Metallurgical and Materials Data 1, no. 1 (2023): 25-31

Publisher: Association of Metallurgical Engineers of Serbia

Metallurgical and Materials Data

www.metall-mater-data.com

# Insights into the application of polyaniline-based composites in environmental engineering

Aleksandar A. Jovanović[1,*], Mladen D. Bugarčić[1], Aleksandar D. Marinković[2], Miroslav D. Sokić[1]

[1] *Institute for Technology of Nuclear and Other Mineral Raw Materials, Bulevar Franš d'Eperea 86, Belgrade, Serbia*
[2] *University of Belgrade, Faculty of Technology and Metallurgy, Karnegijeva 4, Belgrade, Serbia, e-mail: marinko@tmf.bg.ac.rs; ORCID: 0000-0003-3239-5476*

ARTICLE INFORMATION:

https://doi.org/10.56801/MMD1

Received: 13 March 2023
Accepted: 31 March 2023

Type of paper: Review paper

## ABSTRACT

Environmental management demands innovative techniques for its protection and treatment. The essential agreement of the modern world is to overcome every issue in a sustainable way. The two major financial problems in this area are water pollution and material corrosion. Persistent, organic compounds such as pesticides have devastating effects on the water ecosystem. This problem can be solved by applying advanced treatment processes (ATPs) like membrane separation and photocatalysis. Additionally, the corrosion of metal materials needs to be prevented to preserve natural resources and reduce environmental concerns. Therefore, researchers are trying to develop tunable, multifunctional materials with broad applications. Employed materials in these operations must fulfill high criteria, like durability, stability, and chemical and optical activity, to make specified processes efficient and viable. Electroconductive polymers (ECPs) can meet the aforementioned standards. The most used ECP is polyaniline (PANI), due to its catalytic and electrochemical performances. These two properties are beneficial for both water purification and anticorrosion applications. The objectives of the paper are to represent various PANI-based composites utilized in the removal of different classes of pesticides during wastewater treatment by adsorption or photocatalytic degradation. Further corrosion inhibition, utilizing PANI-based inhibitors, will be discussed as well.

*Keywords:* Wastewater Treatment, Polyaniline, Membrane Adsorption, Photodegradation, Corrosion Protection.

## 1. Introduction

Environmental protection represents one of the essential goals of modern society. Mineral source protection, clean drinking water, and public health are merged as demands in sustainable development (Axon & James, 2018). Intending to fulfill them, the discharge of untreated water is unacceptable. As a consequence of the rapid development of new chemicals with unknown or barely known influence on human health and the aquatic environment, the treatment of industrial wastewater is indispensable. Intensive agriculture and plant preservation (Cárceles Rodríguez et al., 2022) have led to the concentration of different types of pesticides in soil, ground, and surface water. Since pesticides are usually harmful, non-biodegradable, and have a tendency to persist and circle in the ecosystem, their contamination of surface waters produces a serious risk (Adabavazeh et al., 2021). Due to the lower selectivity and limited efficiency of conventional treatment plants, the development of new technologies is the main subject of further investigation. Improved materials, like polymer-based composites, can enhance environmental remediation. As a result, applying novel materials and processes to eliminate pollutants is critical.

For the time being, corrosion is mainly kept under control by using organic coatings or paints, which usually contain inhibiting pigments that have detrimental effects on the ecosystem. Since these pigments need to be retained at high concentrations to ensure long-lasting protection, wear and tear together with inevitable deterioration during operation can produce unwanted consequences. Such conditions cause the gradual leaching of the pigments and their byproducts into the environment. Organic compounds known as electroconductive polymers (ECPs) are a great alternative to commercially available products. Fortunately, owing to their reasonable prices, physicochemical properties, ease of synthesis, and commonly non-toxic characteristics ECPs have wide applications in different research fields and are utilized as coatings (Baldissera et al., 2019), solar cells parts, (Hou et al., 2019), corrosion inhibitors (Gvozdenović et al., 2018), actuators (Ismail et al., 2014), energy storage devices (Gojgić et al., 2022) , and more. ECPs possess delocalized π -electrons, which are employed as mobile charge carriers (Nezakati et al., 2018). Therefore, it is not surprising that these materials present a thought-provoking alternative to commercially

---

[*] Corresponding author.
E-mail address: a.jovanovic@itnms.ac.rs (Aleksandar A. Jovanović).

available products. Their constant development has led to applications in the field of environmental protection as well. They can be engaged in processes of adsorption and membrane filtration (Samani & Toghraie, 2019), and photocatalysis (Saha et al., 2020; Sharma et al., 2022). ECPs, as protection agents from corrosion, can be used either alone or as blends, or primers in combination with other organic coatings, and corrosion inhibitors. For now, corrosion is mainly kept under control by using organic coatings or paints, which usually contain inhibiting pigments that have detrimental effects on the ecosystem. Since these pigments need to be retained at high concentrations to ensure long-lasting protection, wear and tear together with inevitable deterioration during operation can produce unwanted consequences. Such conditions cause the gradual leaching of the pigments and their byproducts into the environment. A great alternative can be organic compounds known as electroconductive polymers – ECPs. Fortunately, owing to their reasonable prices, physicochemical properties, ease of synthesis, and commonly non-toxic characteristics, ECPs have wide applications in different research fields and are utilized as coatings (Baldissera et al., 2019), solar cell parts, (Hou et al., 2019), corrosion inhibitors (Gvozdenović et al., 2018), actuators (Ismail et al., 2014), energy storage devices (Gojgić et al., 2022), etc. ECPs possess delocalized $\pi$ -electrons, which are employed as mobile charge carriers (Nezakati et al., 2018). Therefore, it is not surprising that these materials present a thought-provoking alternative to commercially available products. Their constant development has led to applications in the field of environmental protection as well. They can be engaged in processes of adsorption and membrane filtration (Samani & Toghraie, 2019) and photocatalysis (Saha et al., 2020; Sharma et al., 2022). ECPs, as protection agents from corrosion, can be used either alone or as blends, or primers in combination with other organic coatings, and corrosion inhibitors. It was shown that conducting polymers exhibit protective behavior to some extent but are much more efficient when blended with other materials (Armelin et al., 2007; Zhang et al., 2018).

Among all ECPs, special attention is placed on polyaniline (PANI) and its structural modifications. In the available literature, it can be found that these polymer materials, PANI as well as its chemical modifications, are used in different remediation processes with an aim to eliminate and degrade toxic and adverse pollutants from the environment. One of these processes is adsorption. This operation can be explained as an act of accumulation of pollutant compound(s) (adsorbate) on the surface of the so-called adsorbent (Cossu et al., 2018). Depending on the type of interaction between the present pollutant and the surface of the adsorbent, two types of adsorptions are distinguished, physisorption and chemisorption (Berger & Bhown, 2011), and the basic difference between them lies in interactions between the adsorbate and the adsorbent. The adsorption properties of numerous natural and synthetic polymers and their structural modifications are readily determined. Among them, lignin (Popovic et al., 2021), cellulose (Perendija et al., 2020), elderberry pith (Bošnjaković et al., 2022), polyvinylidene fluoride (Zhao et al., 2021), polyaniline (Samadi et al., 2021), chitosan (Saheed et al., 2021), etc., shown great removal capacity for numerous pollutants.

