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FUNCTIONAL COATINGS FOR REMOVING PERSISTENT ORGANIC POLLUTANTS IN WATER: CURRENT STATE OF THE ART REVIEW

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Persistent organic pollutants in water, including per- and polyfluoroalkyl substances, pesticides, dyes, and pharmaceutical residues, are difficult to remove due to their high chemical stability, mobility, and toxicity. Traditional approaches based on the use of bulk sorbents or catalysts are often ineffective due to system pressure drops, material losses, limited on-site regeneration, and difficult integration into compact modular units. This review summarises the current state of functional coatings as immobilised, regenerative and modular-ready platforms for reducing persistent organic pollutants. Adsorption coatings are discussed with a focus on MXenes, layered double hydroxide, metal-organic frameworks / covalent organic framewor films, N-doped carbons, and ion-imprinted polymers, highlighting trade-offs between capacity, selectivity, stability in water, and regeneration pathways. Catalytic coatings for advanced oxidation processes are considered in systems based on g-C_3N_4, TiO_2, $BiVO_4$/BiOBr *photocatalysts, M–N–C materials for electro-Fenton processes, and perovskite oxides, with an emphasis on radical generation efficiency and stability in realistic aquatic environments. Antifouling and hydrophilic top layers, including PEG-type polymers and zwitterionic polymers, are considered as elements that ensure long-term efficiency by reducing organic and biological contamination. Finally, the role of carriers (ceramic monoliths, polymer ultrafiltration/reverse osmosis membranes, and metal or textile frames) and multilayer architectures is analysed in terms of adhesion, compatibility between layers, and scalable production. Key unresolved issues include coating durability, resistance to delamination, regeneration strategies that do not generate secondary waste, and harmonised metrics for comparing performance in complex water bodies.*

Keywords: *adsorption coatings, anti-fouling coatings, catalytic coatings, functional coatings, persistent organic pollutants, water treatment*

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1. Introduction

The contamination of water resources with persistent organic pollutants (POPs) – classes of chemical compounds characterised by exceptional chemical stability and the ability to accumulate in the environment (Jones and de Voogt, 1999) is a pressing environmental issue today. The development of industry, agriculture and the pharmaceutical sector has led to the widespread use of synthetic organic compounds, including pesticides, pharmaceuticals, per- and polyfluoroalkyl substances (PFAS), as well as various synthetic dyes and surfactants. The high chemical and biological stability of these substances, their ability to bioaccumulate and their long-term persistence in the environment make them dangerous even in extremely low concentrations (Jones and de Voogt, 1999).

Traditional water treatment methods, such as biological treatment (Ucar et al., 2025) and classical physicochemical processes (Derrouiche et al., 2013, Kyrii et al., 2015, S. Kyrii et al., 2020), are generally not effective enough to completely remove PFAS. Such substances may remain in wastewater in trace concentrations even after traditional treatment, posing a risk of continuous exposure to humans and ecosystems. In particular, some herbicides and insecticides (atrazine, DDT, etc.) persist in aquatic environments for years, and synthetic organic dyes persist for a long time due to their high chemical stability (Mahdi & Ebrahim, 2024). In this regard, considerable attention is being paid to the development of new materials and technological solutions aimed at improving the efficiency, selectivity and stability of water treatment processes, in particular for the removal of new modern pollutants – POPs. One promising direction is the use of functional coatings that allow active adsorption, catalytic and antifouling materials to be immobilised directly in water purification modules. This approach reduces hydraulic resistance, improves process controllability, allows for the integration of multiple functions into a single element, and enables in-situ regeneration of active layers.

The aim of this work was to systematise modern approaches to the creation of functional coatings for the removal and/or destruction of persistent organic pollutants in water, comparing adsorption, catalytic (AOP) and antifouling coatings according to key mechanisms of action, identifying advantages and limitations, and demonstrating the role of substrates and multilayer architectures in ensuring low hydraulic resistance, modular integration and in situ regeneration potential.

The review analyses typical classes of coating materials (MXene, LDH, MOF/COF, N-doped carbons, IIP/MIP; g-C_3N_4, TiO_2, $BiVO_4$/BiOBr, M–N–C, perovskites; PEG-like and zwitterionic layers) are analysed, and the challenges of scaling, stability and regeneration in real waters are summarised.

2. Persistent organic pollutants

After the end of World War II, against the backdrop of rapid industrialisation, there was an active introduction of persistent organic pollutants (POPs) (Jones and de Voogt, 1999). Due to their lower cost compared to natural analogues, these synthetic chemical compounds quickly became widespread in commercial and industrial practice. Their use proved to be effective in industry, as well as in the fight against pests and diseases in agriculture (Guardans, 2024). At the same time, the long-term persistence of POPs in the environment has led to their accumulation in the biosphere, resulting in significant negative consequences for human health and ecosystem functioning (Boulkhessaim et al., 2022).

Persistent organic pollutants have many physical and chemical properties that make them extremely resistant to the environment, giving them the ability to bioaccumulate and travel long distances.

The key characteristics of these compounds are resistance to chemical, biological and photochemical degradation, as well as pronounced lipophilicity, which contributes to their accumulation in the fatty tissues of living organisms. In addition, POPs are capable of migrating through air and water currents, leading to their spread far beyond the sources of emission. Even in extremely low concentrations, these compounds pose a serious threat as they can cause cancer, disrupt the nervous and immune systems, and negatively affect reproductive and hormonal regulation, making them extremely dangerous to both ecosystems and the human body (Mishra et al., 2022).

2.1 Pesticides

Pesticides that enter water bodies, even in small concentrations, can accumulate in aquatic organisms and enter the human body through the food chain, posing health risks because once they enter the human body, they can mimic the action of hormones, which in turn leads to hormonal imbalance and reduced immunity, causes reproductive problems, has a carcinogenic effect and reduces intelligence, especially in children who are in the stage of physical development (Wolfram et al., 2019, Syafrudin et al., 2021).

2.2 PFAS

Per- and polyfluoroalkyl substances (PFAS) are a large group of synthetic fluorinated aliphatic compounds. Their processing products have oleophobic, hydrophobic and heat-resistant properties due to strong carbon-fluorine (C-F) bonds (O'Hagan, 2008). They are used in many consumer and industrial products and are used by many brands, such as Teflon and Gore-Tex. PFAS contamination, due to their persistence and potential toxicological harm, has been detected in many water bodies around the world, including wastewater treatment plants, surface and groundwater, and even drinking water systems (Mukhopadhyay et al., 2022).

2.3 Dyes

One of the most common water pollutants are dyes, the main ones being methylene blue, rhodamine B (RhB), methyl orange, methyl red and others. The main sources of pollution are various industries, such as textiles, cosmetics, leather, food, and paints and varnishes (Benkhaya et al., 2020, Kyrii et al., 2020).

The direct discharge of untreated wastewater containing dyes into natural water bodies has a negative impact on photosynthetic activity in aquatic ecosystems and a mutagenic and teratogenic effect on aquatic organisms and fish due to the presence of metals and aromatic compounds. In addition, dyes have carcinogenic, allergic and dermatological effects on the human body (Lellis et al., 2019).

2.4 Pharmaceuticals

In recent decades, there has been a significant increase in the production and use of pharmaceuticals, especially during the pandemic, which has led to a rapid increase in the concentration of pharmaceutical compounds in wastewater (Hejna et al., 2022). The main sources of pharmaceutical compounds in aquatic environments, especially during the COVID-19 pandemic, were hospitals and pharmaceutical factories, improper disposal of medicines, and inadequate management of pharmaceuticals (Hejna et al., 2022).

Hazardous substances such as solvents, active pharmaceutical ingredients, metabolites, infectious agents, and heavy metals contained in hospital wastewater can persist in the environment for a long time, posing a significant threat to the ecosystem due to their stability and high mobility in the liquid phase (Ajala et al., 2022).

3. Comparison of the use of traditional reagents (sorbents, catalysts) and functional coatings

Traditional approaches to removing POPs from water involve the use of bulk sorbents (in particular, granulated activated carbon or its modifications (Kyrii et al., 2018; Kyrii et al., 2023) ion resins, etc.) or chemical catalyst reagents (Dontsova et al., 2022; Kyrii et al., 2021) in suspension. Such methods have certain disadvantages: low selectivity, slow kinetics, and the formation of secondary waste that requires disposal.

To avoid the disadvantages of bulk materials, functional coatings on the surface of carriers are increasingly being used today, which act as sorbents or catalysts without adding bulk phases to the water. Such coatings are fixed on a solid substrate (e.g., a membrane or monolith), ensuring a stationary location of the active material in the water flow. This causes a change in the hydrodynamics of the process: instead of water flowing through a layer of granular material, which creates a significant pressure drop, the water comes into contact with a flat or porous surface covered with a functional layer.

Loose layers typically create higher hydraulic resistance, which increases with decreasing particle size and increasing flow velocity. Coatings on carriers provide channeled/ordered flow trajectories, so hydrodynamic pressure is often significantly lower than with bulk reagents, which is one of the advantages of using functional coatings (Kapteijn & Moulijn, 2020).

In addition, loose catalysts/sorbents have a large active surface area, but create problems with material carryover for filtration and regeneration. Coatings solve the problem of retaining material in the module, but require a well-designed layer architecture. This is because an excessively thick/dense layer can cause diffusion limitations and reduce apparent activity compared to bulk reagents (Xu et al., 2025).

Coatings on structured carriers can be integrated into cartridge/membrane modules, where multifunctional configurations can be implemented, with controlled flow channels and predictable hydrodynamic pressure (Xu et al., 2025), as well as regeneration without dismantling and removing material directly in the module (in-situ) (Stampi-Bombelli et al., 2024). For example, a photocatalytic coating on a membrane can be periodically irradiated with ultraviolet light, oxidising adsorbed contaminants and restoring sorption capacity without stopping the filtration process. In contrast, depleted granular sorbents need to be removed from the filter, thermally or chemically regenerated separately, and reloaded, which complicates the operation of treatment facilities.

