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ADVANCED NANOMATERIAL SURFACES FOR THE DETECTION AND REMOVAL OF ORGANIC AND MICROBIAL POLLUTANTS IN WATER: A REVIEW

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ABSTRACT

Water security increasingly depends on confronting two distinct but related problems: organic micropollutants pesticides, dyes, pharmaceuticals, endocrine disruptors and per- and polyfluoroalkyl substances and microbial contaminants ranging from antibiotic-resistant bacteria to enteric viruses. Both categories are typically present at very low concentrations, both must be reliably measured before they can be treated, and both have historically been handled by separate technologies and instruments. This review takes the surface chemistry of advanced nanomaterials as the unifying thread. We argue that the same features high specific area, accessible donor groups, photoactive band structures and tunable porosity that allow a nanostructured surface to bind, signal or transduce an analyte are very often the features that allow that same surface to degrade, sequester or inactivate the contaminant. We survey the principal material families (semiconductor photocatalysts including TiO_2, ZnO and g-C_3N_4, carbon-based materials, plasmonic metals, MOFs and COFs, magnetic iron oxides and MXenes) and the corresponding analytical approaches: electrochemical sensors, surface-enhanced Raman scattering, fluorescent quantum-dot and carbon-dot probes, and aptamer- and antibody-based bio-recognition platforms. We then turn to adsorptive, photocatalytic and antimicrobial mechanisms including reactive-oxygen-species generation, contact-mediated membrane disruption and oligodynamic ion release and to the emerging class of dual-function "same-surface" platforms that perform detection and remediation in a single step. Practical challenges of selectivity in real matrices, regeneration, biocompatibility and scale-up are highlighted, together with the directions that are most likely to bring laboratory performance into field deployment.

INTRODUCTION

Two broad classes of pollutants now dominate the global water-quality agenda: organic micropollutants pesticides, dyes, pharmaceuticals, endocrine disruptors, and per- and polyfluoroalkyl substances (PFAS) and microbial pollutants, including pathogenic bacteria, viruses, protozoan cysts and the steadily more worrying class of antibiotic-resistance genes (ARGs) [1–3]. Although chemically and biologically very different, the two categories share a few inconvenient properties from an engineering point of view. Both are typically present at trace concentrations nanograms to micrograms per litre for most organics, and tens of colony-forming units per millilitre or fewer for indicator bacteria in finished water. Both require sensitive analytical methods before any remediation decision can sensibly be made, and both are routinely handled by separate technologies and separate laboratories. Detection has tended to mean chromatography or culture; removal has tended to mean activated carbon, chlorination, ozonation or membrane filtration.

Advanced nanomaterials offer a different way of organising the problem. As particle dimensions shrink, the fraction of atoms residing at the surface climbs steeply, and that surface is, conveniently, the same place where an analyte is recognised during a measurement and

where a contaminant is captured, degraded or inactivated during treatment [4,5]. High specific surface area, abundant accessible functional groups, designable porosity and in many semiconductors a photoactive band structure together make the same nanostructured platform a useful sensor and a useful remediation agent. The present review follows this thread for the two pollutant classes in turn. We survey the principal material families, summarise the analytical strategies that have been built around them, describe the adsorptive, photocatalytic and antimicrobial mechanisms by which they remove or inactivate contaminants, and then look at the still-young but rapidly growing class of dual-function platforms that combine detection and remediation on a single surface.

2. Organic and Microbial Contaminants in Water: Sources, Risks and Regulatory Context

Organic micropollutants enter natural waters through routes that are essentially impossible to switch off. Agricultural runoff carries pesticides such as atrazine, glyphosate and the more recent neonicotinoids; municipal wastewater discharges contribute pharmaceuticals antibiotics, hormones, NSAIDs, anti-epileptics as well as personal-care residues; industrial effluents add dyes, phenolics, polycyclic aromatic hydrocarbons and persistent fluorinated compounds [3,6]. PFAS, the so-called "forever chemicals", have become emblematic of the broader problem: their extremely stable C–F bonds make them resistant to conventional treatment, they accumulate in biological tissues, and the United States Environmental Protection Agency in April 2024 set the first enforceable national limits at 4 ng L^{-1} (parts per trillion) for both PFOA and PFOS, and 10 ng L^{-1} for PFHxS, PFNA and GenX [7]. By contrast, the WHO drinking-water guideline for atrazine is 100 µg L^{-1} about four orders of magnitude higher while the US EPA lifetime health advisory level for the same herbicide is 3 µg L^{-1} [6,8].