The next process where ECPs are used is photocatalysis. Photocatalysis represents a process of generation of oxidative species because of the interaction between irradiation flux and the surface of the material (Moura & Picão, 2022). Because of its straightforward design, stability, minimal installation costs, and complete transformation of impurities into, mainly, harmless byproducts, heterogenous photocatalysis has seen a fast growth process in recent years. (Madima et al., 2020). The high capacity of photocatalysts to oxidize hazardous contaminants is driven by the generation of holes in their valence bands. Frequently used materials as photocatalysts in the process of photocatalysis are metal oxides, like TiO2 (Armaković et al., 2023), ZnO (Ong et al., 2018), V2O5 (Sajid et al., 2020), WS2 (Yousef et al., 2022), graphene oxide (Sandhu et al., 2020) as mineral materials. On the other hand, polymer-based photocatalysts are developing at a faster rate as a cost-effective material. Therefore, polymers like polyaniline (PANI) (Kausor & Chakrabortty, 2022), polypyrrole (PPy) (Yuan et al., 2019), poly(3,4-ethylene dioxythiophene) (PEDOT) (Ledezma-Espinoza et al., 2022), and polythiophene (PTh) (Ansari et al., 2015) with their structural modifications are mostly applied as ECP materials for this purpose.

This review paper aims to present the extensive application of PANI-based composites in environmental engineering. Special attention will be focused on the research paper that investigates pesticide removal and photodecomposition by PANI-functional composites. The influence of different process parameters and conditions will be examined and discussed. Also, papers where corrosion protection was investigated by exploiting PANI-functionalized materials will be presented. Therefore, the scope of this paper will be focused on representing the PANI-based materials that were employed in the adsorption and photodegradation alongside the application of similar materials into corrosion protection.

## 2. Materials: Polyaniline (PANI)

Due to its highly branched structure, polyaniline (Fig. 1) is one of the ECPs that has received the most research attention (Kumari Jangid et al., 2020). Incredible qualities such as good processability, high conductivity, a large surface area, and chemical stability of the PANI (Ho et al., 2021; Tarawneh et al., 2020; Tran et al., 2022) make it attractive and suitable for environmental applications such as contaminant detection and wastewater treatment. The capacity for transporting electrons through the ECPs structure is very useful for pollutant elimination (Ibanez et al., 2018).

Initiation of artificial polymerization can be realized through various routes, nevertheless, the first step involved is the same for all of them, and it consists of the formation of reactive species that interact with monomers or among themselves, and their product propagates the polymerization process. This rule is true for both addition and condensation polymerization. Aniline polymerization is done through condensation polymerization, where the reactive specimen that initiates polymerization is a radical cation. This radical cation formed via monomer oxidation reacts with a monomer that, after deprotonation and consecutive oxidation, propagates the polymerization until termination occurs. Depending on the monomer oxidation mechanism, PANI synthesis techniques can be classified as follows: chemical, electrochemical, photoinduced, and enzymatic polymerization. The abovementioned approaches have both merits and demerits, whether in terms of ease of scalability, morphology control, polymerization time, or resulting product purity (Nguyen & Yoon, 2016; Singh & Shukla, 2020). Electrochemical and enzymatic synthesis can be classified as environmentally friendly techniques, as there is no need for strong oxidizing agents and reaction conditions are usually milder. In terms of corrosion protection, electrochemical synthesis is extremely appealing, since protective coatings can be directly deposited in their doped form (deposition occurs with simultaneous doping) onto the substrate, as well as modified by the electrodeposition regime (potentiostatic, galvanostatic, potentiodynamic). Morphology can be controlled by varying synthesis parameters. Unfortunately, electrochemical deposition is an anodic process, which can lead to substrate dissolution, although this can be resolved by choosing adequate deposition conditions (i.e., pH, monomer and dopant type and concentration, the composition of the deposition bath, the deposition potential, etc.) (Deshpande et al., 2014). Another difficulty that can occur is substrate passivation, which disables further deposition and leads to non-uniform, highly porous coatings with poor mechanical and protective properties (Gvozdenović et al., 2018).

PANI can occur in three different oxidation forms, such as pernigraniline, leucoemeraldine, and emeraldine (Beygisangchin et al., 2021). By employing a different technique to optimize the parameters, polyaniline's oxidizing potential can be changed (Beygisangchin et al., 2021). The first aniline base is leucoemeraldin (LB) (Fig. 1A), which is

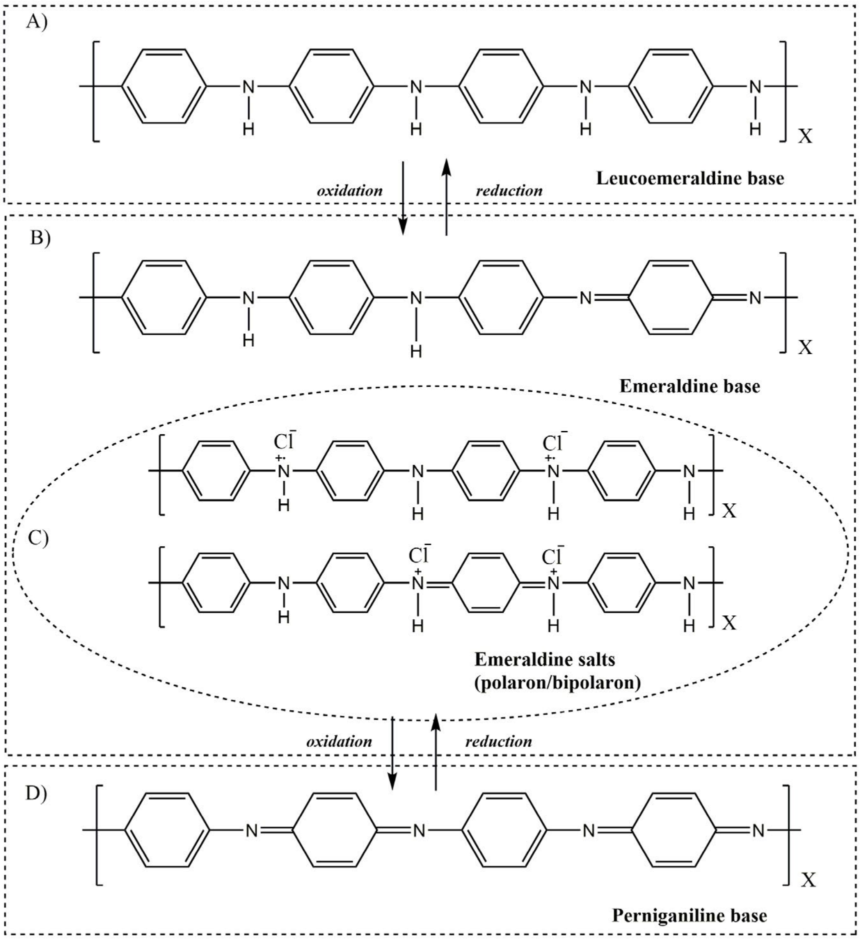

**Fig. 1.** Oxidative states pathways of PANI polymer

in a reduced oxidation state. Even though, leucoemeraldin is unstable and very reactive in atmospheric conditions. The next one is emeraldine (EB) (Fig. 1B), which is partly oxidized and chemically stable. This molecule is the only one that is conductive, besides leucoemeraldine and the fully oxidized perniganiline (PB) (Fig. 1D) (Stejskal & Gilbert, 2002). So, the preparation and synthesis of this polymeric material require careful conditions.