Therefore, functional coatings are now considered an attractive alternative to bulk materials in technologies for the post-treatment of water from POPs.

4. Overview of the current state of functional coatings and carriers

Functional coatings are thin surface layers specially designed to give materials specific functions that are not present in the original substrate. They can protect surfaces, regulate interactions with the environment (adsorption, catalysis, antifouling), improve service life and increase efficiency in technical applications (Wang et al., 2026; Akbarzadeh et al., 2019).

4.1 Adsorption functional coatings

Adsorption functional coatings are thin immobilised layers of materials that selectively bind and retain contaminants from the liquid phase by adsorption.

Currently, various adsorption materials are being developed and researched, which are applied in a thin layer to the surface of carriers (membranes, filters, granules), ensuring effective removal of POPs. These include MXene, layered double hydroxides (LDH), metal-organic frameworks (MOF) and covalent organic frameworks (COF), nitrogen-containing porous carbon sorbents, and ion-imprinted polymers (Table 4.1).

4.1.1 MXene coating

MXene is a class of two-dimensional inorganic materials (Fig. 4.1) consisting of transition metal carbides, nitrides or carbonitrides with the general formula $M_{n+1}X_nT_x$, where M is an early transition metal (Ti, V, Nb, Mo, etc.), X is C or N, and T_x are functional groups (e.g., –OH, –O, –F) formed during synthesis from the MAX-phase precursor by selective etching of the A-element layers (Jose et al., 2025). This composition gives MXene unique properties – large surface area, hydrophilicity, high electrical conductivity. It also allows for fine tuning of surface chemistry for sorption purposes (Jose et al., 2025) (Table 2).

MXene coatings perform well as adsorbents of organic and inorganic pollutants (Dehghani et al., 2024). They effectively remove heavy metals and various organic compounds, including dyes and pharmaceutical micropollutants (tetracycline, rifampicin, amoxicillin) due to their high active surface area and large number of functional groups that promote physical and chemical interactions with pollutants (Hadi Dehghani et al., 2024). For example, the adsorption capacity of MXene for some heavy metals reaches 100–250 mg/g, and organic dyes and drugs are also effectively removed due to specific interactions (π–π stacking, hydrogen bonds) (Hadi Dehghani et al., 2024).

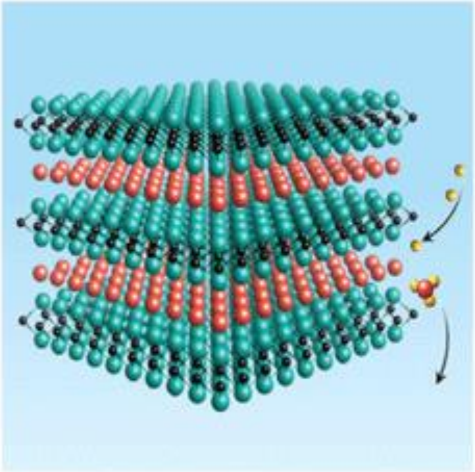

***Fig. 4.1** – MXene structure (Hong et al., 2020)*

The structure of MXene can be modified by making single-layer or multi-layer sheets that can be integrated into composites or membranes to create functional coatings on substrates. This approach will allow, for example, the adsorption advantages of MXene to be combined with membrane filtration (Bhuyan et al., 2025).

4.1.2 LDH coatings

Layered double hydroxides are a class of two-dimensional anionic clays with the general formula $[M^{2+}{}_{1-x}M^{3+}{}_x(OH)_2]^{n+}\cdot(A^{n-})^{x/n}\cdot mH_2O$, where M^{2+} and M^{3+} are divalent and trivalent cations (e.g., Mg^{2+}, Zn^{2+}, Al^{3+}, Fe^{3+}), and A^{n-} are interlayer anions (CO_3^{2-}, NO_3^-) (Fu et al., 2023). This structure provides LDH with high anion exchange capacity and an adaptive surface. Due to their layered morphology and interlayer exchange capacity, LDH materials can capture both heavy metal ions (Pb^{2+}, Cd^{2+})

and organic pollutants (dyes, pharmaceuticals) through electrostatic interactions, ion exchange and complex formation (Fig. 4.20 (Pan et al., 2025).

Fig. 4.2 *– Areas of application of LDH materials in water treatment (Pan et al., 2025)*

By changing the composition of cations (M^{2+} /M^{3+}) and the type of interlayer anions, the material can be adapted to target groups of pollutants in water, allowing for the regulation of sorption selectivity (Hadnadjev-Kostic et al., 2025).

4.1.3 Metal-organic and covalent frameworks (MOF/COF)

Metal-organic frameworks (MOFs) are classes of porous crystalline hybrid materials in which metal nodes are connected via organic ligands, forming a three-dimensional or two-dimensional porous structure with a large surface area (Fig. 4.3) (Gao et al., 2024).

Covalent organic frameworks (COFs) are crystalline porous polymers consisting of organic blocks linked together by covalent bonds (Cote, 2005). Unlike MOFs, COFs consist of light elements (O, N, C, B) with extended structures (Cote, 2005).

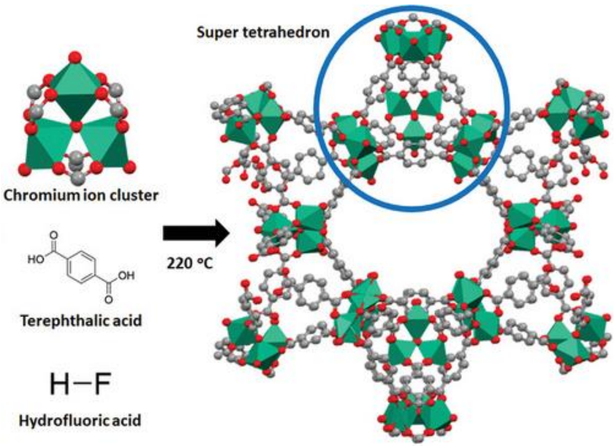

Fig. 4.3 *– Structure of a Cr-based metal-organic framework (Gao et al., 2024).*

Such materials have a large specific surface area with the possibility of controlling the size and shape of the pores, which allows selective capture of molecules of certain pollutants (Cote, 2005).

MOF coatings on membranes significantly increase their ability to remove a wide range of pollutants, including pharmaceuticals, dyes, heavy metals, and other organic micropollutants, due to their high surface area and numerous active sites. MOF structures can also increase membrane water permeability and reduce fouling due to their specific porosity and interaction with pollutant molecules (Islam et al., 2025).

Similarly, COF coatings perform well in water purification due to their crystalline, porous and functional structure, which allows the creation of selective layered membranes with high adsorption capacity and mechanical stability (Rahbari-Sisakht & Ismail, 2025).

4.1.4 N-doped carbons

N-doped carbon materials are a class of carbon adsorbents in which nitrogen atoms are integrated into the carbon matrix in the form of pyridine-N, pyrrole-N, graphite-N or amine functional groups (Fig. 4.4) (Al-Hajri et al., 2022).

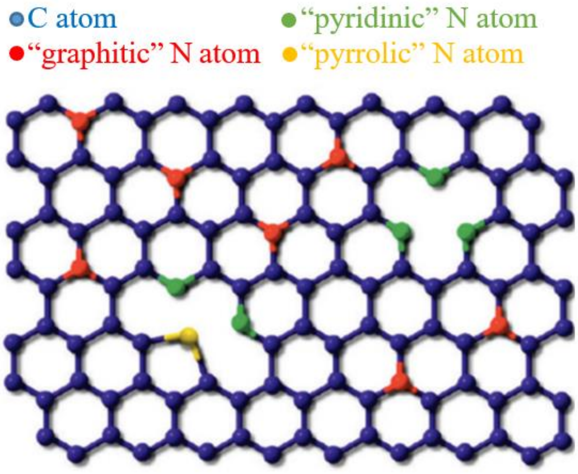

Fig. 4.4 *– Schematic representation of N-doped graphene with different types of nitrogen atoms (Al-Hajri et al., 2022)*

This modification changes the electronic structure and surface chemistry of the material, leading to increased polarity, the appearance of active sorption centres and increased adsorption capacity for organic and inorganic pollutants (Al-Hajri et al., 2022).

Nitrogen-containing functional groups act as active sorption centres that effectively interact with heavy metal ions (Pb^{2+} , Cd^{2+} , Cr^{6+}), as well as enhance π–π interactions with aromatic organic compounds, in particular dyes and pharmaceuticals (Zhang et al., 2022).

4.1.5 Ion-imprinted polymers

Ion-imprinted polymers (IIPs) are a class of functional polymeric materials synthesised in the presence of a target ion template, which, after removal, leaves specific sorption cavities in the polymer matrix that are complementary in size, shape and chemical nature to the corresponding ion (Lazar et al., 2023). complementary in size, shape and chemical nature to the corresponding ion (Lazar et al., 2023).

Ion-imprinted polymers are used for the selective removal of heavy metal ions (Pb^{2+} , Cd^{2+} , Cu^{2+} , Cr^{6+} , Hg^{2+}), where the sorption mechanism is based on a combination of coordination bonds, electrostatic interactions and the "molecular recognition" effect (Lazar et al., 2023).

Surface-printed polymers have faster adsorption kinetics compared to bulk IIPs, as the active centres are located directly on the surface of the layer and are easily accessible to ions in an aqueous environment (Luo et al., 2020).

Table 1 summarises the characteristics of the main types of adsorption materials currently being implemented as coatings for VOC removal.

As can be seen from Table 4.1, none of the materials is ideal, as each has its own optimal areas of application and challenges in implementation. Further research in the field of adsorption coatings may focus on the creation of composite sorbents that combine the advantages of several materials (e.g., MOF on the surface of MXene or graphene, polymer matrices with embedded nanosorbents, etc.). In addition, it is also important to ensure that the adsorbent is firmly fixed to the carrier and prevent it from being washed out in order to fully realise the advantages of coatings over loose sorbents.

