation of dyes

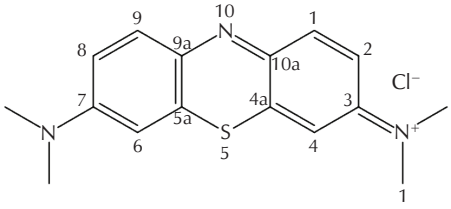
Azo dyes are potentially toxic, allergenic, and have carcinogenic effects.[52] It has been reported that over 100 000 various types of dyes are currently used with annual production exceeding 700 000 t.[53] Recently, binary nanocomposite copper oxide/zinc oxide (CuO/ZnO) and its ternary nanocomposite with beta cyclodextrin (β-CD), β-CD-CuO/ZnO were synthetised by sol-gel method for photocatalytic degradation of textile dyes malachite green (MG) and MB.[54] The chemical structures of MG and MB are presented in Fig. 5.

The coupling of metal oxides (CuO/ZnO) increases the efficiency due to its broad light absorption and fast dynamic process. Introduction of β-CD in generation of β-CD-CuO/ZnO significantly prevented the recombination of e^- - h^+, and its photocatalytic activity was higher than coupled metal oxides CuO/ZnO. The degradation efficiency was almost 90 % for MB and 80 % for MG after 3 h of irradiation using β-CD-CuO/ZnO. The hydrophilic exterior and hydrophobic interior cavity of β-CD-CuO/ZnO may explain a good adsorption tendency of pollutant molecules.

ZnO-Fe_3O_4 nanoparticles were synthesised using the leaves of *Camellia sinensis* and immobilised in crosslinked alginate–chitosan polymer beads, and tested for photocatalytic degradation of acid violet 7 (AV7) dye.[55] The optimisation of reaction conditions ensured higher dye removal efficiency up to 94.21 ± 1.02 % using the nanocomposite under UV-C irradiation of 365 nm. The removal efficiency in tap water, groundwater, and lake water was 83.2 ± 0.4 %, 69.1 ± 1.6 %, and 67.9 ± 0.3 %, respectively. The residual toxicity of the degraded AV7 solution was tested on model organisms like freshwater algae, *Scenedesmus* sp., and plant model, *Allium cepa*, demonstrating the lower



malachite green (MG)



methylene blue (MB)

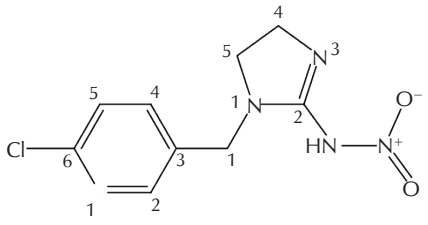
Fig. 5 – Chemical structures of malachite green and methylene blue dyes
Slika 5 – Kemijska struktura bojila malahitno zelenilo i metilensko modrilo

toxicity of the degraded AV7 product. The present work aimed at synthesising photocatalytic NPs, *i.e.*, ZnO-Fe_3O_4 NPs encapsulated in a crosslinked polymer of alginate-chitosan (Cs/Alg). The quantification of AV7 dye concentration was performed using a UV–visible spectrophotometer, by measuring the absorbance at λ_{max} = 556 nm.

2.3.4 Photocatalytic degradation of pesticides

Excessive use of organophosphorus pesticides (OP) in agriculture has led to their accumulation in soil and water. The danger of excessive concentrations of OP can negatively affect the nervous system in humans and other mammals. The degradation of OP is catalysed by the enzyme organophosphorus hydrolase (OPH) to *p*-nitrophenol (*p*-NP), which is still toxic. For this reason, *Zhang et al.* prepared an enzyme-photocatalytic integrated catalyst by immobilising OPH on hollow structured Au-TiO_2 (named OPH@H-Au-TiO_2) and further degradation of *p*-NP.[56] This OPH@H-Au-TiO_2 catalyst was activated under visible light and could successfully degrade methyl parathion to *p*-NP by OPH, and then degrade *p*-NP to hydroquinone. The prepared photocatalyst showed very high stability and activity after 4 cycles of photocatalytic experiments with more than 80 % of generated *p*-NP, which was further degraded into hydroquinone. Each photocatalytic reaction lasted 150 min *per* cycle.