The EB doped with inorganic acid (e.g., hydrochloric acid) or organic acid (e.g., sulfosalicylic acid) is easily converted into an emeraldine salt (ES) form of PANI. ESs possess an increased conductivity due to the protonation of imine nitrogen in the EB by the acid (Fig. 1C) (Yang et al., 2020) et al., 2020). Moreover, the partially oxidated ES form of the PANI is catalytically active compared to LB, and PB and has high electron transfer performance with low $E_g$ due to the formation of the polaron and bipolaron band (Belabed et al., 2013). This formation is due to charge defects created as a result of doping with protonic acid (Kwon & McKee, 2000).

The next chapters will present the application of PANI and its structural modifications in applications of water treatment (adsorption and photocatalysis) and corrosion prevention.

## 3. Utilization of PANI and PANI-modified materials

### 3.1. Adsorption by PANI-based materials

From the literature review, it was found that PANI-based materials were applied for the removal of different classes of pollutants, organic and inorganic ions and anions (Samadi et al., 2021). The most investigated characteristics of fabricated PANI-based adsorbents are structural morphology and textural properties with a determination of the presented functional groups, and the nature of surface interactions with pollutants. PANI-based composites were tested for the removal of chromium (VI), nitrate, cationic dyes, pharmaceuticals, etc.

PANI-based adsorbents are excellent candidates, as PANI has highly reactive adsorption sites (–NH) with enhanced adsorptive properties. Furthermore, PANI has an amphoteric carbonaceous surface with amine and imine functional groups that can be easily protonated (positively charged) or deprotonated (negatively charged) depending on the solution pH. Thus, for the adsorption of the presented cations, suitable pH values are in the range of 5–7. On the other hand, due to the protonation of functional groups at lower pH, a favorable condition for oxyanion removal is achieved (Hlekelele et al., 2019). The biggest problem with PANI is the possible aggregation of molecule chains during preparation, so proper conditions are required. This occurrence can restrict adsorption capacity and selectivity.

Wang et al. (Wang et al., 2009) have done a study where presented Hg(II) ions were removed with PANI fibers. It was observed in both adsorption and complexation during the assays. The determined absorption capacity was considerably high – 600 mg/g. In the study by Karthikeyan et. al. (Karthikeyan et al., 2012), two synthesized composites PANI/montmorillonite and PPy/montmorillonite were investigated in detail. A slightly better selectivity for fluoride ions was shown for PPy/montmorillonite. Further, a composite polypyrrole-polyaniline was applied for the removal of Cr(VI) (Bhaumik et al., 2012), while a sorption capacity of 227 mg/g was reported. It was observed that both ion exchange and reduction were the major mechanisms for the elimination of Cr(VI) from the water solution. The next interesting composite, MnO2-PANI microspheres, was utilized for the removal of Pb(II) ions (C. Cui et al., 2021). The removal rate at atmospheric conditions by this composite was 99.2%. Hsini et. al. (Hsini et al., 2021) described the synthesis of a PANI/WO3 hybrid composite for Cr(VI) removal. At pH = 2, the sorption capacity was 549.37 mg/g, while the rate of removal was 95.13%.

In the study from Janaki et. al. (Janaki et al., 2012), PANI/chitosan composite was thoughtfully synthesized and structurally characterized. The prepared composite showed high efficiency to adsorb dyes congo red, coomassie brilliant blue, and remazol brilliant blue R. Efficiency removal of mentioned dyes was in the range of 95 – 99%. Mu et al. (Mu et al., 2017) prepared graphene/polyaniline and PANI/$Fe_3O_4$ adsorbents and tested them for the removal of congo red dye. Both of them show a similar adsorption capacity of 248.76 mg/g. In the next paper, nanocomposite polyaniline-magnetic graphene oxide (MGO/PANI) was fabricated by Mohammadi Nodeh et al. (Mohammadi Nodeh et al., 2018) and utilized in the removal of ciprofloxacin. It was discovered that the maximal adsorption capacity was 106.38 mg/g at pH = 6. In the next study, Arab et. al. (Aarab et al., 2020) synthesized polyaniline-polypyrrole (PPY-PANi) copolymer as a sorbent for assisted removal of metronidazole from a water solution. This study included varying process parameters, like the initial pH of the solution, temperature, contact time, and initial pollutant concentration. The best result (89.24%) was obtained when 0.40 g/L of the composite was utilized for 10 mg/L. The calculated adsorption capacity of PPY-PANi was 63.34 mg/g. However, the application of these materials for pesticide removal is relatively scarce. In the paper from El-Said et.al. (El-Said et al., 2018) pesticide chlorination was removed from aqueous media by silica/polyaniline composite. The medium adsorption capacity was obtained, which can be explained by the structural robustness of the chosen pollutant. In the other paper from Jevremović et. al. (Jevremović et al., 2019), protonated and deprotonated forms of polyaniline/BEA zeolite composite were synthesized to adsorb nicosulfuron from water samples. Better performance show protonated composite (adsorption capacity in the range 18.4 – 25.4 mg/g), while deprotonated PANI/BEA composites (adsorption capacity in the range 5.5 – 13.0 mg/g). Aziz et. al., (Aziz et al., 2022) reported the synthesis of highly efficient adsorbent Brachychiton populneus shells/polyaniline for the removal of two pesticides thiabendazole and methyl parathion. The composite showed greater affinity toward thiabendazole – 255.39 mg/g than methyl parathion – 78.59 mg/g. In the next study from Ishtiaq et al. (Ishtiaq et al., 2020), the insecticide imidacloprid was removed from the aqueous solution by using a composite peanut husk with PANI. At pH = 3, the sorption capacity was 7.03 mg/g, which could be explained by possible agglomeration of polymer matrixes and blockade of active sites. In the study from Park & Jhung (Park & Jhung, 2020), herbicides atrazine and diuron were removed from water by polyaniline-derived carbons (PDCs). After a detailed investigation, PDCs demonstrated high values of adsorption capacities, 943 and 884 mg/g, for atrazine and diuron, respectively, at pH = 7. For comparison, the sorption capacities of activated carbon were only 123 and 78.0 mg/g, respectively, for atrazine and diuron.

### 3.2. Photocatalytic degradation organic pollutants enhanced by PANI-based photocatalysts

PANI-based photoactive materials have good optical and catalytic properties, just like PANI-functionalized adsorbents. As mentioned earlier, the presence of a polar band in PANI enhances electron mobility. Thus, this fact contributes to the raising of photocatalytic activity (Deb et al., 2016). In addition, PANI can absorb a wide spectral range of radiation, from visible to infrared (Chen et al., 2019). Experimental factors such as solution pH, initial pollutant concentration, catalyst dose, presence of coexisting ions, temperature, radiation source, etc., differently affected photocatalysis pathways boosted by PANI composites. A review of the literature revealed that such materials were used for the degradation of various classes of materials of organic origin.