4.2 Catalytic functional coatings

Catalytic functional coatings are thin immobilised layers of catalyst materials that accelerate chemical reactions on their surface. They convert pollutants into less harmful substances. Table 2 summarises the main characteristics of catalytic coatings for AOP, including their advantages and typical disadvantages in practical application (Qing et al., 2020).

***Table 4.1**. Strengths and weaknesses of modern adsorption coating materials (Dehghani et al., 2024; Zhu et al., 2020; Dai et al., 2025; Marghade et al., 2024; Naghdi et al., 2022; Nguyen et al., 2024; Wang et al., 2025; X. Wang et al., 2024)*

Adsorption material/reference	**Key properties and advantages**	**Limitations (disadvantages)**
MXene (two-dimensional carbides/nitrides, e.g. Ti_3C_2)/	Large specific surface area and the presence of functional groups provide high adsorption capacity for various pollutants (including dyes and pharmaceutical compounds). High electrical conductivity opens up possibilities for electrochemical regeneration.	Prone to layer restacking, which can reduce the available surface area. Possible oxidisability and uncertainty of environmental risks; requires life cycle assessment.
LDH (layered double hydroxides)/	Positively charged layers effectively bind anionic contaminants; record high PFAS adsorption (1000 times higher than activated carbon in experiments). Fast capture kinetics due to ion exchange; possibility of regeneration and pollutant disposal (thermal destruction of PFAS).	Sensitivity to competitive anions in water (chlorides, sulphates). Limited stability during prolonged contact with water: gradual leaching of layers, decrease in activity without regeneration.
MOF/COF (metal- and covalent-organic frameworks)/	Ultra-high porosity and tuning of pore chemistry for specific molecules; some water-resistant MOFs (UiO-66) effectively remove heavy metals and dyes. COF membranes provide selective removal, e.g. continuous COF films successfully filter out PFAS.	Many MOFs are unstable in water (decomposition, loss of metal ions); expensive synthesis. Difficulty in scaling up COF/MOF-based membrane manufacturing technology; fragility of frameworks without a carrier matrix.
N-doped carbons (carbon adsorbents with heteroatoms)/	Increased adsorption of polar organic molecules due to the formation of polar N-centres and preservation of π-structures; doped CNTs adsorb antibiotics 3–4 times better than pure CNTs. High chemical and thermal stability; possibility of regeneration by calcination without loss of structure.	Lack of selectivity: they absorb a wide range of organic compounds, which can reduce their effectiveness in mixtures of pollutants. Manufacturing requires high-temperature doping; the composition of active centres may vary.
Ion-imprinted polymers (IIP/MIP)/	High selectivity to the target ion/molecule due to specific "imprints" in the polymer; for example, an imprinted polymer selectively removes Pb^{2+} even in the presence of other ions. Reusable: desorption of the target contaminant and restoration of sorption centres.	Usually lower adsorption capacity. Complexity of synthesis: need for a contaminant template, lengthy multi-step polymerisation and template removal process.

4.2.1 Graphite carbon nitride (g-C_3N_4)

Graphite carbon nitride (g-C_3N_4) is a solid polymeric material based on carbon and nitrogen, which has a graphite-like structure with connected triazine (C_3N_3) or tri-c-triazine rings (C_6N_7) (Fig. 4.5) (Ruan et al., 2025).

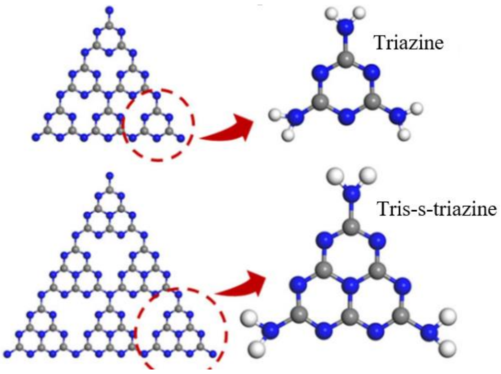

***Fig. 4.5** – Basic structural units of g-C_3N_4 (Ruan et al., 2025)*

Due to this structure, g-C_3N_4 is characterised by significant chemical and thermal stability. As a photocatalytic material, it has a band gap of 2.7 eV and exhibits high sensitivity to the visible part of the light spectrum (Ruan et al., 2025). This makes g-C_3N_4 promising for applications in visible-light photocatalysis. Thus, in a study (Zhong et al., 2021) using model and real wastewater and g-C_3N_4, persistent compounds such as phenols, pesticides and drug residues were successfully decomposed.

Graphite carbon nitride is one of the most important components in modern photocatalytic systems for the degradation of organic pollutants in water. Although the material has natural limitations, such as rapid recombination of photo-generated electron-hole pairs and relatively weak redox properties, these shortcomings can be overcome by modifying the structure and creating hybrid systems (Ruan et al., 2025).

4.2.2 TiO_2/$BiVO_4$/BiOBr-based coatings

Photocatalytic coatings based on TiO_2, $BiVO_4$ and BiOBr are heterostructures that improve the separation of photo-generated electron-hole pairs and extend spectral sensitivity in the visible range (Sun et al., 2025, Dontsova et al., 2020).

The main idea behind such systems is to create heterojoints between different semiconductors, which promotes more efficient charge transfer and reduces carrier recombination, which in turn improves photocatalytic activity under visible light (Sun et al., 2025).

TiO_2/$BiVO_4$ show a significant improvement in the degradation of organic dyes under visible light compared to individual components, due to the efficient transfer of electrons between the conduction band and the valence band of the components and the formation of a type-II heterojunction with aligned Fermi levels (Sun et al., 2025). Electrons excited under visible light in $BiVO_4$ can be transferred to TiO_2, which promotes the separation of charge carriers and enhances the formation of active oxygen radicals ($\cdot O_2^-$), which are directly involved in the destruction of pollutants (Sun et al., 2025).

BiOBr–TiO_2 hybrid nanocomposites demonstrate high activity under visible light due to the synergy between the components: increased active surface area, open mesoporous structure, and optimal arrangement of conduction and valence bands (Wei et al., 2013).

The creation of hetero-bonds between TiO_2, $BiVO_4$ and BiOBr significantly expands spectral sensitivity, reduces charge carrier recombination and promotes the formation of active radicals ($\cdot OH$ and $\cdot O_2^-$), which is crucial for the highly efficient photocatalytic destruction of persistent pollutants in water (Xu et al., 2025).

4.2.3 M–N–C (electro-Fenton)

Electro-Fenton (EF) is an advanced oxidation process (AOP) in which H_2O_2 is produced directly at the cathode (in situ) by electrochemical reduction of oxygen (Nair et al., 2021). H_2O_2 is then activated to form hydroxyl radicals (•OH). This promotes the decomposition of organic pollutants in water. EF has advantages over traditional methods: reduced reagent use, environmental friendliness, and a wide range of applications in water treatment (Nair et al., 2021).

In such systems, M–N–C (Metal–Nitrogen–Carbon) catalysts, where metal atoms are dispersed in a carbon matrix with coordinated nitrogen atoms, act as active centres for the selective electrochemical reduction of oxygen and the formation of H_2O_2 (Zhang et al., 2020). Structurally, M–N–C catalysts are usually single-atom metal centres in an N-doped carbon matrix. This structure allows for maximum metal utilisation and creates well-defined catalytic centres. They significantly influence the electronic structure and catalytic activity (Zhang et al., 2020).

4.2.4 Perovskites

Perovskites are a class of crystalline materials with an adaptive structure. The general formula is ABX_3. A is a monovalent cation (alkaline earth metal or lanthanide), B is a divalent metal cation (typically a transition metal), and X is an anion, most often oxygen in perovskite oxides (Fig. 4.6) (Baray-Calderón et al., 2025).

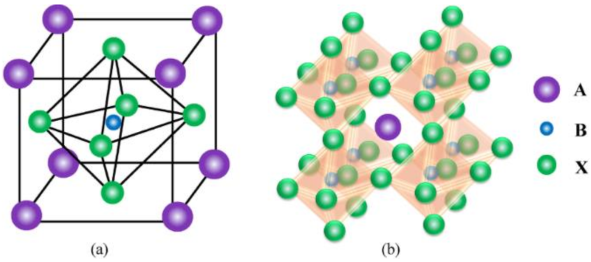

Figure 4.6 *– Perovskite cell ABX_3; b) Schematic representation of the crystal structure of perovskite (Baray-Calderón et al., 2025)*

This structure is characterised by a three-sided network of BX_6 octahedrons. This architecture provides considerable flexibility in changing the composition and rearranging the elements, which makes it possible to more precisely tune the electronic and optical properties of materials to specific needs (Li et al., 2024).

4.3 Antifouling/hydrophilic functional coatings

Antifouling functional coatings are thin surface layers of materials that increase surface wettability and reduce the adhesion of organic, colloidal and biological contaminants by forming a stable hydration layer, which in turn reduces fouling accumulation.

4.3.1 PEG-like layers

Polyethylene glycol (PEG) is a hydrophilic polymer widely used to create coatings with low adhesion of proteins, cells and microorganisms. It forms a thick hydration layer that physically prevents the adsorption of fouling agents on the surface (Fig. 4.7) (Huang & Ghasemi, 2020).

