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DOI: https://doi.org/10.64388/IREV10I3-1722927

Removal of Pharmaceutical Pollutants from Wastewater Using Nanomaterials

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Abstract- ***The rapid development and increasing use of pharmaceutical products have contributed to the contamination of water bodies, as drugs and pharmaceutical residues classified as emerging contaminants are released into aquatic systems, posing a growing environmental problem. Pharmaceuticals frequently detected in urban wastewater, surface water, and reused water include analgesics, antibiotics, anticonvulsants, hormones, antifungals, beta-blockers, and antiepileptics, typically occurring at concentrations ranging from nanograms to micrograms per liter. Because these compounds are biologically active, their presence in the environment raises particular concern even at low concentrations. Conventional wastewater treatment systems were not primarily designed to remove pharmaceutical pollutants and have been reported to be ineffective against several of these compounds. Various techniques, including filtration, biodegradation, photolytic degradation, microextraction, and chemical oxidation, have been applied for their removal, but are limited by high cost and time consumption. Nanomaterials have therefore emerged as a preferred alternative due to their small particle size, high surface area, and favorable interactions with pharmaceutical pollutants, providing more than one removal mechanism within a single material. This review covers the sources of pharmaceutical pollutants and their pathways into wastewater, their occurrence, public health effects, and remediation using nanomaterials including reduced graphene oxide, carbon nanotubes,*** TiO_2***,*** ZnO***, metal–organic frameworks, MXenes, and silver nanoparticles, acting through adsorption, photocatalysis, and advanced oxidation. Reported performance includes tetracycline adsorption capacities exceeding 900 mg/g on magnetic MOF composites, over 90 % ciprofloxacin degradation using Ag-doped ZnO-graphite composites, and up to 98 % ibuprofen removal by functionalized carbon nanotubes. However, limitations such as aggregation, high synthesis cost, incomplete mineralization, and uncertain toxicity of transformation products remain, with most evidence drawn from controlled laboratory systems rather than real wastewater. This review concludes that nanomaterials offer strong potential for pharmaceutical wastewater remediation but require further evaluation for scalability, stability, and safety before practical deployment.***

Keywords: Pharmaceutical pollutants; Wastewater treatment; Nanomaterials; Adsorption

I. INTRODUCTION

Pharmaceuticals are biologically active compounds developed for prevention, diagnosis, and treatment of diseases, and are known to have a particular mode of action in human and animals [1]. The rapid development and widespread use of pharmaceutical products have contributed substantially to improvements in living organisms; however, the same biological activity that makes pharmaceuticals useful in medicine creates an environmental concern when pharmaceutical residues enter natural ecosystems [2], [3]. Recently, global antibiotic consumption has immensely increased to about 42 – 45 billion daily defined dose (DDD) in 2020–21 [4]. Nevertheless, water contamination due to releasing of drugs and pharmaceuticals “emerging contaminants (ECs)” residues into aquatic systems is an emerging environmental problem [5].

The pharmaceuticals most frequently detected pharmaceuticals in urban wastewaters, receiving surface waters or re-used waters are analgesics, antibiotics, anticonvulsants, hormones, fragrances, β-blockers, antidepressants, antiepileptics present at concentrations ranging from few ng L^{-1} until more than µg L^{-1} [6]. Pharmaceutical residues occur in wastewater at concentrations commonly ranging from nanograms per liter to micrograms per liter, although substantially higher concentrations may occur in particular industrial or pharmaceutical-manufacturing

wastewaters. The environmental significance of these concentrations cannot be assessed simply by comparing them with concentrations of conventional pollutants. Pharmaceuticals are biologically active by design, and some can produce biological effects at relatively low concentrations. Consequently, continuous exposure of aquatic organisms to mixtures of pharmaceuticals may represent a concern even when individual compounds occur at low concentrations [2], [7].

Therefore, removal of these pharmaceutical pollutants is very important. A major challenge is that conventional wastewater treatment systems were not originally designed specifically for pharmaceutical micropollutants. Primary treatment generally removes suspended solids, while biological treatment is primarily intended to reduce biodegradable organic matter and nutrients [8], [9]. Conventional biological treatment can also show variable removal performance because pharmaceutical compounds differ considerably in their chemical structures and physicochemical properties. Hossen et al., (2024) reported that biological treatment was ineffective for the complete removal of several pollutants from pharmaceutical wastewater. Similarly, Zhang et al., (2024) observed substantial differences in the removal efficiencies of pharmaceutical compounds during wastewater treatment. These limitations have encouraged the investigation of advanced treatment technologies, including adsorption, membrane processes and advanced oxidation processes. However, some conventional advanced treatments can involve high energy requirements, chemical consumption or the formation of transformation products. Therefore, the development of efficient and sustainable treatment materials remains necessary.

Several techniques were applied for removal of pharmaceutical pollutants from wastewater such as oxidation, filtration, biodegradation, photolytic degradation, microextraction, chlorination and electrochemical oxidation. However, the majority of these methods are associated with certain limitations such as cost un-effectiveness, limited scope, and time consumption [5]. Singh et al., (2026) also reported that mineralization denotes its complete conversion into inorganic end products, e.g., CO2 and H2O; however, while many treatment processes achieve high removal efficiencies, complete mineralization is rare.

Recent research has therefore focused on advanced treatment technologies capable of improving pharmaceutical removal. Among these technologies, nanomaterials have attracted considerable interest [13], [14]. Their small particle size, high surface area and tunable surface chemistry can provide favourable interactions with pharmaceutical molecules. Recent research has investigated carbon-based materials, metal oxides, magnetic nanocomposites, two-dimensional materials and metal–organic frameworks for pharmaceutical removal. For example, Husein et al., (2019) has reported the removal of new emerging pollutants using new generation nano-adsorbents by adsorption technology. Al-Hetlani et al., (2022) developed a magnetic carbonaceous/spinel ferrite nanocomposite for pharmaceutical removal. The material showed strong adsorption performance and could be recovered and regenerated using a magnetic field. Moradi et al., (2024) also developed chitosan/agar-based nanocomposites containing SiO_2 nanoparticles for the removal of amoxicillin and naproxen. The nanocomposite achieved removal efficiencies of 91% for amoxicillin and 99% for naproxen under the reported optimum conditions. Photocatalytic nanomaterials have also demonstrated potential for pharmaceutical degradation. Navidpour et al., (2024) investigated different TiO_2 nanomaterials for degrading propranolol, mebeverine and carbamazepine in water and sewage effluent. These studies demonstrate that nanomaterials can support pharmaceutical removal through different mechanisms, particularly adsorption and photocatalytic degradation.