Saha et. al. (Saha et al., 2020) reported the fabrication of photoactivated PANI nanofibers. The prepared material helped in the decomposition of dyes methylene blue and methyl orange as a photocatalyst under UV irradiation. The following results were obtained: the concentration of methylene blue decreased by 42%, and 97% of methyl orange was degraded after 180 min. In the paper from (Lv et al., 2019), PANI polymer was functionalized with $Sn_3O_4$. To enhance interfacial charge transfer efficiency, presented rhodamine B was degraded (nearly 97%) under visible light after 5 h. It was determined that the maximum degradation efficiency was more than double that in the case of $Sn_3O_4$. Pollutant naproxen was photocatalytically degraded by employing Ag/AgCl–polyaniline under sunlight irradiation (Ghaly et al., 2021). After plenty of tests, the best activity was at pH = 11 with the addition of a 5 g/L catalyst and a 10 mg/L naproxen solution.

In the following study, Ahamad et al. synthesized the nanocomposite g-C3N4/MoS2-PANI (Ahamad et al., 2020) as a photocatalyst to decompose bisphenol-A under visible light irradiation. After 60 minutes, 92.66% of bisphenol-A was degraded. Further, the decomposition of the antibiotic ciprofloxacin was investigated by Vijayalakshmi et al., (Vijayalakshmi et al., 2020). Under UV light, the fabricated PANI/$ZrO_2$ nanocomposite boosted the decomposition of ciprofloxacin after 120 min. Asgari et. al. (Asgari et al., 2019) developed a ZnO/PANI composite and tested its ability to degrade metronidazole under UV and visible light. By monitoring degradation kinetics, it was demonstrated that UV light possesses a better capacity to induce faster decomposition (97%) of target antibiotics than visible light (120 and 150 min, respectively).

The degradation of pesticides by using PANI -based materials was shown in Tab. 1. The prepared materials show different activities for the presented pollutants in aqueous media. Several process parameters, such as pollutant concentration, catalyst dose, irradiation source, etc. were presented. These factors need to be considered when evaluating the capabilities of the different photocatalysts.

Tab. 1 shows that most of the mentioned photocatalysts used for the degradation of pesticides are PANI composites decorated with metal oxides with photocatalytic activity. Their synergistic activity could be evidence of the high degradation of some pesticides. Visible light lamps were mostly used as the irradiation source, suggesting that these materials can be used in environmentally friendly and low-cost water treatment plants.

### 3.3. PANI-based inhibitors

Replacing toxic or expensive inhibitors with some organic compounds represents the desired goal of many scientists. PANI, as a target material in this paper, (Tian et al., 2014; G. Yang et al., 2022), is among the most extensively researched ECPs in corrosion inhibition of ferrous and non-ferrous materials. PANI-based materials can be included in several processes: galvanic protection, ennobling, and passivation (Tallman et al., 2002).

Taheri et al. (Taheri et al., 2018) fabricated the GO-PANI-Zn nanocomposite through a layer-by-layer assembly method and incorporated the composite into epoxy resin. Electrochemical impedance spectroscopy (EIS) and polarization tests proved their effectiveness at preventing corrosion of mild steel samples immersed in the 3.5 wt.% NaCl solutions. $Zn^{2+}$ and PANI demonstrate the synergistic effect and high cation exchange rate.

Currently, protective self-healing coatings containing polyaniline microcapsules are most investigated. Cui et al. (J. Cui et al., 2019) have synthesized PANI/Sodium alginate microcapsules uniformly dispersed in epoxy resin for water distribution pipeline preservation. Corrosion resistance was tested in simulated water-delivery conditions for 50 days and showed high stability, which was confirmed by EIS measurements. A performed scratch test suggested that this coating exhibits rapid self-healing performances since there was no visible knife trace after 12 h upon conducting it. The authors also claim that there were no detectable hazardous substances in the water after coating decay.

Hao et al. (Hao et al., 2020) manufactured PANI-modified graphene containers loaded with benzotriazole, which was incorporated as an inhibitor into the epoxy resin. The release and salt spray tests showed that almost 90% of benzotriazole was released after 4 h, indicating high self-healing quality. Nevertheless, during the adhesion test, modified epoxy resin showed better results than the non-modified one.

Al Jabri et al. (al Jabri et al., 2023) developed thin film coatings based on polyaniline and titanium dioxide for mild steel pipeline protection in the oil industry. Composite films were prepared using the dip technique. The concentration of PANI was kept constant, while the concentration of titanium dioxide was varied. Samples were subjected to different corrosion tests and surface characterization techniques, and it was concluded that the composite films containing 0.5 g of titanium dioxide/PANI exhibit the best corrosion stability.

There are also different PANI/ graphene oxide composites modified by polyurethane system (Xu et al., 2023), and polyvinyl butyral (Li et al., 2021), that claim high corrosion resistance, and high self-healing effect. Recently, polyaniline micro/nano capsules loaded with benzotriazole, and blended with other polymers have been widely studied (Feng et al., 2022; Hao et al., 2019; Zhong et al., 2021), due to the excellent corrosion inhibition properties of benzotriazole on low carbon steel.

## 4. Conclusion

Inadequate treatment of wastewater and the use of toxic corrosion inhibitors are problems that require innovative development and the establishment of new products. As assumed in this paper, PANI -based composites can be a solution to both problems, opening up the possibility of continuous development and improvement in this area. Through the use of innovative chemical or electrochemical techniques for the preparation of photocatalysts, adsorbents, or corrosion inhibitors, materials with exceptional properties can be obtained. PANI can be used in technological areas such as the fabrication of solar cells, coatings, (bio)sensors, batteries, supercapacitors, etc. In addition, structural modifications of PANI with various organic and inorganic compounds have confirmed its effectiveness in wastewater treatment processes, used as adsorbents or photocatalysts to remove and degrade pollutants. The improved properties of PANI-functionalized composites are reflected in their advanced optical, chemical, and morphological properties. Therefore, these materials have the ability to solve problems in the field of material corrosion. As shown, different materials have been treated under different conditions with the addition of PANI-based inhibitors. Some of them, incorporated in different coatings, have self-healing capabilities. The main perspective in the field of environmental science is to reduce and optimize production costs, also by utilizing non-toxic and environmentally friendly materials. Following the principles of circular economy, a new goal has become clear: the design improvement of PANI-based materials with regard to their wider applicability and finding the raw materials that could be refined into such composite materials while taking care of their life cycle assessment.

## Acknowledgment

The authors are truly thankful to Ph.D. student Jelena Gojgić, junior researcher at the Faculty of Technology and Metallurgy for all her ideas and suggestions. Her assistance and corrections improved this paper.

## Funding

This study was financed by the Ministry of Science, Technological Developments and Innovation of the Republic of Serbia (Contract number: 451-03-47/2023-01/200023; 451-03-47/2023-01/200135).