Table 4.2. *Characteristics of the main types of AOP catalysts for functional coatings: strengths/weaknesses (Ruan et al., 2025; Zhong et al., 2021; Sun et al., 2025; Dontsova et al., 2020; Wei et al., 2013; Nair et al., 2021; Zhang et al., 2020; Baray-Calderón et al., 2025; Li et al., 2024)*

Catalytic material/	**Mechanism of action and advantages**	**Limitations (problems)**
g-C_3N_4 (graphite carbon nitride)	Metal-free photocatalyst, active under visible light; provides degradation of micropollutants in real waters under solar irradiation. Stable and reusable; easily immobilised on carriers (membranes, ceramics).	Requires irradiation (solar or artificial); in its pure form, it has moderate quantum efficiency due to charge carrier recombination. Without modifications, it is vulnerable to fouling by organic matter (combination with a hydrophilic layer is necessary).
TiO_2 (titanium dioxide, anatase)	Recognised UV photocatalyst, widely used; chemically inert and non-toxic. Effectively mineralises many organic pollutants; TiO_2 coatings are strong and durable (virtually unlimited catalyst life).	Active only under UV radiation ($\lambda <$ 387 nm), requiring either UV lamps or doping for visible light. – Charge carrier recombination possible if not modified; binding layers often required for application to polymer substrates (which may reduce activity).
$BiVO_4$ (bismuth vanadate)	Visible-sensitive semiconductor; effective in photoelectrocatalysis for the oxidation of trace organic impurities. – Advantages: works under visible light, generates strong oxidants (holes, •OH); $BiVO_4$ heterostructures with sulphites/sulphates enhance radical formation.	Requires a small anode potential or co-catalysts for best performance (photoanode mode). Limited activity in the dark; may partially dissolve under very acidic conditions (Bi losses).
BiOBr (bismuth oxybromide)	Narrow bandgap photocatalyst, active under visible light; capable of rapidly decomposing organic dyes (100% RhB in 10 min). Layered structure promotes efficient charge separation; easily forms nanoheterostructures to increase productivity.	Some decrease in activity due to recombination of charge carriers without doping or combination with other semiconductors. May release halogen (Br^-) during prolonged operation; requires stable fixation on the substrate due to the fragility of the crystals.
M–N–C (metal-nitrogen-carbon, e.g. Fe–N–C)	Catalytic layer on the electrode for electro-Fenton: generates H_2O_2 and radicals *in situ*, destroying pollutants. Does not contain precious metals; active centres (Fe/Co) are atomically dispersed, which ensures high mass activity; activity regeneration is possible by restoring the potential.	Susceptibility to *degradation in an oxidative environment*: during Fenton reactions, destruction of the carbon matrix and loss of active centres is possible. Efficiency depends on the presence of O_2 and optimal pH; requires electrochemical equipment (current source, aeration).
Perovskites (ABO_3 oxides, e.g. $LaFeO_3$, $SrCoO_3$)	Multifunctional oxides with a large number of active centres; capable of catalysing AOP reactions (activation of peroxide compounds, ozone, photocatalysis). Resistant to harsh conditions (high T, strong oxidants); composition can be adjusted for the target process (e.g., $SrCo_{0.7}Ti_{0.3}O_3{-}\delta$ effectively degrades pollutants in alkaline solutions).	Some perovskites require high-temperature synthesis conditions and special equipment for film deposition. Surface contamination with carbonates or organic deposits is possible during prolonged operation; activity is highly dependent on surface cleanliness (antifouling protection is required).

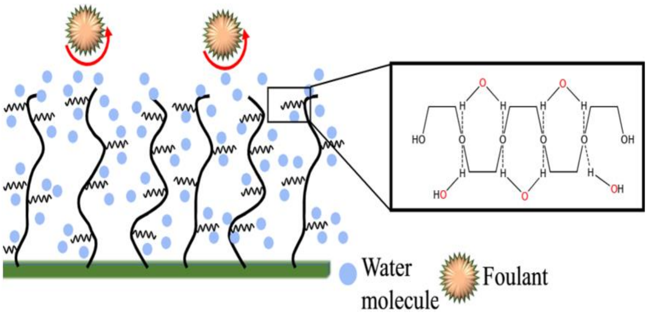

Fig. 4.7 *– Formation of a PEG polymer hydration shell (He et al., 2016)*

Despite its effectiveness when used for short periods, PEG can undergo slow degradation when exposed to oxidants or ultraviolet light. Over time, this can reduce its antifouling properties (Noguer et al., 2016).

4.3.2 Zwitterionic polymers (PSB/PCB)

Polymers whose molecular structure contains both positively and negatively charged groups in each repeating unit are called zwitterionic polymers. Such groups make the macromolecule electrically neutral, hydrophilic and antifouling (Zheng et al., 2017). These polymers can resist protein adsorption, bacterial adhesion and biofilm formation (Zheng et al., 2017).

Zwitterionic polymers contain equal amounts of cations and anions along the polymer chains. Typical cations are ammonium groups, and depending on the anions, a distinction is made between polysulfobetaine (PSB) and polycarboxybetaine (PCB). They have sulfonate and carboxylate anionic groups, respectively (Zheng et al., 2017). Unlike PEG, zwitterionic polymers exhibit better antifouling properties due to their interaction with water through ionic solvation, while the antifouling ability of PEG depends on hydrogen bonding with water (Yue et al., 2013).

Through electrostatic interactions, zwitterionic polymers bind a large number of water molecules and form a strong hydration shell. It acts as a barrier that prevents the contaminant from coming into contact with the surface (Fig. 4.8) (He et al., 2016). This shell is denser than that of PEG and its derivatives because its chains consist of repeating units –CH_2CH_2O–. Each such unit interacts with only one water molecule via hydrogen bonds. The chains of zwitterionic molecules, in turn, can interact with eight water molecules through electrostatic interactions (He et al., 2016).

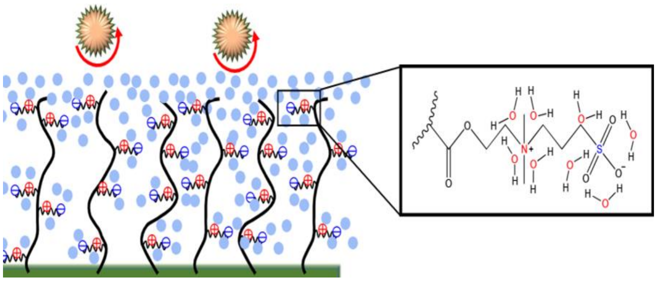

Fig. 4.8 *– Formation of a hydration shell of a zwitterionic polymer (He et al., 2016)*

Due to the hydration shell formed by electrostatic interactions, the dipole arrangement of water molecules is closer to that of free water. Because of this, zwitterionic materials are more biocompatible and better resist biological contaminants than PEG-based polymers (He et al., 2016).

4.4 Carriers and substrates for functional coatings

4.4.1 Ceramic monoliths (αAl_2O_3/SiC)

Ceramic monoliths have an integral matrix with porous channels. Such materials are widely used as catalyst carriers, filter elements, and in reactors where high strength, thermal stability, and controlled porosity are important.

Aluminium oxide (αAl_2O_3) is often used as a ceramic carrier. It is the main crystalline phase of aluminium oxide with high structural hardness and excellent mechanical properties. Silicon carbide (SiC) is a heat-resistant ceramic material that complements α-Al_2O_3due to its corrosion resistance and thermal shock resistance (Portela et al., 2020). The addition of SiC to the α-Al_2O_3matrix strengthens the ceramic structure by inhibiting grain growth and strengthening interphase contacts (Portela et al., 2020).

4.4.2 UF/RO polymer membranes

Ultrafiltration (UF) and reverse osmosis (RO) are membrane processes for separating liquids under pressure. UF uses porous semi-permeable membranes with pore sizes ranging from 0.01 to 0.1μm (Aziz et al., 2024) to separate high-molecular-weight contaminants, colloids, bacteria and viruses from water, while allowing dissolved ions and low-molecular-weight compounds to pass through. RO has a much smaller pore size (0.0001-0.001μm), so it separates even dissolved salts and ions, ensuring almost complete water purification (Aziz et al., 2024).

Most often, polysulfone (PSf) or polyvinylidene fluoride (PVDF) membranes are used for these processes.

PSf is a rigid thermoplastic polymer with high mechanical strength, chemical stability and thermal resistance. PSf tolerates large pressure drops well (Ilyas & Vankelecom, 2025). They are more often flat sheets or hollow fibres wound on a perforated tube.

To improve hydrophilicity and reduce fouling, PSf membranes are modified by adding hydrophilic additives (such as PEG) to the polymer solution before forming (Ilyas & Vankelecom, 2025).

PVDF is a fluorinated polymer with chemical, thermal and mechanical stability, which is also often used in UF membranes. PVDF has natural hydrophobicity, which can lead to greater fouling. This is overcome by modifications or the use of composite materials, such as PVDF/Polypyrrole or PVDF/MOF (Zhang et al., 2024).

4.4.3 Metal/textile frameworks

Metal structural supports are porous, three-dimensional metal forms such as meshes, fibrous structures or metal foams (Fig. 4.9). The latter, in turn, are characterised by high porosity, a large surface area to volume ratio and high mechanical strength (Musavuli et al., 2025).

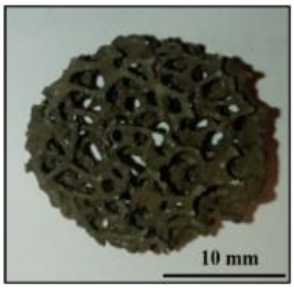

Fig. 4.9 *– Aluminium metal foam (Musavuli et al., 2025)*

Metal fibrous and mesh frames are used in filtration membranes to support thin-film layers or catalyst deposits. Such substrates can be made of steel, aluminium, nickel or their alloys with subsequent surface treatment (Dai et al., 2025).

Textile fibrous materials can also serve as substrates for functional layers (Morshed et al., 2021).

In the context of composite materials, textile fibres can be used as a basis for the formation of MOF-textile composites. Metal structures are combined with textile matrices to create hybrid carriers or structural elements. This enhances mechanical stability with minimal flow resistance (Morshed et al., 2021).

5. Integrated multilayer coatings

Multilayer coatings are structures consisting of several thin layers of materials with different properties stacked on top of each other. An example of such a structure is the alternation of hydrophobic/hydrophilic or organic/inorganic layers to create a multifunctional interface with specified properties (Liu et al., 2022).

Such coatings allow combining the advantages of different components and controlling mechanical, thermal, and functional properties at the layer structure level (Liu et al., 2022). There are periodic and gradient (continuous) architectures.

Periodic architecture has layers of materials A and B that alternate at regular intervals, for example (A/B)n. Such architectures are characterised by layer thickness symmetry and periodicity (Moore & Zhong, 2003).