The application of nanomaterials to pharmaceutical wastewater is particularly promising because a single material can sometimes provide more than one removal mechanism [18], [19]. Despite these promising results, several challenges must be addressed before nanomaterial-based treatment can be widely implemented. The performance of nanomaterials can be affected by aggregation, wastewater composition, competing contaminants and operating conditions. Their recovery and

regeneration are also important because the release of nanoscale materials could create additional environmental concerns. Recent research has therefore emphasized the importance of improving the stability, selectivity, recyclability and scalability of nanomaterial-based adsorbents [20]. Besides, the production of some nanomaterials requires energy-intensive synthesis procedures or hazardous chemicals. Nanoparticles may agglomerate, lose activity, or potentially be released into the environment after treatment. In addition, adsorption transfers contaminants from water to a solid phase rather than necessarily destroying them. Photocatalytic treatment may also produce transformation products whose toxicity is not always adequately characterized. Therefore, the effectiveness of nanomaterial-based treatment should be evaluated in relation to removal efficiency, mineralization, toxicity reduction, material recovery, regeneration, cost and environmental safety.

This review examines pharmaceutical pollutants in wastewater, emphasizing their sources and occurrence, analytical detection, environmental implications and the application of nanomaterials for removal. The objective is to provide an integrated understanding of why pharmaceutical pollutants are environmentally important and why nanomaterial-based technologies are being investigated as advanced treatment approaches.

II. SOURCES

Pharmaceutical pollutants are widely introduced into the aquatic system through point and non-point sources. The primary sources of pharmaceutical pollutants in the environment are pharmaceutical industries, hospitals, animal waste, research activities utilizing therapeutic compounds and discharge of expired medicine in the environment [1]. Effluent coming from hospital contains the pathogen, pharmaceutical residues and their metabolites, drug conjugates, radioactive elements and other chemicals. The discharge of hospital effluent into the municipal WWTP (even at diluted pharmaceutical concentrations) decreases the biodegradation process of the organic contaminant in WWTP [1].

2.1 The Hospitals

The hospital effluents contain a large variety of substances used for medical, laboratories, research purposes, and also include excreta from patients. These wastes include drugs and their metabolites such as antibiotics, lipid regulators, analgesics, antidepressants, antiepileptics, antineoplastic, antipyretics, antiphlogistic, antirheumatics, estrogens, organic matters, radionuclides, solvents, metals, disinfectants, cytostatic agents, anesthetics and sterilization products, specific detergents for endoscopes and other instruments, radioactive markers, and iodinated contrast media [21]. According to the diversity of contaminants, it has been demonstrated that the intrinsic toxicity of the hospital effluents can be 5-15 times greater than an urban effluent as well as the potential inhibition of the activated sludge of wastewater treatment plants [21]. [22] also investigated 74 pharmaceutical active compounds in wastewater from 11 hospitals. They detected 48 compounds in the influents and 50 compounds in the effluents. Acetaminophen reached 69 μg/L in the influent samples. Hospital type can also influence pharmaceutical concentrations. Psychiatric hospitals showed higher concentrations of several pharmaceutical groups than general hospitals. Similar contamination has been reported in Tunisian hospitals.

2.2 Veterinary Medicine and Agriculture

Pharmaceutical pollution is not restricted to human pharmaceutical use because veterinary medicines are extensively used in livestock, poultry, aquaculture and other animal-production systems [23]. Veterinary pharmaceuticals, particularly antibiotics, antiparasitic drugs and hormones, can be excreted by treated animals and subsequently enter manure, soils, drainage systems and surface waters [23].

Veterinary antibiotics and other pharmaceuticals can be excreted by treated animals. These residues can enter manure and agricultural soils. Runoff and leaching can subsequently transport them into surface water and groundwater. Delgado et al., (2023) reviewed the occurrence of veterinary pharmaceuticals in wastewater and surface water. The authors identified 71 veterinary pharmaceuticals in the reviewed aquatic samples. Antibiotics were the

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DOI: https://doi.org/10.64388/IREV10I3-1722927

dominant group detected. Oxytetracycline, amoxicillin and monensin were among compounds reported at relatively high concentrations. This pathway is particularly relevant in areas with intensive livestock production and frequent veterinary drug use.

2.3 Domestic Wastewater

Domestic wastewater is one of the major pathways through which pharmaceutical residues enter wastewater treatment plants because pharmaceuticals consumed by humans and their metabolites are subsequently excreted into urine and feces [25]. Following medication use, a proportion of active pharmaceutical ingredients may be excreted either unchanged or as metabolites, depending on the pharmacokinetic characteristics of individual compounds [2]. These residues are transported through domestic sewer systems and ultimately enter municipal wastewater treatment facilities [9].

The continuous consumption and excretion of pharmaceutical products can result in their continuous introduction into wastewater, contributing to what has been described as pseudo-persistent environmental contamination [26]. Even when a pharmaceutical compound undergoes degradation, continuous input from human activities can maintain its presence in wastewater and receiving environments [2]. The extent to which individual pharmaceuticals occur in wastewater varies according to their consumption patterns, excretion rates, physicochemical properties, metabolism and degradation behaviour [9]. Pharmaceutical residues originating from domestic wastewater have subsequently been detected in wastewater influents, treated effluents and receiving aquatic environments [3].

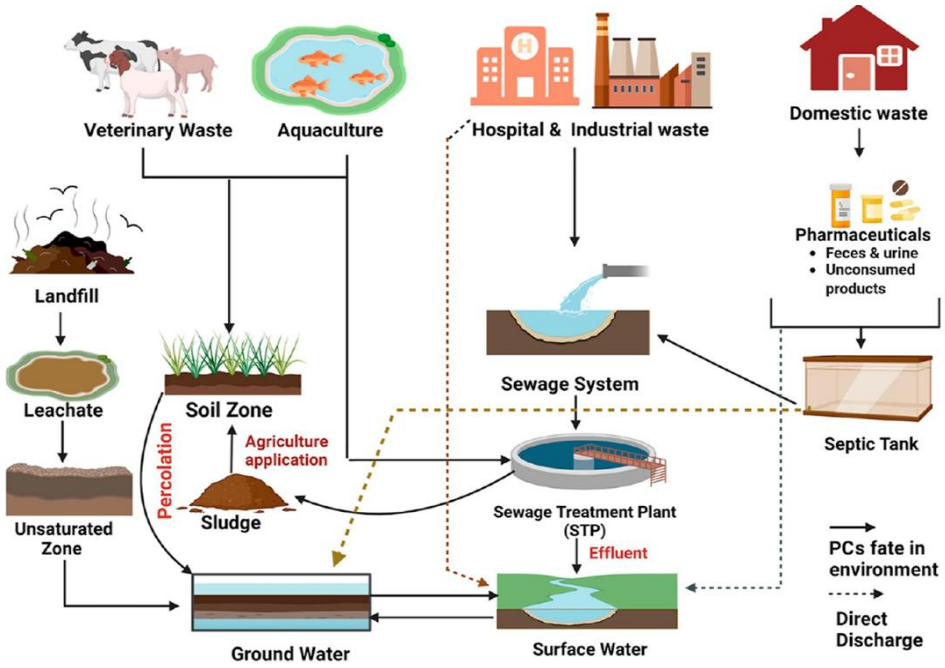

Fig. 1: Potential sources and pathways for pharmaceutical contaminants entering water systems.[27]

III. SOME PHARMACEUTICAL POLLUTANTS, OCCURRENCES, AND PUBLIC HEALTH IMPLICATIONS

Pharmaceuticals are chemicals commonly used to diagnose, treat, repair, or prevent diseases in both human health and veterinary medicine. They include a wide range of medications that can be classified as antibiotics, analgesics and anti-inflammatory drugs, cardiovascular drugs, antiseptics, anticancer drugs, anticonvulsants, antidepressants, and antacids [27].