## Literature

Aarab, N., Hsini, A., Essekri, A., Laabd, M., Lakhmiri, R., & Albourine, A. (2020). Removal of an emerging pharmaceutical pollutant (metronidazole) using PPY-PANi copolymer: Kinetics, equilibrium and DFT identification of adsorption mechanism. *Groundwater for Sustainable Development*, *11*. https://doi.org/10.1016/j.gsd.2020.100416

Adabavazeh, H., Saljooqi, A., Shamspur, T., & Mostafavi, A. (2021). Synthesis of polyaniline decorated with ZnO and CoMoO4 nanoparticles for enhanced photocatalytic degradation of imidacloprid pesticide under visible light. *Polyhedron*, *198*, 115058. https://doi.org/10.1016/j.poly.2021.115058

Ahamad, T., Naushad, M., Alzaharani, Y., & Alshehri, S. M. (2020). Photocatalytic degradation of bisphenol-A with g-C3N4/MoS2-PANI nanocomposite: Kinetics, main active species, intermediates and pathways. *Journal of Molecular Liquids*, *311*. https://doi.org/10.1016/j.molliq.2020.113339

al Jabri, H., Devi, M. G., & Al-Shukaili, M. A. (2023). Development of polyaniline – TiO2 nano composite films and its application in corrosion inhibition of oil pipelines. *Journal of the Indian Chemical Society*, *100*(1). https://doi.org/10.1016/j.jics.2022.100826

Anirudhan, T. S., Shainy, F., & Manasa Mohan, A. (2018). Fabrication of zinc oxide nanorod incorporated carboxylic graphene/polyaniline composite and its photocatalytic activity for the effective degradation of diuron from aqueous solutions. *Solar Energy*, *171*, 534–546. https://doi.org/10.1016/j.solener.2018.06.111

Ansari, M. O., Khan, M. M., Ansari, S. A., & Cho, M. H. (2015). Polythiophene nanocomposites for photodegradation applications: Past, present and future. In *Journal of Saudi Chemical Society* (Vol. 19, Issue 5, pp. 494–504). Elsevier B.V. https://doi.org/10.1016/j.jscs.2015.06.004

**Table 1.** Summary of pesticide degradation assisted by PANI-based photocatalysts

| Material | Irradiation source | Pollutant and initial pollutant concentration | Catalyst amount | Efficiency and degradation time | Reference |
|---|---|---|---|---|---|
| PANI/$WO_3$-CdS | visible light irradiation | imidacloprid, 10 ppm | 150 g/L | 94.7%, 180 min | (Merci et al., 2021) |
| PANI/ZnO-$CoMoO_4$ | LED irradiation | imidacloprid, 4.5 ppm | 40 g/L | 97.38%, 180 min | (Adabavazeh et al., 2021) |
| PANI-modified $TiO_2$ | sun irradiation | sulcotrione, 16.4 ppm | 0.5 g/L | 35.0%, 240 min | (Lazarević et al., 2019) |
| $Ag_3PO_4$/polyaniline/g-$C_3N_4$ | Sun irradiation | monocrotophos, 15 ppm | 0.08 g/L | 99.6%, 50 min | (Balasubramanian et al., 2020) |
| $TiO_2$/$Bi_2O_3$/PANI | LED irradiation | triclopyr, 10 ppm | 0.5 g/L | 76.1%, 120 min | (Sharma et al., 2022) |
| CuO/$TiO_2$/PANI | visible light irradiation | chlorpyrifos, 5 ppm | 0.45 g/L | 95.0%, 90 min | (Nekooie et al., 2021) |
| Ag/PANI/$ZnTiO_3$ | visible light irradiation | imidacloprid, 20 ppm | 1.0 g/L | 100.0%, 60 min | (Faisal et al., 2021) |
| PANI: $CoFe_2O_4$/g-CN | visible light irradiation | malathion, 50 ppm | 0.5 g/L | 60.0%, 120 min | (Singh et al., 2022) |
| ZnR/CGR/PANI | solar simulator | diuron, 5 ppm | 20.0 g/L | 100.0%, 40 min | (Anirudhan et al., 2018) |
| PANI/g-$C_3N_4$/$CeO_2$ | UV irradiation | diazinon, 10 ppm | 0.10 g/L | 94.08%, 40 min | (Hussen, 2021) |

Armaković, S. J., Savanović, M. M., & Armaković, S. (2023). Titanium Dioxide as the Most Used Photocatalyst for Water Purification: An Overview. In *Catalysts* (Vol. 13, Issue 1). MDPI. https://doi.org/10.3390/catal13010026

Armelin, E., Oliver, R., Liesa, F., Iribarren, J. I., Estrany, F., & Alemán, C. (2007). Marine paint fomulations: Conducting polymers as anticorrosive additives. *Progress in Organic Coatings*, *59*(1), 46–52. https://doi.org/10.1016/j.porgcoat.2007.01.013

Asgari, E., Esrafili, A., Jafari, A. J., Kalantary, R. R., Nourmoradi, H., & Farzadkia, M. (2019). The comparison of ZnO/polyaniline nanocomposite under UV and visible radiations for decomposition of metronidazole: Degradation rate, mechanism and mineralization. *Process Safety and Environmental Protection*, *128*, 65–76. https://doi.org/10.1016/j.psep.2019.05.050

Axon, S., & James, D. (2018). The UN Sustainable Development Goals: How can sustainable chemistry contribute? A view from the chemical industry. In *Current Opinion in Green and Sustainable Chemistry* (Vol. 13, pp. 140–145). Elsevier B.V. https://doi.org/10.1016/j.cogsc.2018.04.010

Aziz, K., Aziz, F., Mamouni, R., Aziz, L., & Saffaj, N. (2022). Engineering of highly Brachychiton populneus shells@polyaniline bio-sorbent for efficient removal of pesticides from wastewater: Optimization using BBD-RSM approach. *Journal of Molecular Liquids*, *346*. https://doi.org/10.1016/j.molliq.2021.117092

Balasubramanian, J., Ponnaiah, S. K., Periakaruppan, P., & Kamaraj, D. (2020). Accelerated photodeterioration of class I toxic monocrotophos in the presence of one-pot constructed Ag3PO4/polyaniline@g-C3N4 nanocomposite: efficacy in light harvesting. *Environmental Science and Pollution Research*, *27*(2), 2328–2339. https://doi.org/10.1007/s11356-019-06811-6

Baldissera, A. F., Silveira, M. R. D. S., Beraldo, C. H., Tocchetto, N. S., & Ferreira, C. A. (2019). Polymeric organic coatings based on PANI-ES and PANI-ES/APP for fire protection. *Journal of Materials Research and Technology*, *8*(3), 2832–2845. https://doi.org/10.1016/j.jmrt.2019.04.022

Berger, A. H., & Bhown, A. S. (2011). Comparing physisorption and chemisorption solid sorbents for use separating $CO_2$ from flue gas using temperature swing adsorption. *Energy Procedia*, *4*, 562–567. https://doi.org/10.1016/j.egypro.2011.01.089

Beygisangchin, M., Abdul Rashid, S., Shafie, S., Sadrolhosseini, A. R., & Lim, H. N. (2021). Preparations, Properties, and Applications of Polyaniline and Polyaniline Thin Films—A Review. *Polymers*, *13*(12). https://doi.org/10.3390/polym13122003

Bhaumik, M., Maity, A., Srinivasu, V. v., & Onyango, M. S. (2012). Removal of hexavalent chromium from aqueous solution using polypyrrole-polyaniline nanofibers. *Chemical Engineering Journal*, *181–182*, 323–333. https://doi.org/10.1016/j.cej.2011.11.088