An example of such architecture is TMN (transition-metal nitride) coating. Ti- and Cr-based coatings are widely used (Liu et al., 2022). These elements serve as an adhesive layer between the multilayer coating and metal substrates. This architecture is often used in PVD coatings for tool steel, where hard materials with different hardnesses or hard phases are alternated to simultaneously increase strength, hardness and wear resistance (Liu et al., 2022).

Gradient multilayer structures do not have clear boundaries between individual components: the composition, hardness or other property changes gradually throughout the thickness of the coating, creating a deep gradient layer. This approach eliminates stress concentrations at the layer boundaries and compensates for thermal and structural differences between the base matrix and the functional layer. Such coatings are used in membrane functional films, where a gradual transition of properties from the substrate to the surface layer is required.

Modern research uses architectures that combine several functions within a single system. For example, mechanically strong base layers → gradient layers → surface functional layers (e.g., antifouling or catalytic) (Maksakova et al., 2024). Compared to monolithic coatings, multilayer architectures demonstrate higher mechanical properties due to their discontinuous structure, which inhibits crack propagation and also adds the possibility of combined functions (Liu et al., 2022).

A typical multilayer architecture of composite membranes can be represented as follows:

1. An antifouling outer layer;
2. Adsorption layer;
3. Catalytic (AOP) active layer;
4. A frame (backing).

One of the main problems in creating multilayer coatings is interfacial adhesion between layers. It determines the durability and stability of the system. Weak adhesion leads to delamination (delamination) and loss of functionality (Viana & Machado, 2009).

To overcome this problem, special adhesive layers can be added between the substrate and the functional coating. This improves the bonding between the layers and prevents them from delaminating under mechanical, thermal or chemical loads (Viana & Machado, 2009). One of the indicators of the strength of the bond between layers is adhesive strength, which is defined as the totality of interatomic and molecular interactions at the boundary between contacting layers. It directly affects the durability and functionality of the entire multilayer system (Viana & Machado, 2009).

To improve the adhesion of polymer and composite coatings, special primers are used to increase the surface energy of the substrate and ensure better spreading and wetting of the functional layers (Rosenkranz et al., 2025). For example, before applying an adsorbent to a polymer membrane, its surface can be coated with an ultrathin layer of polydopamine, a bioadhesive that adheres to almost any surface and has reactive groups for binding particles (Rosenkranz et al., 2025).

In terms of structural features, multilayer coatings are usually designed so that porosity increases with depth: the outer antifouling layer is made as dense as possible, the adsorption layer is more porous, and the inner catalytic layer can even be discrete (islands or nanoparticles) on the surface of the carrier for better reagent flow. The thickness of the layers also plays a role, as an excessively thick antifouling layer can slow down the diffusion of contaminants to the adsorbent, and an excessively thick adsorbent layer can hinder the penetration of radicals from the catalyst. Therefore, finding the optimal ratios is a pressing task. For example, a multilayer coating on porous ceramics may consist of: ~100 nm of hydrophilic polymer on the outside, ~1–5 μm of adsorption layer (MOF or activated carbon) underneath, and ~0.5 μm of nanocatalyst layer (TiO_2 or Fe–N–C) layer on the substrate. In addition, it is also very important to avoid damaging previously applied layers when forming subsequent ones (Lim & Goei, n.d.)

Thus, multilayer integrated coatings are a logical development of the concept of functional coatings, as they allow a single technological solution to solve several problems at once, from removal and decomposition to prevention of fouling for persistent organic pollutants. Although such systems are still in the laboratory research stage, the initial results are very promising, demonstrating that properly designed coatings can maintain high performance over a long period of time without operator intervention (Hassnain et al., 2025).

6. Challenges

Despite the significant progress described above in the practical application of functional coatings in water treatment, a number of challenges remain. The main challenge is fouling and performance degradation over time. The fouling of coatings with various contaminants from water is a major problem for any surface or membrane technology. Organic and biological fouling gradually reduces the efficiency of the active centres of adsorbents and catalysts. For example, due to the inactivation of the catalyst by deposits and a reduction in the photoflux, the activity of photocatalytic membrane reactors decreases (Hassnain et al., 2025). Although anti-fouling layers significantly slow down fouling, it is impossible to avoid it completely, especially during long periods of operation in real waters rich in organic matter.

Another challenge is the stability of functional coatings in an aquatic environment. Although some nanomaterials perform well in pure distilled water, they may be unstable in real-world conditions. For example, MOFs can gradually break down, leading to the release of metals and organic substances into the water. LDH-based adsorbents can leach layered plates, and polymer antifouling agents can hydrolyse or dissolve. The leaching of active components reduces the quality of the coating and increases the risk of secondary contamination. For example, a study (Kajau et al., 2021) showed that during long-term filtration, nanocomposite membranes with CuO particles gradually lost CuO. This led to a decrease in the antibacterial effect of the membrane and the appearance of Cu ions in the permeate. To prevent this, much attention is paid to methods of fixing nanomaterials. These methods include chemical bonding, encapsulation of particles in stable matrices, and the application of protective outer layers. However, achieving a balance between strong fixation and accessibility of active centres can be a difficult task. The stability of coatings also depends on the stability of the carrier itself. Oxidants can destroy polymer carriers and cause swelling, for example, if H_2O_2 or radicals are created in the coating.

An equally critical challenge is the scalability of production and the reproducibility of results. Many promising coatings perform well in laboratory samples but cannot be scaled up to industrial levels. The development of new technologies, such as roll coating or 3D printing, is necessary for applying multilayer structures to membranes or the inner surfaces of modules. Currently, most of the work is done using multi-step manual operations on samples measuring a few square centimetres. Without automation, it is impossible to transfer this to square metres of industrial membranes. Existing coating preparation methods, such as aging, multi-step syntheses, washing and others, are the most labour-intensive and time-consuming (Chisăliţă et al., 2024). Simplifying and accelerating the application processes is necessary for large-scale implementation. Examples of this include self-assembly methods that can be implemented in a flow-through manner, or 3D printing of structured sorbents directly onto the substrate. Reproducibility of properties is also crucial, as coatings obtained from different batches must be identical in thickness, composition and activity. This requires continuous quality control at every stage, as well as an understanding of how changes in synthesis conditions affect the final result. Introducing new coatings to the market is risky without a detailed technical and economic analysis that takes into account the cost of materials, resources, coating life, etc. (Chisăliţă et al., 2024).

Regeneration and restoration of the activity of functional coatings is also a separate and significant challenge. Although many coatings can theoretically be regenerated in situ, in practice this is also difficult to achieve. Adsorption coatings require desorption of accumulated pollutants over time. The use of chemical regenerants, such as NaOH solution, can damage the layer or substrate. To prevent this, gentle regeneration methods are being investigated, such as hot water washing, short-term temperature elevation (e.g., heating carbon coatings with electricity to burn off organic matter), electro-regeneration (e.g., changing polarity to desorb ions), and others (Ersan et al., 2023).Catalyst coatings face the problem of gradual poisoning or deactivation of active sites. For example, reaction intermediates can accumulate on the surface of the photocatalyst, leading to a decrease in the number of active sites. It is known that even highly stable catalysts, such as Fe–N–C, lose their activity over time and require regeneration (e.g., by hydrogenation or calcination) (Sabhapathy et al., 2023). Regeneration for combined coatings is even more difficult, as it is necessary to regenerate the sorbent and catalyst without damaging the antifouling layer. One solution may be so-called self-regeneration, where the coating's own operation contributes to its cleaning. For example, a photocatalytic layer can destroy organic fouling during irradiation, or an electrocatalytic layer can produce gas bubbles (H_2, O_2) when switching potentials, which peel off the deposits. New research based on Cu–Al LDH for PFAS has demonstrated the idea of a closed cycle of "capture–decontamination–recovery." Captured PFAS are thermally destroyed on the adsorbent, after which the adsorbent is recovered and can be reused. This demonstrates how the regeneration problem can be solved by combining adsorption and catalytic functions. However, this solution is not yet available for many systems, and regeneration remains a weak point that limits the service life of coatings.

Awareness of the current challenges associated with the use of functional coatings is driving modern research towards the search for more durable materials, the development of methods for protecting and restoring coatings, and the optimisation of system designs to compensate for the inevitable loss of efficiency over time (Hassnain et al., 2025; Chen et al., 2025). Overcoming these barriers is a prerequisite for functional coatings to move from the laboratory level to widespread use in water treatment practice.

6. Conclusions

Functional coatings are a promising alternative to bulk sorbents and catalysts because they allow the active phase to be fixed on structured carriers, reduce the risk of particle carryover, maintain low hydraulic resistance, and simplify integration into modules. Adsorption coatings demonstrate the highest technological readiness for rapid removal of POPs, but their effectiveness in mixed matrices is determined by a compromise between capacity and selectivity, as well as the stability of the material in water and the possibility of repeated regeneration. Catalytic coatings (AOP) provide not only removal but also chemical transformation of pollutants, but require control of the conditions for the formation of active forms (radicals), minimisation of by-products and demonstration of long-term stability in waters with high organic content and ionic background. Antifouling and hydrophilic top layers are critical for the long-term performance of coatings in real waters, as fouling is often the main cause of performance degradation, regardless of the activity of the adsorption or catalytic layer. The most practical development path is multi-layer architectures of "adsorption – AOP – antifouling" on mechanically strong substrates (ceramic monoliths, polymer membranes, metal/textile frames), where the key engineering challenges are adhesion, interlayer compatibility, regeneration without secondary contamination, and standardised comparison protocols.