Antibiotics are one of the most prominent pharmaceutical pollutants in wastewater. They are classified into aminoglycosides, macrolides, tetracyclines, glycopeptides, lincosamides, carbapenems, penicillins, cephalosporins, sulfonamides, fluoroquinolones, and others [27]. Ciprofloxacin (CIP) is among the leading fluoroquinolones (FQs) of choice and also the most widely used chemotherapeutic antibiotics worldwide [28]. Igwegbe et al., (2021) reported that CIP in surface water has been found at levels ranging from 2.45 × 104 mg/L and 6.3 × 104 mg/L and from 7.0 × 104 to 0.1245 mg/L in hospital effluent.

Among various water organic pollutants, Non-Steroidal Anti-Inflammatory drugs (NSAIDs) constitute a group of pharmaceuticals with analgesic, antipyretic and anti-inflammatory effects [5]. The most abundant members of the NSAIDs family are Diclofenac (Dic), Naproxen (Nap) and Ibuprofen (Ibu). Continuous introduction of diclofenac in anoxic sludge treatment process causes a reduction in gas production and reduce the denitrifying potential of microbial community present in WWTP [30]. Ibuprofen is found in water at a concentration of up to 24.6 µg/l, thus it represents hazardous pollutants for human health [31].

Analgesics and anti-inflammatory compounds are applied to eliminate pain and inflammation [1]. As they are available over-the-counter (OTC) in many countries, they must be aware of their possible release into the water. However, our knowledge in this regard is limited. Nevertheless, the most significant sources of opioid analgesics are human body excretions since analgesics are extensively metabolized in humans [32], [33]. In this area, the adverse effects of Diclofenac in wastewater on the endocrine system and tissue damage following co-exposure to Acetaminophen, Carbamazepine, Gemfibrozil, and Venlafaxine at 0.5 to 10 µg/L concentrations were shown [34].

Consequently, anti-cancer compounds have carcinogenic, mutagenic, and reprotoxic impact, and thus their wastes may cause similar serious adverse effects on healthy cells of living creatures [35]. Information on the actual impact of anti-cancer wastes in water bodies is still limited, but it is confirmed that higher levels of these substances with low degradation rates produce more hazardous effects. For instance, Vinblastine and Cyclophosphamide are rarely degraded thus they persist and may have considerable dangerous consequences. Moreover, Chlorambucil, Melphalan, and Methotrexate have high concentrations in the aquatic ecosystem due to their high dissociation rates [36].

Beta-adrenergic antagonists or beta-blockers are commonly used for treating arterial hypertension, anxiety, angina, cardiac dysrhythmia, and coronary artery diseases [35], [37], and their use may vary among different regions, leading to alternations in their existence in the wastewater. For instance, it was estimated that consumption of betablockers in Germany is above 100 tons per year or that over 35 tons of Propranolol was taken in France in 1999. Based on the literature, beta-blockers generally exist in treated wastewater, surface waters, municipal effluents, and hospital wastes [37], [38]. Beta-blockers are detected in municipal wastewater as they are partially metabolized in human bodies [38].

Table 1: Class of Some Pharmaceuticals, Compounds, and Countries of Occurrence

Class of Pharmaceuticals	Compounds	Countries	References
Antibiotics	Ciproflaxin	USA	[39]
	Ofloxacin	Hong Kong	[40]
Analgesics	Ibuprofen	France, Europe, Spain	[41]
	Diclofenac	Spain	[41]
Antiepileptic Drugs	Carbamazepine	Spain, Europe	[42]
β-blockers	Propranolol	UK	[43]
Blood Lipid Regulator	Gemfibrozil	Spain, Europe	[44]
NSAIDS	Naproxen	Turia River Basin, Europe	[45]

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DOI: https://doi.org/10.64388/IREV10I3-1722927

Table 2: Pharmaceutical Pollutants and their Public Health Implications

Class of Compound	Pharmaceutical Compounds	Public Health Implications	Reported concentration	References
NSAIDs	Indomethacin	Postoperative bleeding, presyncope, syncope, decreased appetite, heartburn, and increased liver enzymes.	maximum concentration: 113 ng/L wastewater, Spain, via GC-MS technique, 2008 [46].	[47]
NSAIDs	Acetylsalicylic acid and salicylic acid	Cardiac arrhythmia, disruption in electrolyte balance, metabolic acidosis, gastrointestinal bleeding, perforation, and ulcers, post-term pregnancy, prolonged labor, stillborn infant, low birth weight, brain edema, coma, deafness, acute kidney injuries, and respiratory alkalosis.	9.5–295 ng/L, Yellow, Hai, and Liao River, China, via HPLC technique, 2008 [48].	[49], [50]
Hormonal compounds	Tamoxifen	Hot flashes, vaginal dryness, sleep problems, weight gain, and depression, irritability or mood swings, venous thromboembolic events, endometrial cancers.	27-212 ng/L, United Kingdom, surface water, 2006 [51].	[52], [53]
Hormonal compounds	Megestrol acetate	Phlebitis, abdominal distention, flatulence, and pulmonary edema.	0.04–0.33 ng/L, River Wenyu, China, 2012 [54].	[55], [56]
Anticancer agents	Melphalan	Decreased appetite, mucositis, dysgeusia, stomatitis, dyspepsia, anemia, decreased white blood cell count, amenorrhea, and renal failure.	Maximum concentration: 11 ng/L, Catalonia, Spain, via LC-MS/MS and LC-HRMS technique, 2012 [57].	[58]
Illegal drugs (Opioids)	Morphine	Urinary retention, atrial fibrillation, bradycardia, facial flushing, syncope, depression, anxiety, abnormality in thinking and dreaming, seizure, agitation, ataxia, chills, decreased cough reflex, malaise, myoclonus, slurred speech, voice disorder, decubitus ulcer, pallor, amenorrhea, apnea etc.	-	[59]
Antibiotics	Sulfonamides	Severe allergic reactions, agranulocytosis, Stevens- Johnson syndrome, and hepatic necrosis.	Sulfadimidine: maximum concentration: 0.005–1.31 µg/L Tianjin China, municipal wastewaters influent, 2018 [60].	[61]
Antibiotics	Penicillin	Melanoglossia, convulsions, positive direct COOMBS test, serum-sickness-like reaction, vulvovaginal infection, lethargy, myoclonus, seizure, urticaria,	Amoxicillin: 0.008–0.035 µg/L Tianjin China, municipal wastewaters influent,	[62]

		flatulence, hairy tongue, increased serum alkaline phosphatase, laryngospasm, serum sickness-like reaction, myoclonus, abnormal platelet aggregation (high doses), and Jarisch-Herxheimer reaction.	2018 [60].	
Lipid regulators (Fibrates)	Gemfibrozil	Atrial fibrillation, angioedema, arthralgia, blurred vision, bone marrow, depression, decreased libido, hypokalemia, impotence, increased creatine phosphokinase, increased serum alkaline phosphatase, increased serum bilirubin, increased serum transaminases, laryngeal edema, myopathy, and Raynaud phenomenon	1.2–5.7 µg/L, river water (Jarama, Manzanares, Guadarrama, Henares, and Tagus), Spain, via HPLC technique, 2010 [63].	[64], [65]
Lipid regulators (Statins)	Mainly Atorvastatin, Fluvastatin, Simvastatin.	Hepatic dysfunction, muscle injury, hypothyroidism, renal dysfunction, behavioral and cognitive, & diabetes mellitus.	Simvastatin: 1.23 µg /L WWTPs, USA, via LC-MS technique, 2011 [66].	[67]