Bošnjaković, J. M., Bugarčić, M. D., Čutović, N., Jovanović, A. A., Manasijević, S., Marinković, A. D., & Veličković, Z. S. (2022). ECO-FRIENDLY ELDERBERRY BASED SORBENT FOR REMOVING Pb2+ IONS FROM AQUEOUS SOLUTIONS. *Metallurgical and Materials Engineering*, *28*(2), 391–401. https://doi.org/10.30544/710

Cárceles Rodríguez, B., Durán-Zuazo, V. H., Soriano Rodríguez, M., García-Tejero, I. F., Gálvez Ruiz, B., & Cuadros Tavira, S. (2022). Conservation Agriculture as a Sustainable System for Soil Health: A Review. In *Soil Systems* (Vol. 6, Issue 4). MDPI. https://doi.org/10.3390/soilsystems6040087

Chen, S., Huang, D., Zeng, G., Gong, X., Xue, W., Li, J., Yang, Y., Zhou, C., Li, Z., Yan, X., Li, T., & Zhang, Q. (2019). Modifying delafossite silver ferrite with polyaniline: Visible-light-response Z-scheme heterojunction with charge transfer driven by internal electric field. *Chemical Engineering Journal*, *370*, 1087–1100. https://doi.org/10.1016/j.cej.2019.03.282

Cossu, R., Ehrig, H.-J., & Muntoni, A. (2018). Chapter 10.4 - Physical–Chemical Leachate Treatment. In R. Cossu & R. Stegmann (Eds.), *Solid Waste Landfilling* (pp. 575–632). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-407721-8.00028-0

Cui, C., Sun, X., Zhou, C., Liu, Y., Xiong, H., Li, Y., & Han, J. (2021). Pomegranate-like MnO2@PANI sub-microspheres: Synthesis and application for Pb(II) ions removal from water. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *616*. https://doi.org/10.1016/j.colsurfa.2021.126336

Cui, J., Li, X., Pei, Z., & Pei, Y. (2019). A long-term stable and environmental friendly self-healing coating with polyaniline/sodium alginate microcapsule structure for corrosion protection of water-delivery pipelines. *Chemical Engineering Journal*, *358*, 379–388. https://doi.org/10.1016/j.cej.2018.10.062

Deb, K., Bera, A., & Saha, B. (2016). Tuning of electrical and optical properties of polyaniline incorporated functional paper for flexible circuits through oxidative chemical polymerization. *RSC Advances*, *6*(97), 94795–94802. https://doi.org/10.1039/c6ra16079d

Deshpande, P. P., Jadhav, N. G., Gelling, V. J., & Sazou, D. (2014). Conducting polymers for corrosion protection: A review. *Journal of Coatings Technology and Research*, *11*(4), 473–494. https://doi.org/10.1007/s11998-014-9586-7

El-Said, W. A., El-Khouly, M. E., Ali, M. H., Rashad, R. T., Elshehy, E. A., & Al-Bogami, A. S. (2018). Synthesis of mesoporous silica-polymer composite for the chloridazon pesticide removal from aqueous media. *Journal of Environmental Chemical Engineering*, *6*(2), 2214–2221. https://doi.org/10.1016/j.jece.2018.03.027

Faisal, M., Jalalah, M., Harraz, F. A., El-Toni, A. M., Labis, J. P., & Al-Assiri, M. S. (2021). A novel Ag/PANI/ZnTiO3 ternary nanocomposite as a highly-efficient visible-light-driven photocatalyst. *Separation and Purification Technology*, *256*. https://doi.org/10.1016/j.seppur.2020.117847

Feng, Y., Li, H., Zhang, M., Jin, J., Zhang, B., Wang, Y., & Li, Z. (2022). Preparation of BTA@PDA/PANI microcapsules and anti-corrosion performance of self-healing epoxy coatings on low carbon steel. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *649*. https://doi.org/10.1016/j.colsurfa.2022.129481

Ghaly, H. A., El-Kalliny, A. S., Gad-Allah, T. A., & El-Sattar, N. E. A. A. (2021). Photodegradation of Naproxen Using Ag/AgCl–PANI Composite under Solar Light: Transformation Product and Reaction Kinetics. *Kinetics and Catalysis*, *62*(3), 367–374. https://doi.org/10.1134/S0023158421030034

Gojgić, J., Petrović, M., Jugović, B., Jokić, B., Grgur, B., & Gvozdenović, M. (2022). Electrochemical and Electrical Performances of High Energy Storage Polyaniline Electrode with Supercapattery Behavior. *Polymers*, *14*(24). https://doi.org/10.3390/polym14245365

Gvozdenović, M., Džunuzović, E., Jugović, B., & Grgur, B. (2018). Polyaniline based corrosion inhibitors for conventional organic coatings. *Zastita Materijala*, *59*(2), 282–292. https://doi.org/10.5937/zasmat1802282g

Hao, Y., Zhao, Y., Li, B., Song, L., & Guo, Z. (2020). Self-healing effect of graphene@PANI loaded with benzotriazole for carbon steel. *Corrosion Science*, *163*. https://doi.org/10.1016/j.corsci.2019.108246

Hao, Y., Zhao, Y., Yang, X., Hu, B., Ye, S., Song, L., & Li, R. (2019). Self-healing epoxy coating loaded with phytic acid doped polyaniline nanofibers impregnated with benzotriazole for Q235 carbon steel. *Corrosion Science*, *151*, 175–189. https://doi.org/10.1016/j.corsci.2019.02.023

Hlekelele, L., Nomadolo, N. E., Setshedi, K. Z., Mofokeng, L. E., Chetty, A., & Chauke, V. P. (2019). Synthesis and characterization of polyaniline, polypyrrole and zero-valent iron-based materials for the adsorptive and oxidative removal of bisphenol-A from aqueous solution. *RSC Advances*, *9*(25), 14531–14543. https://doi.org/10.1039/c9ra01666j

Hou, W., Xiao, Y., Han, G., & Lin, J. Y. (2019). The applications of polymers in solar cells: A review. In *Polymers* (Vol. 11, Issue 1). MDPI AG. https://doi.org/10.3390/polym11010143

Hsini, A., Naciri, Y., Laabd, M., Bouziani, A., Navío, J. A., Puga, F., Boukherroub, R., Lakhmiri, R., & Albourine, A. (2021). Development of a novel PANI@WO3 hybrid composite and its application as a promising adsorbent for Cr(VI) ions removal. *Journal of Environmental Chemical Engineering*, *9*(5). https://doi.org/10.1016/j.jece.2021.105885

Hussen, A. (2021). PANI/g-C 3 N 4 /CeO 2 Nanocomposite for Photodegradation of Diazinon in Aqueous Solution. *Middle East Journal of Applied Science & Technology*, *4*(1), 1–22. www.mejast.com

Ishtiaq, F., Bhatti, H. N., Khan, A., Iqbal, M., & Kausar, A. (2020). Polypyrole, polyaniline and sodium alginate biocomposites and adsorption-desorption efficiency for imidacloprid insecticide. *International Journal of Biological Macromolecules*, *147*, 217–232. https://doi.org/10.1016/j.ijbiomac.2020.01.022

Ismail, Y. A., Martínez, J. G., & Otero, T. F. (2014). Fibroin/Polyaniline microfibrous mat. Preparation and electrochemical characterization as reactive sensor. *Electrochimica Acta*, *123*(January), 501–510. https://doi.org/10.1016/j.electacta.2014.01.073