References

1. Jones, K. C.; de Voogt, P. Persistent organic pollutants (POPs): state of the science. *Environmental Pollution* **1999**, *100* (1-3), 209–221. https://doi.org/10.1016/s0269-7491(99)00098-6

2. Ucar, D.; Sahinkaya, E.; Sabba, F.; Capua, F. D. Biological denitrification for water detoxification: A review. *Chemical Engineering Journal* **2025**, 163799. https://doi.org/10.1016/j.cej.2025.163799

3. Derrouiche, S.; Bourdin, D.; Roche, P.; Houssais, B.; Machinal, C.; Coste, M.; Restivo, J.; Órfão, J. J. M.; Pereira, M. F. R.; Marco, Y.; Garcia-Bordeje, E. Process design for wastewater treatment: catalytic ozonation of organic pollutants. *Water Science and Technology* **2013**, *68* (6), 1377–1383. https://doi.org/10.2166/wst.2013.384

4. Kyrii, S. O.; Kosogina, I. V.; Astrelin, I. M.; Kyrienko, O. U. The efficiency of coagulation treatment wastewater by reagent obtained from waste alumina production. *Research Bulletin of the*

National Technical University of Ukraine "Kyiv Polytechnic Institute" **2015** (6), 95–101. https://doi.org/10.20535/1810-0546.2015.6.51173

5. Kyrii, S. O.; Kosogina, I. V.; Astrelin, I. M.; Mosiyuk, V. Y. Utilization of "red mud" being a part of new effective adsorbent in water treatment. *Water and water purification technologies. Scientific and technical news* **2017**, 21 (1), 3–11. https://doi.org/10.20535/2218-93002112017121418

6. Mahdi, M. M.; Ebrahim, S. E. A Review of BiOBr-Based Photocatalysts for Wastewater Treatment. *International Journal of Heat and Technology* **2024**, *42* (1), 219–237. https://doi.org/10.18280/ijht.420123

7. Guardans, R. Global monitoring of persistent organic pollutants (POPs) in biota, water and sediments: its role in screening for unregulated POPs, in compiling time trends of regulated POPs under the Stockholm Convention (SC) and their relevance for biodiversity in a changing climate. *Environmental Science: Advances* **2024**. https://doi.org/10.1039/d4va00023d

8. Boulkhessaim, S.; Gacem, A.; Khan, S. H.; Amari, A.; Yadav, V. K.; Harharah, H. N.; Elkhaleefa, A. M.; Yadav, K. K.; Rather, S.-u.; Ahn, H.-J.; Jeon, B.-H. Emerging Trends in the Remediation of Persistent Organic Pollutants Using Nanomaterials and Related Processes: A Review. *Nanomaterials* **2022**, *12* (13), 2148. https://doi.org/10.3390/nano12132148

9. Mishra, A.; Kumari, M.; Swati; Kumar, R.; Iqbal, K.; Thakur, I. S. Persistent organic pollutants in the environment: Risk assessment, hazards, and mitigation strategies. *Bioresource Technology Reports* **2022**, 101143. https://doi.org/10.1016/j.biteb.2022.101143

10. Syafrudin, M.; Kristanti, R. A.; Yuniarto, A.; Hadibarata, T.; Rhee, J.; Al-onazi, W. A.; Algarni, T. S.; Almarri, A. H.; Al-Mohaimeed, A. M. Pesticides in Drinking Water—A Review. *International Journal of Environmental Research and Public Health* **2021**, *18* (2), 468. https://doi.org/10.3390/ijerph18020468

11. Wolfram, J.; Stehle, S.; Bub, S.; Petschick, L. L.; Schulz, R. Insecticide Risk in US Surface Waters: Drivers and Spatiotemporal Modelling. *Environmental Science & Technology* **2019** *53*(20), 12071–12080. https://doi.org/10.1021/acs.est.9b04285

12. O'Hagan, D. Understanding organofluorine chemistry. An introduction to the C–F bond. *Chem. Soc. Rev.* **2008**, *37* (2), 308–319. https://doi.org/10.1039/b711844a

13. Mukhopadhyay, A.; Duttagupta, S.; Mukherjee, A. Emerging organic contaminants in global community drinking water sources and supply: A review of occurrence, processes and remediation. *Journal of Environmental Chemical Engineering* **2022**, *10* (3), 107560. https://doi.org/10.1016/j.jece.2022.107560

14. Benkhaya, S.; M' rabet, S.; El Harfi, A. A review on classifications, recent synthesis and applications of textile dyes. *Inorganic Chemistry Communications* **2020**, *115*, 107891. https://doi.org/10.1016/j.inoche.2020.107891

15. Kyrii, S.; Dontsova, T.; Kosogina, I.; Astrelin, I.; Klymenko, N.; Nechyporuk, D. Local Wastewater Treatment by Effective Coagulants Based on Wastes. *Journal of Ecological Engineering* **2020**, *21* (5), 34–41. https://doi.org/10.12911/22998993/122184

16. Lellis, B.; Fávaro-Polonio, C. Z.; Pamphile, J. A.; Polonio, J. C. Effects of textile dyes on health and the environment and bioremediation potential of living organisms. *Biotechnology Research and Innovation* **2019**, *3* (2), 275–290. https://doi.org/10.1016/j.biori.2019.09.001

17. Hejna, M.; Kapuścińska, D.; Aksmann, A. Pharmaceuticals in the Aquatic Environment: A Review on Eco-Toxicology and the Remediation Potential of Algae. *International Journal of Environmental Research and Public Health* **2022**, *19* (13), 7717. https://doi.org/10.3390/ijerph19137717

18. Ajala, O. J.; Tijani, J. O.; Salau, R. B.; Abdulkareem, A. S.; Aremu, O. S. A review of emerging micro-pollutants in hospital wastewater: Environmental fate and remediation options. *Results in Engineering* **2022**, 100671. https://doi.org/10.1016/j.rineng.2022.100671

19. Kyrii S.O.; Kosogina, I.V.; Astrelin, I.M.; Obodenko, L.S. Investigation of activated carbon modified by wastes from alumina production. *Questions of Chemistry and Chemical Technology* **2018**, *2*, 70-78.

20. Kyrii, S.; Maletskyi, Z.; Klymenko, N.; Ratnaweera, H.; Mitchenko, T.; Dontsova, T.; Kosogina, I. Impact of modification by red mud components on the sorption properties of activated carbon. *Applied Surface Science Advances* **2023**, *16*, 100412. https://doi.org/10.1016/j.apsadv.2023.100412

21. Dontsova, T.; Kyrii, S.; Yanushevska, O.; Suprunchuk, V.; Kosogina, I. Physicochemical properties of TIO_2, ZrO_2, Fe_3O_4 nanocrystalline

adsorbents and photocatalysts. *Chemical Papers* **2022**. https://doi.org/10.1007/s11696-022-02433-4

22. Kyrii, S.; Dontsova, T.; Kosogina, I.; Podopryhor, V.; Serhiienko, A. Influence of yttrium and niobium oxides modifiers on physicochemical and photocatalytic properties of titanium (IV) oxide. *Eastern-European Journal of Enterprise Technologies* **2021**, *4* (6(112)), 67–74. https://doi.org/10.15587/1729-4061.2021.238347

23. Kapteijn, F.; Moulijn, J. A. Structured catalysts and reactors – Perspectives for demanding applications. *Catalysis Today* **2020**. https://doi.org/10.1016/j.cattod.2020.09.026

24. Xu, R.; Qin, S.; Lu, T.; Wang, S.; Chen, J.; He, Z. Engineering Photocatalytic Membrane Reactors for Sustainable Energy and Environmental Applications. *Catalysts* **2025**, *15* (10), 947. https://doi.org/10.3390/catal15100947

25. Stampi-Bombelli, V.; Storione, A.; Grossmann, Q.; Mazzotti, M. On Comparing Packed Beds and Monoliths for CO_2 Capture from Air Through Experiments, Theory, and Modeling. *Industrial & Engineering Chemistry Research* **2024**. https://doi.org/10.1021/acs.iecr.4c01392

26. Wang, Y.-J.; Senthil Raja, D.; Nguyen, K. N.; Tsai, D.-H. Tailored functional coatings on metal surface using silane-nanoparticle composite colloid. *International Journal of Adhesion and Adhesives* **2026**, *145*, 104224. https://doi.org/10.1016/j.ijadhadh.2025.104224

27. Akbarzadeh, S.; Naderi, R.; Mahdavian, M. Fabrication of a highly protective silane composite coating with limited water uptake utilizing functionalized carbon nano-tubes. *Composites Part B: Engineering* **2019**, *175*, 107109. https://doi.org/10.1016/j.compositesb.2019.107109

28. Antony Jose, S.; Price, J.; Lopez, J.; Perez-Perez, E.; Menezes, P. L. Advances in MXene Materials: Fabrication, Properties, and Applications. *Materials* **2025**, *18* (21), 4894. https://doi.org/10.3390/ma18214894

29. Hong, W.; Wyatt, B. C.; Nemani, S. K.; Anasori, B. Double transition-metal MXenes: Atomistic design of two-dimensional carbides and nitrides. *MRS Bulletin* **2020**, *45* (10), 850–861. https://doi.org/10.1557/mrs.2020.251

30. Hadi Dehghani, M.; Hussain Solangi, N.; Mujawar Mubarak, N.; Rajamohan, N.; Bosua, S.; Othmani, A.; Ahmaruzzaman, M.; Ranjan Mishra, S.; Bhattacharjee, B.; Gadore, V.; Hussain Banglani, T.; Waris, N.; hyder, A.; Ali Memon, A.; Hussain Thebo, K.; Joshi, P.; Boczkaj, G.; Rao Karri, R. Mxene-based materials as adsorbents, photocatalysts, membranes and sensors for detection and removal of emerging and gaseous pollutants: A comprehensive review. *Arabian Journal of Chemistry* **2024**, 106052. https://doi.org/10.1016/j.arabjc.2024.106052

31. Chinmoy, B.; Prarthana, B.; Swapnali, H. MXenes in membrane engineering: Unlocking the new potential for water treatment. *Water Supply* **2025**; *25* (8): 1209–1234. https://doi.org/10.2166/ws.2025.072

32. Fu, Y.; Fu, X.; Song, W.; Li, Y.; Li, X.; Yan, L. Recent Progress of Layered Double Hydroxide-Based Materials in Wastewater Treatment. *Materials* **2023**, *16* (16), 5723. https://doi.org/10.3390/ma16165723