IV. REMEDIATION USING NANOMATERIALS

Nanomaterials have emerged as promising materials for the remediation of pharmaceutical contaminants in water. Their effectiveness is associated with their high surface area and tunable surface properties [68]. They can remove pharmaceuticals through adsorption, photocatalysis, reduction, and advanced oxidation processes [68]. Iron-based nanoparticles, metal oxides, transition-metal dichalcogenides, and MXenes have therefore been investigated for pharmaceutical removal. Their performance depends on the material structure, pharmaceutical properties, pH, catalyst dosage, and treatment conditions [68].

4.1 Iron (III) oxide (Fe_2O_3) nanoparticles

Fe_2O_3 nanoparticles have been investigated mainly for photocatalytic and photo-Fenton-like degradation of pharmaceutical contaminants [69]. Their surface properties and morphology can influence their catalytic activity. Hematite (α-Fe_2O_3) nanocrystals have been used to degrade p-hydroxybenzoic acid and sulfachloropyridazine [70]. The study showed that exposed crystal facets affected the degradation efficiency. Fe_2O_3 has also been incorporated into composite photocatalysts for pharmaceutical degradation. For example, Fe_2O_3@ZrO_2 was investigated for the photocatalytic remediation of ciprofloxacin under visible light. However, charge recombination and limited light utilization can restrict the efficiency of Fe_2O_3-based photocatalysts [69], [71].

4.2 Titanium dioxide (TiO_2)

Navidpour et al., (2024) reported that the photocatalytic degradation of pharmaceutical compounds propranolol, mebeverine, and carbamazepine was studied using different titanium dioxide nanostructures suspended in water under UV and UV-visible irradiation. Among three different photocatalysts, the degradation was most effective by using Degussa P25 TiO2, followed by Hombikat UV100 and Aldrich TiO2. The photocatalytic performance was dependent on photocatalyst dosage, with an optimum concentration of 150 mg L−1. The natural aquatic colloids were shown to enhance the extent of photocatalysis, and the effect was correlated with their aromatic carbon content.

Do et al., (2019) also fabricated TiO2 nanotube arrays (TNAs), TiO2 nanowires on nanotube arrays (TNWs/TNAs), Au nanoparticle (NP)-decorated-TNAs, and TNWs/TNAs, which were applied for assessing the photocatalytic degradation of eight antibiotics, simultaneously. They reported that the TNAs and TNWs/TNAs were synthesized by anodization using an aqueous NH4F/ethylene glycol

solution. Au NPs were synthesized by chemical reduction method, and used to decorate on TNAs and TNWs/TNAs. All the TiO2 nanostructures exhibited anatase phase and well-defined morphology. From their reports, the photocatalytic performance of TNAs, TNWs/TNAs, Au-TNAs and Au-TNWs/TNAs was studied by monitoring the degradation of amoxicillin, ampicillin, doxycycline, oxytetracycline, lincomycin, vancomycin, sulfamethazine, and sulfamethoxazole under ultraviolet (UV)-visible (VIS), or VIS illumination by LC-MS/MS method.

Andronic et al., (2022) synthesized titanium dioxide and black TiO2 for photodegradation and mineralization of persistent organic pollutants in water, especially under visible radiation, presents interest from scientific and application points of view. They reported that chemical reduction by heating a TiO2 and NaBH4 mixture at 350 °C successfully introduced Ti3+ defects and oxygen vacancies at the surface of TiO2, with an increase in the photocatalytic degradation of amoxicillin, an antibiotic that is present in wastewater due to its intense use in human and animal medicine.

4.3 Zinc oxide (ZnO)

El-Kemary et al., (2010) synthesized nanostructure ZnO semiconductor with ∼2.1 nm diameter using a chemical precipitation method. They reported that the photocatalytic activity of the prepared ZnO nanoparticles has been investigated for the degradation of ciprofloxacin drug under UV light irradiation in aqueous solutions of different pH values. The results showed that the photocatalytic degradation process is effective at pH 7 and 10, but it is rather slow at pH 4. Higher degradation efficiency (∼50%) of the drug was observed at pH 10 after 60 min. Photodegradation of the drug follows a pseudo-first-order kinetics.

Core shell g-C3N4@ZnO, and ZnO defects photocatalysts presented an improved morphology in its characterization, and enhanced photodegradation of sulfamethoxazole, Nitenpyram and Tetracycline. Different composites were obtained as confirmed by the various characterization techniques studied, including core shell g-C3N4@ZnO, and ZnO defects photocatalyst. The synthesized photocatalysts showed high visible light absorption efficiency within a range of ~655 to 420 nm. Core shell g-C3N4@ZnO, and ZnO defects photocatalysts demonstrated high photocatalytic activity ascribed to high load separation and transition as shown in PL, Photocurrent reaction and EIS [76].

Roy et al., (2023) utilized the hydrothermal technique to prepare Ag-doped ZnO hybridizing Graphite (Gp) sheet (ZnO–Ag-Gp) to degrade pharmaceuticals pollutant ciproflaxin (CIP) from an aqueous medium. Dose optimization study found that 1.2 g/L is optimum for single (ZnO) and binary (ZnO-Gp and ZnO–Ag), where 0.3 g/L ternary (ZnO–Ag-Gp) exhibited maximum degradation efficiency (98%) within 60 min for 5 mg/L CIP. Pseudo 1st order reaction kinetics rate was found highest for ZnO–Ag-Gp (0.05983 min−1) and it decreased to 0.03428 min−1 for annealed sample. Removal efficiency decreased to only 90.97% at 5th run and hydroxyl radicals played a vital role to degrade CIP from aqueous solution. UV/ZnO–Ag-Gp will be a promising technique to degrade wide-ranging pharmaceutical antibiotics from the aquatic medium.

4.4 Graphene Oxide (GO) and Reduced Graphene Oxide (rGO)

GO is a graphene derivative with oxygen-containing functional groups such as hydroxyl, carboxyl, and epoxy groups, which disrupt its lattice and alter its properties [78].

Graphene oxide and its derivatives show excellent adsorption capacities for Pharmaceuticals (PhAs), which is crucial for their applications in the environmental pollution cleanup [79]. They reported that graphene oxide and its derivatives show excellent adsorption capacities for betablockers (atenolol and propranolol), antibiotics (tetracycline, ciprofloxacin and sulfamethoxazole), pharmaceutically active compounds (carbamazepine) and analgesics such as diclofenac.