Janaki, V., Oh, B. T., Shanthi, K., Lee, K. J., Ramasamy, A. K., & Kamala-Kannan, S. (2012). Polyaniline/chitosan composite: An eco-friendly polymer for enhanced removal of dyes from aqueous solution. *Synthetic Metals*, *162*(11–12), 974–980. https://doi.org/10.1016/j.synthmet.2012.04.015

Jevremović, A., Bober, P., Mičušík, M., Kuliček, J., Acharya, U., Pfleger, J., Milojević-Rakić, M., Krajišnik, D., Trchová, M., Stejskal, J., & Ćirić-Marjanović, G. (2019). Synthesis and characterization of polyaniline/BEA zeolite composites and their application in nicosulfuron adsorption. *Microporous and Mesoporous Materials*, *287*, 234–245. https://doi.org/10.1016/j.micromeso.2019.06.006

Karthikeyan, M., Kumar, K. K. S., & Elango, K. P. (2012). Studies on the defluoridation of water using conducting polymer/montmorillonite composites. *Environmental Technology (United Kingdom)*, *33*(7), 733–739. https://doi.org/10.1080/09593330.2011.592224

Kausor, M. al, & Chakrabortty, D. (2022). Polyaniline (PANI) grafted hierarchical heterostructure nanocomposites for photocatalytic degradation of organic pollutants in waste water: A review. *Surfaces and Interfaces*, *31*. https://doi.org/10.1016/j.surfin.2022.102079

Lazarević, M. J., Despotović, V. N., Šojić Merkulov, D. V., Banić, N. D., Finčur, N. L., Četojević-Simin, D. D., Čomor, M. I., & Abramović, B. F. (2019). Photodegradation of selected pesticides: Photocatalytic activity of bare and PANI-modified TiO2 under simulated solar irradiation. *Journal of the Serbian Chemical Society*, *84*(12), 1455–1468. https://doi.org/10.2298/JSC190301083L

Ledezma-Espinoza, A., Rodríguez-Quesada, L., Araya-Leitón, M., Avendaño-Soto, E. D., & Starbird-Perez, R. (2022). Modified cellulose/poly(3,4-ethylenedioxythiophene) composite as photocatalyst for the removal of sulindac and carbamazepine from water. *Environmental Technology and Innovation*, *27*. https://doi.org/10.1016/j.eti.2022.102483

Li, A., Chen, S., Ma, Z., Sun, M., Zhu, G., Zhang, Y., & Wang, W. (2021). Corrosion protection properties of polyvinyl butyral/polyaniline-graphene oxide/poly (methylhydrosiloxane) composite coating for AA2024 aluminum alloy. *Diamond and Related Materials*, *116*. https://doi.org/10.1016/j.diamond.2021.108397

Lv, M., Yang, L., Wang, X., Cheng, X., Song, Y., Yin, Y., Liu, H., Han, Y., Cao, K., Ma, W., Qi, G., & Li, S. (2019). Visible-light photocatalytic capability and the mechanism investigation of a novel PANI/Sn3O4 p-n heterostructure. *RSC Advances*, *9*(69), 40694–40707. https://doi.org/10.1039/c9ra07562c

Madima, N., Mishra, S. B., Inamuddin, I., & Mishra, A. K. (2020). Carbon-based nanomaterials for remediation of organic and inorganic pollutants from wastewater. A review. *Environmental Chemistry Letters*, *18*(4), 1169–1191. https://doi.org/10.1007/s10311-020-01001-0

Merci, S., Saljooqi, A., Shamspur, T., & Mostafavi, A. (2021). WO3 nanoplates decorated with polyaniline and CdS nanoparticles as a new photocatalyst for degradation of imidacloprid pesticide from water. *Environmental Science and Pollution Research*, *28*(27), 35764–35776. https://doi.org/10.1007/s11356-021-13031-4

Mohammadi Nodeh, M. K., Soltani, S., Shahabuddin, S., Rashidi Nodeh, H., & Sereshti, H. (2018). Equilibrium, Kinetic and Thermodynamic Study of Magnetic Polyaniline/Graphene Oxide Based Nanocomposites for Ciprofloxacin Removal from Water. *Journal of Inorganic and Organometallic Polymers and Materials*, *28*(3), 1226–1234. https://doi.org/10.1007/s10904-018-0782-2

Moura, L., & Picão, R. C. (2022). Chapter 23 - Removal of antimicrobial resistance determinants from wastewater: a risk perspective on conventional and emerging technologies. In H. Sarma, D. C. Dominguez, & W.-Y. Lee (Eds.), *Emerging Contaminants in the Environment* (pp. 603–642). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-323-85160-2.00023-8

Mu, B., Tang, J., Zhang, L., & Wang, A. (2017). Facile fabrication of superparamagnetic graphene/polyaniline/Fe3O4 nanocomposites for fast magnetic separation and efficient removal of dye. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-05755-6

Nekooie, R., Shamspur, T., & Mostafavi, A. (2021). Novel CuO/TiO2/PANI nanocomposite: Preparation and photocatalytic investigation for chlorpyrifos degradation in water under visible light irradiation. *Journal of Photochemistry and Photobiology A: Chemistry*, *407*. https://doi.org/10.1016/j.jphotochem.2020.113038

Nguyen, D. N., & Yoon, H. (2016). Recent advances in nanostructured conducting polymers: From synthesis to practical applications. In *Polymers* (Vol. 8, Issue 4). MDPI AG. https://doi.org/10.3390/polym8040118

Ong, C. B., Ng, L. Y., & Mohammad, A. W. (2018). A review of ZnO nanoparticles as solar photocatalysts: Synthesis, mechanisms and applications. In *Renewable and Sustainable Energy Reviews* (Vol. 81, pp. 536–551). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.08.020

Park, J. M., & Jhung, S. H. (2020). Polyaniline-derived carbons: Remarkable adsorbents to remove atrazine and diuron herbicides from water. *Journal of Hazardous Materials*, *396*. https://doi.org/10.1016/j.jhazmat.2020.122624

Perendija, J., Veličković, Z. S., Cvijetić, I., Rusmirović, J. D., Ugrinović, V., Marinković, A. D., & Onjia, A. (2020). Batch and column adsorption of cations, oxyanions and dyes on a magnetite modified cellulose-based membrane. *Cellulose*, *27*(14), 8215–8235. https://doi.org/10.1007/s10570-020-03352-x

Popovic, A. L., Rusmirovic, J. D., Velickovic, Z., Kovacevic, T., Jovanovic, A., Cvijetic, I., & Marinkovic, A. D. (2021). Kinetics and column adsorption study of diclofenac and heavy-metal ions removal by amino-functionalized lignin microspheres. *Journal of Industrial and Engineering Chemistry*, *93*, 302–314. https://doi.org/https://doi.org/10.1016/j.jiec.2020.10.006

Saha, S., Chaudhary, N., Kumar, A., & Khanuja, M. (2020). Polymeric nanostructures for photocatalytic dye degradation: polyaniline for photocatalysis. *SN Applied Sciences*, *2*(6). https://doi.org/10.1007/s42452-020-2928-4

Saheed, I. O., Oh, W. da, & Suah, F. B. M. (2021). Chitosan modifications for adsorption of pollutants – A review. *Journal of Hazardous Materials*, *408*, 124889. https://doi.org/https://doi.org/10.1016/j.jhazmat.2020.124889