Microbial pollutants are equally diverse and equally difficult to monitor. Faecal contamination of source water carries Escherichia coli, Salmonella, Shigella and Campylobacter, enteric viruses such as norovirus and rotavirus, and protozoa including Cryptosporidium and Giardia. The compliance benchmark in essentially every regulatory framework is the absence of E. coli in 100 mL of finished drinking water and the absence of total coliforms [1,9]. Beyond the classical pathogens, two phenomena have raised the analytical stakes considerably. The first is the increasing prevalence of antibiotic-resistant bacteria (ARB) and the associated resistance genes (ARGs) in wastewater, which complicate both detection and removal: even successful inactivation of culture-viable cells may leave intact resistance-encoding DNA in the effluent. The second is the appearance of viable-but-non-culturable (VBNC) cells, which evade standard culture-based monitoring while remaining potentially infectious [10].

The toxicological endpoints differ but overlap in their consequences. Organic micropollutants are linked to endocrine disruption, carcinogenicity, reproductive and developmental effects and immune dysfunction, often at concentrations well below the analytical detection limits of older instruments [3,7]. Microbial contaminants produce acute waterborne disease diarrhoea remains a leading cause of paediatric mortality in low- and middle-income settings but they also act over longer time scales, both through low-level chronic exposure and through their role in disseminating resistance. The practical conclusion is the same in both cases: any analytical platform intended for compliance monitoring must reach detection limits comfortably below the regulatory threshold, and any treatment process must achieve removal or inactivation down to the same range. Representative limits for both pollutant classes are collected in Table 01.

Table 01: Representative organic and microbial contaminants in drinking water, with their classes and regulatory thresholds.

Contaminant	Class	Regulatory limit	Health relevance
Atrazine	Herbicide	EPA 3 µg L^{-1}; WHO 100 µg L^{-1}	Endocrine disruption; reproductive effects
Glyphosate	Herbicide	EPA 700 µg L^{-1}	Debated genotoxicity
PFOA / PFOS	Per-/polyfluoroalkyl	EPA 4 ng L^{-1} each (2024)	Cancer; immune and developmental effects
PFHxS / PFNA / GenX	Per-/polyfluoroalkyl	EPA 10 ng L^{-1} each (2024)	Developmental and hepatic toxicity
Bisphenol A	Endocrine disruptor	EU TDI guidance; not formally MCL	Endocrine disruption
Benzene	Volatile aromatic	EPA 5 µg L^{-1}; WHO 10 µg L^{-1}	Leukaemia (carcinogen)
Sulfamethoxazole	Antibiotic	Not formally regulated in DW	Resistance selection
Methylene blue	Industrial dye (model)	Not regulated in DW	Aquatic toxicity; common test pollutant

E. coli	Bacterium (indicator)	0 CFU per 100 mL	Indicator of faecal contamination
Total coliforms	Bacterial group	Absent	Sanitary indicator
Cryptosporidium	Protozoan oocyst	< 1 oocyst per 10 L (treated)	Acute diarrhoeal disease

3. ADVANCED NANOMATERIALS: A SURFACE-CENTRED OVERVIEW

The attraction of nanomaterials for both detection and treatment comes back, repeatedly, to surface. As a bulk solid is reduced to particles of a few tens of nanometres, the surface-to-volume ratio climbs dramatically, and specific areas of hundreds to thousands of square metres per gram become routine [4]. Surface chemistry then does most of the rest: oxygen-containing groups on graphene oxide, terminal hydroxyl groups on metal oxides, thiol or amine functionalities introduced by post-synthetic modification on MOFs and silicas, and the metallic terminations on MXenes all participate in binding, recognition or catalysis. The subsections below sketch the principal families; Figure 01 summarises them schematically and Table 02 gathers the key surface characteristics.