Chen et al., (2015) evaluated the ability and mechanism of graphene oxide to remove sulfamethoxazole (SMX) and ciprofloxacin (CIP) from aqueous solution. Experimental and modeling

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DOI: https://doi.org/10.64388/IREV10I3-1722927

results showed that GO effectively sorbed both CIP and SMX with maximum sorption capacity of 379 and 240 mg g-1, respectively. The sorption of CIP was mainly controlled by the electrostatic attractions; while SMX sorption was mainly though π-π EDA attraction on the basal planes of the GO. Solution pH showed strong effect on the sorption ability of GO to the two antibiotics: at pH of 2, GO sorption ability decreased for both CIP and SMX; at pH of 9, GO completely lost SMX sorption ability but still showed strong sorption to CIP.

4.4.1 Reduced Graphene Oxide (rGO) for the Remediation of Pharmaceutical Pollutants

Reduced graphene oxide (rGO) is produced through the chemical, thermal, or other reduction of graphene oxide (GO), resulting in the removal of part of the oxygen-containing functional groups and restoration of larger sp^2-conjugated carbon domains [81]. The restoration of the graphitic structure gives rGO greater hydrophobicity and electrical conductivity than GO while retaining some residual oxygen-containing functional groups that can participate in interactions with pharmaceutical molecules [81]. These characteristics make rGO particularly attractive for pharmaceutical remediation because its extended π-conjugated surface can interact with aromatic pharmaceutical structures while its residual surface functional groups provide additional adsorption sites [81].

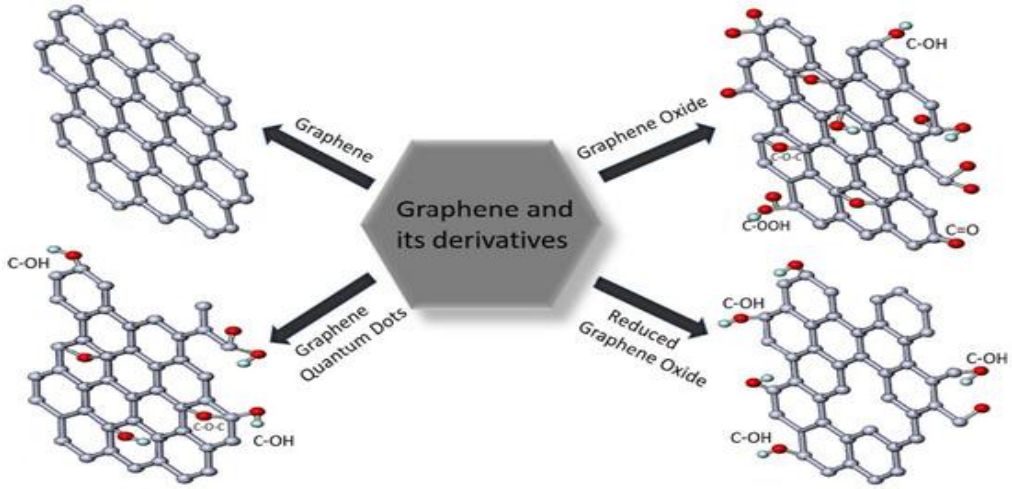

Fig. 2: Graphene and its derivatives[82]

4.5 Magnetite (Fe_3O_4) nanoparticles

Fe_3O_4 nanoparticles are attractive because they combine catalytic activity with magnetic recoverability [83]. Their Fe^{2+}/Fe^{3+} redox cycling can activate oxidants and generate reactive species. Bare Fe_3O_4 nanospheres achieved more than 80% tetracycline degradation in an H_2O_2-assisted Fenton-like system [84]. The process involved hydroxyl and superoxide-related species, with hydroxyl radicals playing a major role. Fe_3O_4-based composites have also shown high removal of tetracycline and ciprofloxacin. Magnetic separation provides an additional advantage for catalyst recovery and reuse [85], [86].

4.6 Tungsten trioxide (WO_3) nanoparticles

WO_3 is a visible-light-responsive semiconductor that has been investigated for pharmaceutical photocatalysis. Its photocatalytic activity results from light-induced charge generation at the semiconductor surface [87]. WO_3/CNT heterojunctions have been used for tetracycline degradation and pharmaceutical wastewater treatment. The combined visible-light and ultrasound process improved the treatment performance [88]. WO_3 has also been investigated in photocatalytic ozonation for pharmaceutical pollutants such as cephalexin [89]. However, charge-carrier recombination and poor reduction ability can restrict pristine WO_3 performance [90].

4.7 Cerium oxide (CeO_2) nanoparticles

CeO_2 nanoparticles have been investigated for pharmaceutical remediation because of their redox properties and oxygen-storage capacity. The Ce^{3+}/Ce^{4+} redox couple and oxygen vacancies can influence their photocatalytic activity [91]. CeO_2 has been used for the photocatalytic degradation of ciprofloxacin under simulated solar light. Photogenerated holes were identified as major active species in that process. However, pristine CeO_2 has limited visible-light activity because of its relatively high band gap [92]. Doping and heterojunction formation have therefore been used to improve visible-light absorption and charge separation [91].

4.8 Molybdenum disulfide (MoS_2) nanomaterials

MoS_2 is a two-dimensional transition-metal dichalcogenide with layered structures and tunable electronic properties. Its remediation potential includes both adsorption and photocatalytic degradation. MoS_2 nanosheets have been shown to adsorb pharmaceutical and personal-care compounds such as erythromycin and 17β-estradiol [93]. MoS_2-based photocatalysts have also been investigated for antibiotics such as ciprofloxacin. In one study, MoS_2–biochar achieved 92.01% ciprofloxacin photodegradation, compared with 44.50% for MoS_2 alone. Aggregation and inefficient electron migration can limit pristine MoS_2 performance [94].

4.9 MXenes

MXenes are two-dimensional transition-metal carbides and nitrides with high surface area, hydrophilic surfaces, and tunable functional groups. These properties make them attractive for pharmaceutical adsorption and other water-treatment processes. MXene-based materials have been investigated for adsorption, photocatalysis, and membrane separation of pharmaceutical contaminants [95]. Their surface terminations can influence interactions with pharmaceutical molecules. Recent studies have also focused on modifying MXenes to improve adsorption capacity and reusability [96]. However, synthesis cost, oxidation, and scale-up remain important challenges [95].

4.10 Carbon nanotubes (CNTs)

Hanbali et al., (2020) assess the use of a multiwall carbon nanotube after derivatization and magnetization as a new and renewable absorbent for removing ibuprofen (Ibu) from an aqueous medium. They reported that the adsorbents were prepared by first oxidizing a multiwall carbon nanotube and then deriving the oxidized product with hydroxyl amine (m-MWCNT–HA), hydrazine (m-MWCNT–HYD), and amino acid (m-MWCNT–CYS). The results show that the optimal pH for nearly complete removal of Ibu in a short time at room temperature was 4 for three adsorbents. The adsorption followed the Langmuir isotherm model with pseudo-second-order kinetics. The percentage of removal of ibuprofen reached up to 98.4%, 93%, and 61.5% for m-MWCNT–CYS, m-MWCNT–HYD, and m-MWCNT–HA respectively.