Sajid, M. M., Shad, N. A., Javed, Y., Khan, S. B., Zhang, Z., Amin, N., & Zhai, H. (2020). Preparation and characterization of Vanadium pentoxide (V2O5) for photocatalytic degradation of monoazo and diazo dyes. *Surfaces and Interfaces*, *19*. https://doi.org/10.1016/j.surfin.2020.100502

Samadi, A., Xie, M., Li, J., Shon, H., Zheng, C., & Zhao, S. (2021). Polyaniline-based adsorbents for aqueous pollutants removal: A review. In *Chemical Engineering Journal* (Vol. 418). Elsevier B.V. https://doi.org/10.1016/j.cej.2021.129425

Samani, M. R., & Toghraie, D. (2019). Removal of hexavalent chromium from water using polyaniline/ wood sawdust/ poly ethylene glycol composite: an experimental study. *Journal of Environmental Health Science & Engineering*, *17*(1), 53–62. https://doi.org/10.1007/s40201-018-00325-y

Sandhu, I. S., Chitkara, M., Rana, S., Dhillon, G., Taneja, A., & Kumar, S. (2020). Photocatalytic performances of stand-alone graphene oxide (GO) and reduced graphene oxide (rGO) nanostructures. *Optical and Quantum Electronics*, *52*(7). https://doi.org/10.1007/s11082-020-02473-8

Sharma, S., Sharma, A., Chauhan, N. S., Tahir, M., Kumari, K., Mittal, A., & Kumar, N. (2022). TiO2/Bi2O3/PANI nanocomposite materials for enhanced photocatalytic decontamination of organic pollutants. *Inorganic Chemistry Communications*, *146*. https://doi.org/10.1016/j.inoche.2022.110093

Singh, P., & Shukla, S. K. (2020). Advances in polyaniline-based nanocomposites. In *Journal of Materials Science* (Vol. 55, Issue 4, pp. 1331–1365). Springer New York LLC. https://doi.org/10.1007/s10853-019-04141-z

Singh, S., Kaur, P., Aggarwal, D., Kumar, V., Tikoo, K., Bansal, S., & Singhal, S. (2022). Polyaniline enwrapped CoFe2O4/g-CN ternary nanocomposite for adsorption driven photocatalytic degradation of explicitly diverse organic pollutants. *Journal of Alloys and Compounds*, *923*. https://doi.org/10.1016/j.jallcom.2022.166255

Stejskal, J., & Gilbert, R. G. (2002). POLYANILINE. PREPARATION OF A CONDUCTING POLYMER (IUPAC Technical Report). In *Pure Appl. Chem* (Vol. 74, Issue 5).

Taheri, N. N., Ramezanzadeh, B., Mahdavian, M., & Bahlakeh, G. (2018). In-situ synthesis of Zn doped polyaniline on graphene oxide for inhibition of mild steel corrosion in 3.5 wt.% chloride solution. *Journal of Industrial and Engineering Chemistry*, *63*, 322–339. https://doi.org/10.1016/j.jiec.2018.02.033

Tallman, D. E., Spinks, G., Dominis, A., & Wallace, G. G. (2002). Electroactive conducting polymers for corrosion control: Part 1. General introduction and a review of non-ferrous metals. In *Journal of Solid State Electrochemistry* (Vol. 6, Issue 2, pp. 73–84). Springer New York LLC. https://doi.org/10.1007/s100080100212

Tian, Z., Yu, H., Wang, L., Saleem, M., Ren, F., Ren, P., Chen, Y., Sun, R., Sun, Y., & Huang, L. (2014). Recent progress in the preparation of polyaniline nanostructures and their applications in anticorrosive coatings. In *RSC Advances* (Vol. 4, Issue 54, pp. 28195–28208). Royal Society of Chemistry. https://doi.org/10.1039/c4ra03146f

Vijayalakshmi, S., Kumar, E., Venkatesh, P. S., & Raja, A. (2020). Preparation of zirconium oxide with polyaniline nanocatalyst for the decomposition of pharmaceutical industrial wastewater. *Ionics*, *26*(3), 1507–1513. https://doi.org/10.1007/s11581-019-03323-8

Wang, J., Deng, B., Chen, H., Wang, X., & Zheng, J. (2009). Removal of Aqueous Hg(II) by Polyaniline: Sorption Characteristics and Mechanisms. *Environmental Science & Technology*, *43*(14), 5223–5228. https://doi.org/10.1021/es803710k

Xu, J., Gao, F., Wang, H., Dai, R., Dong, S., & Wang, H. (2023). Organic/inorganic hybrid waterborne polyurethane coatings with self-healing properties for anticorrosion application. *Progress in Organic Coatings*, *174*. https://doi.org/10.1016/j.porgcoat.2022.107244

Yang, G., Liu, F., Hou, N., Peng, S., He, C., & Fang, P. (2022). Preparation of One-Dimensional Polyaniline Nanotubes as Anticorrosion Coatings. *Materials (Basel, Switzerland)*, *15*(9). https://doi.org/10.3390/ma15093192

Yang, H. D., Huang, J. H., Shibata, K., Lu, D., Maeda, K., & Hu, C. (2020). Boosting photocatalytic $H_2O_2$ production by coupling of sulfuric acid and 5-sulfosalicylic acid incorporated polyaniline with g-C3N4. *Sustainable Energy and Fuels*, *4*(8), 4186–4195. https://doi.org/10.1039/d0se00337a

Yousef, A., Thiehmed, Z., Abdul Shakoor, R., & Altahtamouni, T. (2022). Recent Progress in WS2-Based Nanomaterials Employed for Photocatalytic Water Treatment. In *Catalysts* (Vol. 12, Issue 10). MDPI. https://doi.org/10.3390/catal12101138

Yuan, X., Floresyona, D., Aubert, P. H., Bui, T. T., Remita, S., Ghosh, S., Brisset, F., Goubard, F., & Remita, H. (2019). Photocatalytic degradation of organic pollutant with polypyrrole nanostructures under UV and visible light. *Applied Catalysis B: Environmental*, *242*, 284–292. https://doi.org/10.1016/j.apcatb.2018.10.002

Zhang, L., Du, W., Nautiyal, A., Liu, Z., & Zhang, X. (2018). Recent progress on nanostructured conducting polymers and composites: synthesis, application and future aspects. In *Science China Materials* (Vol. 61, Issue 3, pp. 303–352). Science China Press. https://doi.org/10.1007/s40843-017-9206-4

Zhao, J., Liu, H., Xue, P., Tian, S., Sun, S., & Lv, X. (2021). Highly-efficient PVDF adsorptive membrane filtration based on chitosan@CNTs-COOH simultaneous removal of anionic and cationic dyes. *Carbohydrate Polymers*, *274*, 118664. https://doi.org/https://doi.org/10.1016/j.carbpol.2021.118664

Zhong, F., He, Y., Wang, P., Chen, C., Li, H., Zhang, C., & Xie, P. (2021). Novel graphene/hollow polyaniline carrier with high loading of benzotriazole improves barrier and long-term self-healing properties of nanocomposite coatings. *Progress in Organic Coatings*, *151*. https://doi.org/10.1016/j.porgcoat.2020.106086