33. Pan, Y.; Li, L.; Liu, D.; Wang, F.; Xia, M.; Wang, F. Macroscale structures of layered double hydroxides: A review of formation strategies and applications in water treatment. *Journal of Environmental Chemical Engineering* **2025**, *13* (1), 115284. https://doi.org/10.1016/j.jece.2024.115284

34. Hadnadjev-Kostic, M.; Vulic, T.; Karanovic, D.; Tomic, A.; Cvetkovic, D. Layered Double Hydroxide-Based Materials for Wastewater Treatment: Recent Progress in Multifunctional Environmental Applications. *Processes* **2025**, *13* (12), 3757. https://doi.org/10.3390/pr13123757

35. Gao, P.; Mukherjee, S.; Zahid Hussain, M.; Ye, S.; Wang, X.; Li, W.; Cao, R.; Elsner, M.; Fischer, R. A. Porphyrin-based MOFs for sensing environmental pollutants. *Chemical Engineering Journal* **2024**, *492*, 152377. https://doi.org/10.1016/j.cej.2024.152377

36. Cote, A. P. Porous, Crystalline, Covalent Organic Frameworks. *Science* **2005**, *310* (5751), 1166–1170. https://doi.org/10.1126/science.1120411

37. Islam, I. U.; Hu, X.; Shang, J.; Ashraf, M. A.; Ali, T.; Aslam, A. A.; Li, S.; Li, D.; Nazir, M. S.; Wang, X.; Yabalak, E. MOF and MOF-based membranes: promising solutions for pharmaceutical wastewater treatment. *Journal of Materials Science* **2025**. https://doi.org/10.1007/s10853-025-10659-2

38. Rahbari-Sisakht, M.; Ismail, A. F. Covalent organic framework membranes for water purification: Current status and future research directions. *Separation and Purification Technology* **2025**, *359*, 130759. https://doi.org/10.1016/j.seppur.2024.130759

39. Al-Hajri, W.; De Luna, Y.; Bensalah, N. Review on recent applications of Nitrogen-Doped

Carbon materials in CO_2 capture and energy conversion and storage. *Energy Technology* **2022**. https://doi.org/10.1002/ente.202200498

40. Zhang, C.; Wang, G.; Gao, Y.; Ma, H.; Dong, X.; Zhang, X. Surface and pore co-functionalized ceramic membrane with nitrogen doped carbon for enhanced water treatment through coupling peroxymonosulfate activation. *Separation and Purification Technology* **2022**, *292*, 120998. https://doi.org/10.1016/j.seppur.2022.120998

41. Lazar, M. M.; Ghiorghita, C.-A.; Dragan, E. S.; Humelnicu, D.; Dinu, M. V. Ion-Imprinted Polymeric Materials for Selective Adsorption of Heavy Metal Ions from Aqueous Solution. *Molecules* **2023**, *28* (6), 2798. https://doi.org/10.3390/molecules28062798

42. Luo, Q.; Zeng, M.; Wang, X.; Huang, H.; Wang, X.; Liu, N.; Huang, X. Glycidol-functionalized macroporous polymer for boron removal from aqueous solution. *Reactive and Functional Polymers* **2020**, *150*, 104543. https://doi.org/10.1016/j.reactfunctpolym.2020.104543

43. Zhu, Z.; Ouyang, S.; Li, P.; Shan, L.; Ma, R.; Zhang, P. Persistent organic pollutants removal via hierarchical flower-like layered double hydroxide: Adsorption behaviors and mechanism investigation. *Applied Clay Science* **2020**, *188*, 105500. https://doi.org/10.1016/j.clay.2020.105500

44. Dai, C.; Wu, X.; Wang, Q.; Bai, Y.; Zhao, D.; Fu, J.; Fu, B.; Ding, H. Layered double hydroxides for efficient treatment of heavy metals and organic pollutants: Recent progress and future perspectives. *Separation and Purification Technology* **2025**, *352*, 128277. https://doi.org/10.1016/j.seppur.2024.128277

45. Marghade, D.; Shelare, S.; Prakash, C.; Soudagar, M. E. M.; Yunus Khan, T. M.; Kalam, M. A. Innovations in Metal-Organic Frameworks (MOFs): Pioneering Adsorption Approaches for Persistent Organic Pollutant (POP) Removal. *Environmental Research* **2024**, 119404. https://doi.org/10.1016/j.envres.2024.119404

46. Naghdi, S.; Shahrestani, M. M.; Zendehbad, M.; Djahaniani, H.; Kazemian, H.; Eder, D. Recent Advances in Application of Metal-Organic Frameworks (MOFs) as Adsorbent and Catalyst in Removal of Persistent Organic Pollutants (POPs). *Journal of Hazardous Materials* **2022**, 130127. https://doi.org/10.1016/j.jhazmat.2022.130127

47. Nguyen, T.-T.; Min, X.; Xia, W.; Qiang, Z.; Khandge, R. S.; Yu, H.-K.; Wang, J.; Wang, Y.; Ma, X. Anionic covalent organic framework membranes for the removal of per- and polyfluoroalkyl substances with enhanced selectivity. *Journal of Membrane Science* **2024**, 122925. https://doi.org/10.1016/j.memsci.2024.122925

48. Wang, T.; Ling, C.; Si, Y.; Li, L.; Xing, B. Fabrication of a graphitic N-doped sp/sp carbon interface in carbon-based materials for efficient removal of antibiotics. *Chemical Engineering Journal* **2025**, *513*, 162770. https://doi.org/10.1016/j.cej.2025.162770

49. Wang, X.; Lyu, H.; Hu, Z.; Shen, B. Application of molecular imprinting for targeted removal of organic contaminants and resistance genes from water: A review. *Journal of Environmental Chemical Engineering* **2024**, *12* (2), 112068. https://doi.org/10.1016/j.jece.2024.112068

50. Qing, W.; Liu, F.; Yao, H.; Sun, S.; Chen, C.; Zhang, W. Functional catalytic membrane development: A review of catalyst coating techniques. *Advances in Colloid and Interface Science* **2020**, *282*, 102207. https://doi.org/10.1016/j.cis.2020.102207

51. Ruan, Y.; Hu, Y.; Cheng, H. Recent Progress in g-C3N4-Based Photocatalysts for Organic Pollutant Degradation: Strategies to Improve Photocatalytic Activity. *Catalysts* **2025**, *15* (2), 148. https://doi.org/10.3390/catal15020148

52. Zhong, J.; Jiang, H.; Wang, Z.; Yu, Z.; Wang, L.; Mueller, J. F.; Guo, J. Efficient photocatalytic destruction of recalcitrant micropollutants using graphitic carbon nitride under simulated sunlight irradiation. *Environmental Science and Ecotechnology* **2021**, *5*, 100079. https://doi.org/10.1016/j.ese.2021.100079

53. Sun, A.; Kong, C.; Wang, J.; Zhou, B.; Chen, H.; Yuan, R.; Bai, Z. Photoelectrocatalytic Degradation of Rhodamine B in the Presence of TiO_2-$BiVO_4$. *Materials* **2025**, *18* (18), 4253. https://doi.org/10.3390/ma18184253

54. Dontsova, T. A.; Kutuzova, A. S.; Bila, K. O.; Kyrii, S. O.; Kosogina, I. V.; Nechyporuk, D. O. Enhanced Photocatalytic Activity of TiO_2/SnO_2 Binary Nanocomposites. *Journal of Nanomaterials* **2020**, 1–13. https://doi.org/10.1155/2020/8349480

55. Wei, X.-X.; Cui, H.; Guo, S.; Zhao, L.; Li, W. Hybrid BiOBr–TiO_2 nanocomposites with high visible light photocatalytic activity for water treatment. *Journal of Hazardous Materials* **2013**, *263*, 650–658. https://doi.org/10.1016/j.jhazmat.2013.10.027

56. Xu, R.; Wang, X.; Wu, N.; Liu, Z.; Di, S.; Zhao, H.; Wang, Z.; Gu, C.; Qi, P. Construction of Z-scheme heterojunction BiOBr/TiO_2 for highly efficient photodegradation of sodium pentachlorophenate under visible light. *SSRN* **2025**. http://dx.doi.org/10.2139/ssrn.5717607

57. Nair, K. M.; Kumaravel, V.; Pillai, S. C. Carbonaceous cathode materials for electro-Fenton technology: Mechanism, kinetics, recent advances, opportunities and challenges. *Chemosphere* **2021**, *269*, 129325. https://doi.org/10.1016/j.chemosphere.2020.129325

58. Zhang, D.; Liu, T.; Yin, K.; Liu, C.; Wei, Y. Selective H2O2 production on N-doped porous carbon from direct carbonization of metal organic frameworks for electro-Fenton mineralization of antibiotics. *Chemical Engineering Journal* **2020**, *383*, 123184. https://doi.org/10.1016/j.cej.2019.123184

59. Baray-Calderón, A.; Aleman-Ramirez, J. L.; Díaz-Cruz, E. B.; Martinez-Alonso, C.; Fuentes-Pérez, M.; Olvera-Vargas, H.; Becerra-Paniagua, D. K. Recent Advances in Perovskite-Based Heterojunction Photocatalysts: Synthesis, Properties, and Applications. *Korean Journal of Chemical Engineering* **2025**. https://doi.org/10.1007/s11814-025-00416-1

60. Li, S.; Wu, H.; Yan, C. Perovskite materials for highly efficient Photo(electro)catalytic water splitting: A mini-review. *Nano Materials Science* **2024**. https://doi.org/10.1016/j.nanoms.2024.05.010

61. Huang, Z.; Ghasemi, H. Hydrophilic polymer-based anti-biofouling coatings: Preparation, mechanism, and durability. *Advances in Colloid and Interface Science* **2020**, *284*, 102264. https://doi.org/10.1016/j.cis.2020.102264

62. He, M.; Gao, K.; Zhou, L.; Jiao, Z.; Wu, M.; Cao, J.; You, X.; Cai, Z.; Su, Y.; Jiang, Z. Zwitterionic materials for antifouling membrane surface construction. *Acta Biomaterialia* **2016**, *40*, 142–152. https://doi.org/10.1016/j.actbio.2016.03.038