Almanassra et al., (2020) synthesized carbide derived carbon (CDC) for the first time as a new adsorbent to remove ibuprofen from synthetic water and wastewater effluent. They reported that the effects of CDC dosage, temperature, initial pH and agitation speed on the adsorption process were examined by using batch adsorption experiments. Adsorption and kinetic equilibrium data demonstrate that the adsorption of ibuprofen onto the CDC obeys the Langmuir isotherm model and the kinetics follow the pseudo-2nd order mechanism. The thermodynamic results reveal that ibuprofen adsorption is endothermic and spontaneous. The ibuprofen removal by CDC was mainly controlled by the electrostatic forces at high pH of the feed solution and by the dispersive interactions in acidic media. The ibuprofen removal is promoted at high temperature, high agitation speed and low pH. The highest adsorption capacity of ibuprofen onto the CDC was 367 mg/g at pH 3.

4.11 Multiwalled Carbon Nano-tubes (MWCNTs)

Recently, multiwalled carbon nanotubes (MWCNTs) have been introduced as novel adsorbents which are shown to be useful in different types of waste treatments [99], [100]. High porosity, multilayered, cost affectivity, biocompatibility, and capacity of MWCNTs make them ideal adsorbents to remove

various toxic compounds from aqueous solutions [101], [102].

The adsorption performance and functionality of polysaccharide-based adsorbents can be enhanced by incorporating inorganic or carbonaceous fillers into the polysaccharide matrix. For example, magnetic chitosan nanocomposites have been developed for contaminant removal, while $CoFe_2O_4$/activated carbon@chitosan composites have demonstrated high removal efficiency for ciprofloxacin from aqueous solutions [103], [104].

Beyond raw carbon nanotubes and activated carbon individually, modified adsorbents have also been developed to target specific antibiotics. Activated carbon modified with the cationic surfactant hexadecyl trimethyl ammonium bromide was found to be highly effective at adsorbing the sulfonamide antibiotics sulfamethazine and sulfamethoxazole [105]. In a different approach, nano zero-valent manganese alone was shown to degrade ciprofloxacin moderately, but combining it with peroxydisulfate ($S_2O_8^{2-}$) substantially boosted degradation efficiency via hydroxyl and sulfate radical generation [106]. A photocatalytic route was also explored, engineering CNT/$LaVO_4$ nanostructures that degraded tetracycline roughly twice as fast as pure $LaVO_4$, an improvement attributed to better separation and transfer of photogenerated charge carriers [107].

The removal of pharmaceuticals by MWCNTs occurs primarily through adsorption involving multiple interactions, including π–π interactions, hydrophobic interactions, electrostatic interactions and hydrogen bonding. The graphitic, sp^2-hybridized surface of MWCNTs provides π-electron-rich domains that can interact with aromatic pharmaceutical structures through π–π coupling or electron-donor–acceptor interactions [108], [109].

Tetracycline is particularly amenable to adsorption onto MWCNTs because its aromatic and conjugated structure can interact with the graphitic domains of the nanotubes. The adsorption process is influenced by the oxygen-containing functional groups present on the MWCNT surface, with π-related interactions occurring alongside hydrophobic and electrostatic interactions [110]. Differences in pharmaceutical molecular characteristics, including hydrophobicity, polarity, and substituent groups, can also affect their affinity for MWCNT surfaces and consequently influence their adsorption behavior [109].

4.12 Carbon dots (CDs)

Carbon dots possess unique photophysical and chemical properties such as light-harvesting over a broad-spectrum region, upconversion photoluminescence, photosensitizers, chemical inertness, and bivalent redox character, etc [111]. The ease of synthesis of carbon dots at low cost also contributes hugely to their utilizations as an efficient photocatalyst for the degradation of aqueous pollutants [111].

To date, there is no report in literature where bare carbon dots were utilized for the photodegradation of antibiotics. Only C-dots hybrids thus far fit the purpose [111]. However, there are few reports where C-dots were utilized as active light-harvesting material and generated electron–hole pairs transferred to other catalysts. For instance, Sharma et al., (2017) fabricated trimetallic La/Cu/Zr C-dots hybrids and tested them for photodegradation of malachite green dye and ampicillin antibiotic, under visible light irradiation. Trimetallic nanoparticles hybrid fabrication resulted in bandgap reduction of bare C-dots from 2.55 to 1.56 eV, which lead to enhanced light absorption in the visible region, the key to increase the photocatalytic properties of the composite. 96% of ampicillin antibiotic and 75% of malachite green was removed by La/Cu/Zr C-dots hybrid after 4 h of photodegradation. It is however worth noting that adsorption alone (in dark for 1 h) was able to remove 88% of ampicillin and 48% of dye, before 4 h of photodegradation, suggesting the important role of these materials in lowering the antibiotic/dye concentration in the wastewater.

Photodegradation of antibiotics conducted under just UV-light also shows enhanced efficiencies for C-dots hybrids, compared to bare semiconductors, a case consistent with dye photodegradation. C-dots strongly absorb in UV range, which results in the generation of even more electron–hole pairs, now contributing to photodegradation. Further, C-dots can

accept photogenerated electron–hole pairs and enhance efficiencies [111]. For instance, Di et al., (2017) tested (N-CQDs)/BiPO4 hybrid and bare BiPO4 for photodegradation of antibiotic CIP, enrofloxacin, tetracycline, and phenol 4-chlorophenol under UV irradiation. 87.5% of CIP was photodegraded with (N-CQDs)/BiPO4 compared to 64.4% with BiPO4 under identical testing conditions.

4.13 Graphitic Carbon Nitride (g-C_3N_4)

Graphitic carbon nitride (g-C_3N_4) has attracted attention as a metal-free semiconductor for photocatalytic water treatment because of its visible-light photocatalytic activity and chemical stability [114]. Despite these advantages, pristine g-C_3N_4 has limitations such as inefficient separation of photogenerated charge carriers and a relatively low surface area, which can reduce its photocatalytic efficiency. Consequently, various modification strategies, including morphology control, heteroatom doping and heterostructure construction, have been developed to improve its photocatalytic performance [115].

g-C_3N_4-based photocatalysts have been investigated for the degradation of pharmaceutical pollutants, including antibiotics and non-antibiotic pharmaceuticals [115]. In the treatment of diclofenac, carbon quantum dot-modified porous g-C_3N_4 achieved approximately 15-fold higher degradation kinetics than pristine g-C_3N_4, with the enhanced performance attributed to improved charge-carrier separation and modification of the material's band structure [116].

For tetracycline degradation, g-C_3N_4 has increasingly been incorporated into Z-scheme photocatalytic systems, which can improve photogenerated charge-carrier separation while maintaining strong redox capabilities and visible-light utilization [117]. These studies demonstrate the potential of g-C_3N_4 for pharmaceutical degradation while indicating that modification of the pristine material can improve its performance.