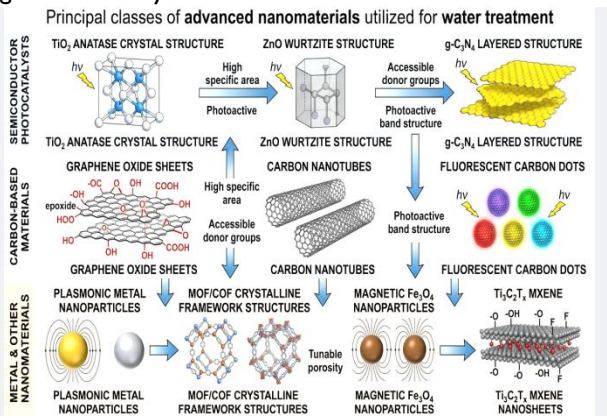

Figure 01: Illustration of the principal classes of advanced nanomaterials used for organic and microbial pollutant management, highlighting the surface features shared between sensing and remediation roles.

Table 02: Principal classes of nanomaterials and their key surface characteristics relevant to organic and microbial pollutants.

Class	Representative materials	Key surface characteristics	Principal role
Semiconductor photocatalysts	TiO_2, ZnO, g-C_3N_4, WO_3, $BiVO_4$	Band-gap excitation; ROS generation; tunable via doping/heterojunctions	Photocatalytic degradation; antimicrobial action
Carbon-based	GO, rGO, CNTs, carbon dots, activated carbon, biochar	Very high specific area; –OH, –COOH, –O– groups; π-systems	Adsorption; electrochemical and fluorescent sensing
Plasmonic metals	Ag, Au and Cu nanoparticles	Localised surface plasmon resonance; controlled Ag^+/Cu^+ release	SERS sensing; antimicrobial and photothermal action
MOFs and COFs	MOF-808, ZIF-8, UiO-66, imine COFs, porphyrin-MOFs	Ultrahigh porosity; tunable binding pockets; photoactive linkers	Selective adsorption; fluorescent sensing; photocatalysis
Magnetic nanoparticles	Fe_3O_4, γ-Fe_2O_3, magnetic nanocomposites	Reactive hydroxylated surface; magnetic separability	Capture-and-recover; preconcentration; antimicrobial carrier
MXenes and 2D materials	$Ti_3C_2T_x$ MXene, MoS_2	Terminal –O/–OH/–F groups; metallic conductivity	Electrochemical sensing; antimicrobial action; adsorption

3.1. Semiconductor photocatalysts

Anatase TiO_2 remains the prototype, much as it has been since Fujishima and Honda's 1972 demonstration of photoinduced water splitting on a TiO_2 electrode [11]. Its 3.2 eV band gap restricts intrinsic activity to UV irradiation, but doping, sensitisation and heterojunction formation with carbon, narrower-gap oxides or g-C_3N_4 have shifted activity into the visible region reductions of the effective gap to around 2.9 eV are routinely reported, and degradation efficiencies of 93–98% for the model dye methylene blue are now standard under UV or solar irradiation [12,13]. ZnO, WO_3 and $BiVO_4$ play similar roles. Graphitic carbon nitride (g-C_3N_4), first introduced as a metal-free visible-light photocatalyst in 2009, has subsequently become a workhorse for both organic-pollutant degradation and antimicrobial applications [14].

3.2. Carbon-based nanomaterials

Graphene oxide (GO), reduced GO, carbon nanotubes, activated carbons and biochars dominate the adsorption literature for organic contaminants. The Hummers oxidation [15] produces a heavily decorated material whose hydroxyl, epoxide and carboxyl groups simultaneously enable π–π stacking, hydrogen bonding and electrostatic interactions with aromatic organics

[16]. Quantum dots, both semiconductor and carbon, occupy a related slot [17]: their tunable photoluminescence drives fluorescence sensing, while their photoactivity makes them candidate photocatalysts, and several carbon-dot/TiO_2 composites have been reported to enhance the visible-light response of the parent oxide.