63. Camós Noguer, A.; Olsen, S. M.; Hvilsted, S.; Kiil, S. Long-term stability of PEG-based antifouling surfaces in seawater. *Journal of Coatings Technology and Research* **2016**, *13* (4), 567–575. https://doi.org/10.1007/s11998-016-9801-9

64. Zheng, L.; Sundaram, H. S.; Wei, Z.; Li, C.; Yuan, Z. Applications of zwitterionic polymers. *Reactive and Functional Polymers* **2017**, *118*, 51–61. https://doi.org/10.1016/j.reactfunctpolym.2017.07.006

65. Yue, W.-W.; Li, H.-J.; Xiang, T.; Qin, H.; Sun, S.-D.; Zhao, C.-S. Grafting of zwitterion from polysulfone membrane via surface-initiated ATRP with enhanced antifouling property and biocompatibility. *Journal of Membrane Science* **2013**, *446*, 79–91. https://doi.org/10.1016/j.memsci.2013.06.029

66. Portela, R., Marinkovic, J. M., Logemann, M., Schörner, M., Zahrtman, N., Eray, E., Haumann, M., García-Suárez, E. J., Wessling, M., Ávila, P., Riisager, A., & Fehrmann, R. Monolithic SiC supports with tailored hierarchical porosity for molecularly selective membranes and supported liquid-phase catalysis. *Catalysis Today* **2020**. https://doi.org/10.1016/j.cattod.2020.06.045

67. Aziz, S.; Mazhar, A. R.; Ubaid, A.; Shah, S. M. H.; Riaz, Y.; Talha, T.; Jung, D.-W. A comprehensive review of membrane-based water filtration techniques. *Applied Water Science* **2024**, *14* (8). https://doi.org/10.1007/s13201-024-02226-y

68. Ilyas, A.; Vankelecom, I. F. J. Pilot-Scale Polysulfone Ultrafiltration Patterned Membranes: Phase-Inversion Parametric Optimization on a Roll-to-Roll Casting System. *Membranes* **2025**, *15* (8), 228. https://doi.org/10.3390/membranes15080228

69. Zhang, J.; Zhao, W.; Shi, C.; Zhao, L.; Chu, Y.; Ren, Y.; Wang, Q.; Chi, Y.; Zhou, S. A Novel PVDF Ultrafiltration Membrane Modified by C60(OH)n-Ag. *Polymers* **2024**, *16* (23), 3359. https://doi.org/10.3390/polym16233359

70. Musavuli, K. C.; Modisha, P.; Everson, R. C.; Malakhov, A.; Bessarabov, D. Metal Foam as Surface-Extended Catalyst Support Structure for Process Intensification in the Dehydrogenation of Perhydro-Dibenzyltoluene on a Pt/Al_2O_3 Catalyst. *Catalysts* **2025**, *15* (1), 44. https://doi.org/10.3390/catal15010044

71. Dai, J.; Zhuang, Y.; Shah, K. J.; Sun, Y. A Review on the Application of Catalytic Membranes Technology in Water Treatment. *Catalysts* **2025**, *15* (11), 1081. https://doi.org/10.3390/catal15111081

72. Morshed, M. N.; Behary, N.; Bouazizi, N.; Guan, J.; Nierstrasz, V. A. An overview on biocatalysts immobilization on textiles: Preparation, progress and application in wastewater treatment. *Chemosphere* **2021**, *279*, 130481. https://doi.org/10.1016/j.chemosphere.2021.130481

73. Liu, Y.; Yu, S.; Shi, Q.; Ge, X.; Wang, W. Multilayer Coatings for Tribology: A Mini Review. *Nanomaterials* **2022**, *12* (9), 1388.

https://doi.org/10.3390/nano12091388

74. Moore, J. J.; Zhong, D. Advanced Coatings for Structural Materials. *Encyclopedia of Materials: Science and Technology*; Elsevier, 2003; pp 1–12. https://doi.org/10.1016/b0-08-043152-6/01887-8

75. Maksakova, O. V.; Lytovchenko, S. V.; Beresnev, V. M.; Klymenko, S. A.; Horokh, D. V.; Mazilin, B. O.; Kopeykina, M. Y.; Klymenko, S. A; Grudnitski, V. V.; Gluhov, O. V.; Galushkov, R. S. A Review of Vacuum-ARC Multilayer Coatings with High-Strength Characteristics and Adhesive Properties. *East European Journal of Physics* **2024**, (4), 11–24. https://doi.org/10.26565/2312-4334-2024-4-01

76. Viana, R.; Machado, A. R. Influence of adhesion between coating and substrate on the performance of coated HSS twist drills. *Journal of the Brazilian Society of Mechanical Sciences and Engineering* **2009**, *31* (4), 327–332. https://doi.org/10.1590/s1678-58782009000400007

77. Rosenkranz, A.; Soler, M.; Boidi, G.; Ronai, B.; Varga, M.; Pineda, F.; Righi, M. C. Physical and chemical approaches to tailor 2D coating/substrate adhesion - Experimental and theoretical insights. *Advances in Colloid and Interface Science* **2025**, 103631. https://doi.org/10.1016/j.cis.2025.103631

78. Lim, T.-T.; Goei, R. Chapter 5. Combined Photocatalysis–Separation Processes for Water Treatment Using Hybrid Photocatalytic Membrane Reactors. *Energy and Environment Series*; Royal Society of Chemistry: Cambridge, 2016; pp 130–156. https://doi.org/10.1039/9781782627104-00130

79. Hassnain, M.; Ali, A.; Azhar, M. R.; Abutaleb, A.; Mubashir, M. Challenges and Perspectives on Photocatalytic Membrane Reactors for Volatile Organic Compounds Degradation and Nitrogen Oxides Treatment. *Global Challenges* **2025**. https://doi.org/10.1002/gch2.202500035

80. Kajau, A.; Motsa, M.; Mamba, B. B.; Mahlangu, O. Leaching of CuO Nanoparticles from PES Ultrafiltration Membranes. *ACS Omega* **2021**, *6* (47), 31797–31809. https://doi.org/10.1021/acsomega.1c04431

81. Chisăliţă, D.-A.; Boon, J.; Lücking, L. Adsorbent shaping as enabler for intensified pressure swing adsorption (PSA): A critical review. *Separation and Purification Technology* **2024**, 128466. https://doi.org/10.1016/j.seppur.2024.128466

82. Ersan, G.; Cerrón-Calle, G. A.; Ersan, M. S.; Garcia-Segura, S. Opportunities for in situ electro-regeneration of organic contaminant-laden carbonaceous adsorbents. *Water Research* **2023**, *232*, 119718. https://doi.org/10.1016/j.watres.2023.119718

83. Sabhapathy, P.; Raghunath, P.; Sabbah, A.; Shown, I.; Bayikadi, K. S.; Xie, R.; Krishnamoorthy, V.; Lin, M.; Chen, K.; Chen, L. Axial Chlorine Induced Electron Delocalization in Atomically Dispersed FeN_4 Electrocatalyst for Oxygen Reduction Reaction with Improved Hydrogen Peroxide Tolerance. *Small* **2023**. https://doi.org/10.1002/smll.202303598

84. Chen, Y.; Wang, Q.; Hou, L.; Huang, H.; Gao, Z.; Wei, Y. Self-Warning and Self-Repairing Mechanisms in Functional Coatings: A Review. *Exploration* **2025**. https://doi.org/10.1002/exp.20240066

ФУНКЦІОНАЛЬНІ ПОКРИТТЯ ДЛЯ ВИДАЛЕННЯ СТІЙКИХ ОРГАНІЧНИХ ЗАБРУДНЮВАЧІВ У ВОДІ: ОГЛЯД СУЧАСНОГО СТАНУ РОЗВИТКУ

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Стійкі органічні забруднювачі у воді, включаючи поліфторалкільні речовини, пестициди, барвники та фармацевтичні залишки, важко видалити через їх високу хімічну стабільність, рухливість та токсичність. Традиційні підходи, засновані на використанні об'ємних сорбентів або каталізаторів, часто неефективнічерез падіння тиску системи, втрати матеріалу, обмеженої регенерації на місці та складної інтеграції в компактні модульні блоки. У цьому огляді підсумовується сучасний стан функціональних покриттів як іммобілізованих, регенераційних і готових до модульного використання платформ для зменшення стійких органічних забруднювачів. Обговорюються адсорбційні покриття з акцентом на MXenes, шаруватих подвійних гідроксидах, метал-органічних/ковалентних каркасах, N-легованих вуглецях та іонно-імпринтованих полімерах, підкреслюючи компроміси між ємністю, селективністю, стабільністю у воді та шляхами регенерації. Каталітичні покриття для прогресивних процесів окислення розглядаються в системах на основі g-C_3N_4, TiO_2, фотокаталізаторах $BiVO_4$/BiOBr, матеріалах M–N–C для електро-Фентонових процесів та оксидах перовскиту, з акцентом на ефективності генерації радикалів та стабільності в реалістичних водних об'єктах. Антифаулінгові та гідрофільні верхні шари, включаючи полімери типу поліетиленгліколь та цвітеріонні полімери, розглядаються як елементи, що забезпечують довгострокову ефективність за рахунок зменшення органічного та біологічного забруднення. Нарешті, роль носіїв (керамічних монолітів, полімерних ультрафільтраційних/зворотньо-осмотичних мембран та металевих або текстильних каркасів) та багатошарових архітектур аналізується з точки зору адгезії, сумісності між шарами та масштабованого виробництва. Основні невирішені проблеми включають довговічність покриття, стійкість до розшарування, стратегії регенерації, що не створюють вторинних відходів, та гармонізовані показники для порівняння продуктивності в складних водних об'єктах.

Ключові слова: *адсорбційні покриття, антифоулінгові покриття, каталітичні покриття, функціональні покриття, стійкі органічні забруднювачі, очищення води*