Structural design in a semiconductor photocatalyst is significant to improve the photocatalytic efficiency to solve current energy or environmental problems. A Z-scheme photocatalyst consisting of polyaniline/zinc oxide/cobalt molybdate (PANI/ZnO-$CoMoO_4$) under visible-light irradiation for pesticide degradation of imidacloprid (IMI) has been developed by *Adabavazeh et al.*[57] Under optimal conditions (4.5 ppm of IMI, pH = 4, and 163.5 mg photocatalyst), about 97 % of the IMI was degraded within 180 min of irradiation. The prepared photocatalyst can be readily recovered and reutilised with the centrifugation process. The chemical structure of imidacloprid pesticide is presented in Fig. 6.



imidacloprid (IMI)

Fig. 6 – Chemical structure of imidacloprid pesticide
Slika 6 – Kemijska struktura pesticida imidakloprida

3 Conclusions

Heterogeneous photocatalysis has proven to be a very encouraging method for purifying waters loaded with various high molecular weight and complex organic compounds. The paper presents the advantages of photocatalytic methods compared to conventional methods of purification. A different selection of components for the preparation of various composite photocatalysts is presented with the aim of achieving a greater photocatalytic effect in degradation, but also using visible light for their activation, and reducing the recombination process of electrons and holes. In future research, experiments should be carried out on real wastewater samples, instead of the mostly studied modal synthetic solutions of individual organic contaminants.

List of abbreviations
Popis kratica

EOCs – emerging organic contaminants
– nastajući organski zagađivači

WWTPs – wastewater treatment plants
– postrojenje za pročišćavanje otpadnih voda

TrOCs – trace organic contaminants
– organski zagađivači u tragovima

AOPs – advanced oxidation processes
– napredni oksidacijski procesi

•OH – hydroxyl radical
– hidroksilni radikal

UV – ultraviolet
– ultraljubičasto

E_g – gap energy
– energetski procjep

e^- – h^+ – electron-hole pairs
– par elektron-šupljina

pzc – point of zero charge
– točka nultog naboja

AO7 – acid orange 7
– *kiselo narančasto 7*

MB – methylene blue
– metilen plavo

IC – indigo carmine
– indigo karmin

CA – cellulose acetate
– celulozni acetat

CNT – carbon nanotubes
– ugljikove nanocjevčice

TOC – total organic carbon
– ukupni organski ugljik

COD – chemical oxygen demand
– kemijska potrošnja kisika

TC – tetracycline
– tetraciklin

PS – polystyrene
– polistiren

PS-NPs – polystyrene nanoparticles
–nanočestice polistirena

NPs – nanoparticles
– nanočestice

MTZ – metronidazole
– metronidazol

Ag_3PO_4 – silver phosphate
– srebrni fosfat

g–C_3N_4 – graphitic carbon nitride
– grafitni ugljikov nitrid

OTC – oxytetracycline
– oksitetraciklin

PP – polypropylene
– polipropilen

PE – polyethylene
– polietilen

PLA – polylactide
– polilaktid

PHA – polyhydroxyalkanoates
– polihidroksialkanoat

TS-1/C_3N_4 – titanium silica-carbon nitride
– titanijev silika-ugljik nitrid

OFX – ofloxacin
– ofloksacin

BS – bismuth sulphide
– bizmitov sulfid

CN – g-C_3N_4 nanosheets
– g-C_3N_4 nanocjevčice

β-CD – beta cyclodextrin
– beta ciklodekstrin

MG – malachite green
– malahit zelena

AV7 – acid violet 7
– kiseli violet 7

Cs/Alg – alginate-chitosan
– alginat-hitozan

λ_{max} – maximum wavelength
– maksimalna valna duljina

OP – organophosphorus pesticides
– organofosforni pesticidi

OPH – organophosphorus hydrolase
– organofosforna hidrolaza

p-NP – *p*-nitrophenol
– *p*-nitrofenol

PANI – polyaniline
– polianilin

$CoMoO_4$– cobalt molybdate
– kobaltov molibdat

IMI – imidacloprid
– imidakloprid

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SAŽETAK

Najnovija dostignuća u fotokatalitičkoj degradaciji organskih onečišćujućih tvari u vodama

Amra Bratovčić

Kemijska složenost organskih onečišćujućih tvari u prirodnim vodama, poput lijekova, agrokemikalija i boja, zahtijeva primjenu novih i naprednijih načina njihova uklanjanja iz voda u odnosu na konvencionalne metode njihova pročišćavanja. Jedna od takvih metoda je fotokatalitička razgradnja. U ovom radu opisani su mehanizmi razgradnje štetnih organskih spojeva pomoću poluvodičkih materijala s aktivnim fotokatalitičkim svojstvima uz djelovanje UV ili vidljivog zračenja. Raspravljat će se o metodama i odabiru komponenata za pripravu najnovijih fotokatalizatora, o njihovoj stabilnosti te učinkovitosti uklanjanja organskih onečišćujućih tvari. Rasprava će također obuhvatiti prednosti i nedostatke fotokatalitičkih metoda, kao i buduća istraživanja u tom području.

Ključne riječi
Fotokataliza, organske onečišćujuće tvari, plastika, boje, lijekovi, pesticidi

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Pregledni rad
Prispjelo 28. rujna 2022.
Prihvaćeno 16. prosinca 2022.