Heterojunction construction has become an important strategy for improving the photocatalytic performance of g-C_3N_4. In particular, g-C_3N_4-based Z-scheme photocatalysts have been investigated for tetracycline degradation because their configuration can promote effective charge-carrier separation while retaining strong redox ability and visible-light utilization [117]. Importantly, pharmaceutical degradation does not necessarily indicate complete mineralization, and studies employing advanced analytical techniques have identified transformation products during g-C_3N_4 photocatalysis, as demonstrated for diclofenac [116].

Evidence from real wastewater is particularly valuable because it provides a more realistic assessment of photocatalytic performance than experiments conducted solely with prepared laboratory solutions. In a pilot-scale study using secondary effluent from a hospital wastewater treatment plant, g-C_3N_4 under solar irradiation removed all ten detected pharmaceutical compounds by more than 54% at an optimum catalyst loading of 200–300 mg L^{-1}; however, catalyst reuse over two consecutive cycles resulted in a significant decrease in removal efficiency [118]. In a separate study, a 1% MoS_2/g-C_3N_4 composite achieved higher removal rates than pristine g-C_3N_4 for ten psychiatric pharmaceuticals in real hospital wastewater, with removal rates above 54% compared with above 30% for g-C_3N_4; transformation products formed during treatment were also investigated [119].

4.14 Metal–Organic Frameworks (MOFs)

Metal–organic frameworks (MOFs) have attracted interest as adsorbents for pharmaceutical contaminants because of their adjustable composition, diverse structures, high surface area, controllable pore size and recyclability, which can facilitate the removal of pharmaceutical and personal-care contaminants from water [120].

For example, the porphyrinic zirconium MOF PCN-224 was investigated for the adsorption and photocatalytic removal of tetracycline and ciprofloxacin from water. The 300-nm PCN-224 exhibited adsorption capacities of 354.81 mg g^{-1} for tetracycline and 207.16 mg g^{-1} for ciprofloxacin, with hydrogen bonding, π–π interactions and electrostatic attraction identified as important adsorption interactions [121]. The same study showed that PCN-

224 could be regenerated through visible-light photocatalysis and retained more than 85% adsorption–desorption efficiency after five cycles, demonstrating the potential for combining contaminant capture with photocatalytic regeneration [121].

Magnetic modification has been investigated to facilitate the recovery and reuse of MOF-based adsorbents. An Fe_3O_4@Zr-MOF nanocomposite exhibited a maximum tetracycline adsorption capacity of 942.12 mg g^{-1} and could be readily separated from aqueous solution using a magnetic field. The adsorbent retained its chemical composition and crystallinity after repeated use, demonstrating its potential for recovery and reuse in tetracycline removal [122].

The removal of pharmaceutical contaminants by MOFs is influenced by interactions between the pharmaceutical molecules and the structural and chemical characteristics of the framework, with mechanisms including hydrogen bonding, electrostatic interactions, π–π interactions and pore-related adsorption [120].

Despite the promising adsorption performance reported for MOFs, their application for pharmaceutical removal still requires further investigation, particularly regarding adsorption mechanisms, material recyclability and the development of MOFs with suitable properties for effective removal of pharmaceutical contaminants from wastewater [120].

4.15 Silver Nanoparticles (AgNPs)

Silver nanoparticles (AgNPs) have been investigated as components of semiconductor photocatalysts for pharmaceutical-contaminated water because incorporating Ag into TiO_2 can extend photocatalytic activity toward visible light, reduce photogenerated electron–hole recombination, and enhance antibacterial performance [123]. Ag/TiO_2 photocatalysts have demonstrated potential for degrading pharmaceutical compounds, including antibiotics, while some systems can simultaneously contribute to bacterial inactivation [124], [125]. Ag/TiO_2 has been investigated for the treatment of pharmaceutical-contaminated water under simulated sunlight, demonstrating the potential of silver modification to enhance TiO_2-based photocatalysis [124]. In one study, the Ag/TiO_2 photocatalyst was applied to simulated hospital wastewater containing five pharmaceutical compounds, with the highest overall photodegradation achieved using 0.1% Ag/TiO_2, a catalyst concentration of 1000 ppm, a calcination temperature of 300 °C, and pH 5. However, the optimum pH varied among the pharmaceuticals, which was attributed to differences in their pKa values. These findings demonstrate the potential of Ag-modified TiO_2 for the simultaneous treatment of multiple pharmaceutical contaminants rather than only individual model compounds [124].

More recent research has demonstrated the effectiveness of Ag–TiO_2 for visible-light degradation of pharmaceutical antibiotics. Under 240 min of visible-light irradiation, Ag–TiO_2 nanoparticles achieved 92% degradation of ciprofloxacin and 94% degradation of norfloxacin, with degradation rate constants approximately 2.1 and 1.7 times higher, respectively, than those obtained with commercial TiO_2 P25. The enhanced degradation was mainly associated with the contribution of photogenerated holes and hydroxyl radicals (•OH), while the Ag–TiO_2 nanoparticles maintained their photocatalytic activity over five consecutive ciprofloxacin-treatment cycles, with only an 8% decrease in efficiency. In addition to pharmaceutical degradation, the nanoparticles demonstrated antibacterial activity against Escherichia coli, indicating their potential for simultaneously addressing pharmaceutical contamination and microbial pollution in water [125]. Ag nanoparticles have also been incorporated into more complex heterojunctions to enhance the photocatalytic degradation of pharmaceutical contaminants under visible light. An Ag/g-C_3N_4/ZnO nanorod heterojunction was developed and evaluated against paracetamol, cefalexin and amoxicillin at a concentration of 40 mg/L, demonstrating the potential of Ag-based composite photocatalysts for treating multiple pharmaceutical contaminants [126]. Using a relatively low catalyst dosage of 0.08 g/L, the composite achieved degradation efficiencies of 85.3% for paracetamol, 71.74% for cefalexin and

41.36% for amoxicillin after 180 min. The Ag-containing heterojunction also showed greater paracetamol degradation than pristine g-C_3N_4, ZnO nanorods and the g-C_3N_4/ZnO heterostructure, while 78% paracetamol degradation was retained after five cycles, indicating good reusability and chemical stability [126].

Immobilisation of Ag/TiO_2 within a 3D-printed chitosan scaffold has also been investigated as a strategy for supporting the photocatalyst during pharmaceutical degradation Chitosan/Ag/TiO_2 scaffolds containing 10, 100 and 1000 ppm Ag were evaluated under UV–Vis irradiation using amoxicillin, paracetamol and their 1:1 mixture as target pharmaceuticals [127]. The Chitosan/Ag_{100}/TiO_2 system achieved complete removal of the selected pharmaceuticals in approximately 2 h [127]. LC–MS was used to identify the resulting degradation products, which were subsequently assessed for their toxicological impact against six bacterial strains; no antibacterial activity was detected for the identified degradation products under the experimental conditions, these findings demonstrate why evaluating transformation products and their residual biological activity is important, since disappearance of the parent pharmaceutical does not necessarily establish that the resulting products are biologically inactive [127].

