

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

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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.



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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

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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 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 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 & Bhowan, 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 & Chakraborty, 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

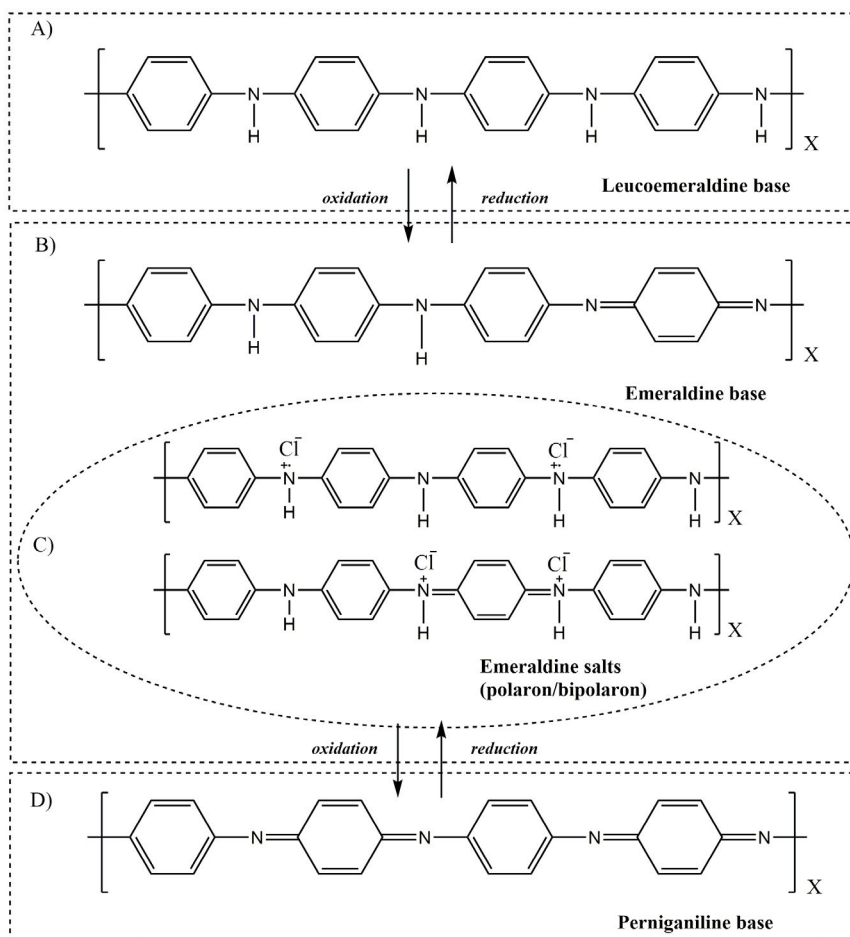


Fig. 1. Oxidative states pathways of PANI polymer

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 pernigraniline (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_s 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/Fe₃O₄ 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 Sn₃O₄. 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 Sn₃O₄. 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/ZrO₂ 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. Zn²⁺ 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.

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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 ₃ PO ₄ /polyaniline/g-C ₃ N ₄	Sun irradiation	monocrotophos, 15 ppm	0.08 g/L	99.6%, 50 min	(Balasubramanian et al., 2020)
TiO ₂ /Bi ₂ O 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 ₂ O 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 ₃ N ₄ /CeO ₂	UV irradiation	diazinon, 10 ppm	0.10 g/L	94.08%, 40 min	(Hussen, 2021)

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