The feasibility of producing Ag/TiO_2 at a larger preparation scale has also been demonstrated through the gram-scale synthesis of mesoporous Ag/TiO_2 for paracetamol removal under natural sunlight [128]. Incorporation of 1 wt% Ag enhanced the photocatalytic performance of TiO_2, with the Ag-containing material exhibiting improved visible-light response and charge separation [128]. The enhanced activity was associated with the Ag–TiO_2 interface, which promotes charge separation and suppresses electron–hole recombination, together with improved utilization of visible light (Cherif et al., 2023).

Recent research has further expanded the assessment of Ag/TiO_2 beyond parent-compound removal to include antibiotic activity and microbial inactivation. The photocatalytic treatment of levofloxacin under simulated solar irradiation has been investigated using TiO_2 and Ag/TiO_2, both in the presence and absence of peroxydisulfate [129]. The combined light/catalyst/peroxydisulfate system promoted levofloxacin degradation and reduced its residual antibiotic activity, while also producing effective E. coli inactivation. LC–MS analysis identified transformations involving the piperazine ring, carboxylic acid and cyclic ether moieties of levofloxacin, linking the reduction in antibiotic activity to chemical transformation of the parent compound [129].

4.16 Nanostructured biochar

Biochar, a carbon-rich and porous material, offers a promising solution for the remediation of PCs, particularly when modified [130]. Modified biochar enables multiple adsorption mechanisms, including pore diffusion, electrostatic interactions, hydrophobic effects, hydrogen bonding, and π–π interactions, which act synergistically to remove PCs from water [130]. The demand for sustainable, eco-friendly adsorbents has led to biochar-based materials emerging as a green, effective solution for removing PCs using adsorption methods [131].

Hamadeen & Elkhatib, (2022) assessed the nanostructured activated biochar (nPPAB) derived from pomegranate peels (PP) as a promising sorbent for efficient removal of the antibiotic ciprofloxacin (CIP). The results affirm that the second order and Langmuir models fit well to adsorption kinetics and equilibrium data respectively. The nPPAB adsorption capacity of Langmuir (qmax) for CIP was 142.86 mg g-1 which is 26.85 times greater than that of bulk PP. Hydrogen bonding, π-π interaction, hydrophobic and electrostatic interactions are the dominant mechanisms of CIP adsorption by nPPAB. The efficiency of nPPAB for CIP removal from real wastewater using batch and packed-bed reactor were 89.94 and 84.74% respectively.

El-Azazy et al., (2023) used mango seeds kernel (MSK), both as a pristine biochar (Py–MSK) and as a nano-ceria-laden (Ce–Py–MSK) were applied for the remediation of rifampicin (RIFM) and tigecycline (TIGC). To save time and resources, adsorption experiments were managed using a multivariate-based scheme executing the fractional factorial

design (FrFD). Percentage removal (%R) of both antibiotics was exploited in terms of four variables: pH, adsorbent dosage, initial drug concentration, and contact time. Preliminary experiments showed that Ce–Py–MSK has higher adsorption efficiency for both RIFM and TIGC compared to Py–MSK. The %R was 92.36% for RIFM compared to 90.13% for TIGC. Isotherm parameters also revealed that Freundlich model best fit Ce–Py–MSK–drug interactions. A maximum adsorption capacity (qm) of 102.25 and 49.28 mg/g was attained for RIFM and TIGC, respectively.

V. KNOWLEDGE GAPS

Despite the growing application of nanomaterials for the remediation of pharmaceutical contaminants, several knowledge gaps remain. A major limitation of existing studies is the frequent use of single pharmaceutical compounds in controlled aqueous solutions, which may not adequately represent the complexity of real wastewater. Pharmaceutical contaminants commonly occur as mixtures and coexist with organic matter, inorganic ions and other pollutants that can compete for active sites and influence catalytic or adsorption processes. Therefore, the performance and selectivity of nanomaterials under realistic wastewater conditions require further investigation.

Another important gap concerns the relationship between pharmaceutical removal and actual detoxification. High removal efficiencies do not necessarily indicate complete degradation, since transformation products may remain in the treated water. Although advanced analytical techniques such as LC-HRMS can identify pharmaceutical residues and transformation products, their integration with nanomaterial-based remediation studies remains limited. More research is therefore needed to establish degradation pathways and evaluate the potential toxicity of transformation products.

The long-term stability, recovery and reusability of nanomaterials also remain insufficiently addressed. Problems such as aggregation, oxidation, surface passivation and loss of catalytic activity can reduce treatment performance over repeated cycles. In addition, the possible release of nanoparticles into treated water raises concerns about secondary environmental contamination. Consequently, the development of stable, recoverable and environmentally compatible nanomaterials remains an important research priority.

Finally, there is a gap between laboratory-scale demonstrations and practical wastewater treatment applications. Many promising nanomaterials have been evaluated under optimized laboratory conditions, while their performance in complex wastewater matrices, long-term operation and large-scale treatment systems remains less understood. Addressing these gaps will require research that combines material optimization with realistic wastewater testing, regeneration studies, mechanistic investigation and assessment of environmental safety. These efforts are essential for translating nanomaterial-based pharmaceutical remediation from laboratory research into sustainable and scalable water-treatment technologies.

VI. FUTURE RECOMMENDATIONS

Further research should pay attention to the effect of ionic strength, natural organic matter, pH, and other suspended solids. Relying mainly on laboratory-prepared solutions should also be replaced with evaluating nano-materials based pharmaceutical removal under realistic wastewater conditions.

In addition, toxicity assessments should be carried out to determine the less toxicity or high toxicity of the transformation products compared to the original pharmaceutical compounds. There should be a means whereby investigation of the performance of nanomaterials over several regeneration cycles can take place, and the extent of nanoparticles or metal-ion leaching into treated water can be determined.

Conclusively, environmentally friendly and economically viable methods should be developed to synthesize nanomaterials. Agricultural wastes, microorganisms, plant extracts, and other renewable resources for the green synthesis of nanomaterials and nanocomposites should be explored. This exploration will reduce the use of energy-intensive

preparation process and toxic chemicals while enabling the conversion of locally available wastes into valuable treatment materials.

Author Contributions

Al-islam Abimbola Balogun conceptualized the review and wrote the Introduction, Pharmaceutical Pollutants and Occurrences. He also compiled and formatted the final manuscript.

Samuel Inaolaji Olusesan wrote the sections on Sources, and part of the Remediation using Nanomaterials.

Wajiat Adebukola Salaudeen wrote the section on Pharmaceutical Pollutants, Public Health Implications, and the remaining part of the Remediation using Nanomaterials section.

All three authors contributed to writing the Knowledge Gaps and Future Recommendations sections, and all authors read, reviewed, and approved the final manuscript.

Acknowledgements

The authors wish to acknowledge and thank one another for the collaborative effort, commitment, and mutual support shown throughout the preparation of this review article.

Conflict of Interests

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary materials of the article.

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