3.3. Plasmonic metals

Silver nanoparticles are the canonical antimicrobial nanomaterial, with the mechanistic picture established by the early work of Sondi and Salopek-Sondi and by Morones and colleagues [18,19]. They are also strong SERS substrates and effective electrochemical mediators. Gold and copper nanoparticles play overlapping but complementary roles: gold is exploited mainly for SERS and colorimetric assays through plasmon-coupled aggregation, while copper combines sensing capability with intrinsic antimicrobial activity through Cu^+ release and ROS generation. Bimetallic Ag/Au and Ag/Pt nanostructures, in which one metal moderates the release kinetics of the other, frequently outperform single-component nanoparticles in both roles.

3.4. Metal–organic and covalent organic frameworks

Metal–organic frameworks (MOFs) and covalent organic frameworks (COFs) bring crystallinity, exceptional porosity and a degree of synthetic control over binding sites that is unusual among solid sorbents [20,21]. The metal node and the organic linker can each be chosen for specific function: photoactive linkers (porphyrins, naphthalenediimides) confer visible-light absorption, Fe- or Zr-containing nodes enable Fenton or photo-Fenton chemistry, and post-synthetic functionalisation introduces task-specific groups for recognition of pesticides, antibiotics or whole bacterial cells [22,23]. The same scaffold can therefore present a binding pocket for fluorescent or electrochemical sensing and a photoactive surface for catalytic destruction a property heavily exploited in the dual-function platforms discussed in Section 6.

3.5. Magnetic nanoparticles, MXenes and other emerging materials

Iron oxide nanoparticles (Fe_3O_4, γ-Fe_2O_3) add a property no other family has: magnetic separability. They can be coated with silica, gold or polymeric shells and decorated with antibodies, aptamers or thiol/amine ligands, then recollected with a simple external magnet a workflow that dramatically simplifies handling of contaminated water samples and is heavily used in pathogen capture. MXenes [24], two-dimensional transition-metal carbides and nitrides, combine metallic conductivity with hydrophilic, easily functionalised terminations and are now widely used in both electrochemical sensing and photocatalysis. Mesoporous silicas (SBA-15, MCM-41), molecularly imprinted polymers, and various nanofibres complete the list.

4. ANALYTICAL DETECTION OF ORGANIC AND MICROBIAL POLLUTANTS

Reliable measurement remains the precondition for everything that follows. Chromatographic techniques high-performance liquid chromatography coupled to mass spectrometry (LC–MS) for non-volatile organics, gas chromatography–MS for volatile and semi-volatile species, and culture-based plate counts followed by molecular confirmation for microbes are the laboratory references against which everything else is judged [3,9]. Their sensitivity, specificity and accuracy are difficult to challenge, but they are also slow, instrument-bound and expensive, and they do not lend themselves to rapid screening or on-site decisions. Nanomaterials enter the analytical story largely as the means to bridge that gap: either as the active sensing element or as the preconcentration medium upstream of a classical instrument. Table 03 contrasts the principal techniques.

Table 03: Comparison of analytical techniques for organic and microbial pollutants (detection limits are indicative and matrix-dependent).

Technique	Typical target	Typical detection limit	Advantages	Limitations
LC–MS / GC–MS	Organic micropollutants	ng L^{-1} to pg L^{-1}	Ultra-trace, specific, multi-analyte	Costly, bench-bound
Electrochemical sensors	Organics and microbes	nM to µM; 10–40 CFU mL^{-1}	Portable, low cost, multi-target	Electrode fouling; matrix effects
SERS	Organics; microbial markers	nM to pM	Molecular fingerprint; very sensitive	Substrate reproducibility; cost
Fluorescence (QDs, MOFs, C-dots)	Organic micropollutants	nM to µM	Turn-on/off readout; sensitive	Quenching by matrix
Colorimetric (AuNP, AgNP)	Organics and microbes	µM; ~10 CFU mL^{-1}	Visual; ultra-low cost	Selectivity; lower sensitivity
Aptasensor / immunosensor	Specific organics and microbes	pM–nM; 10–40 CFU mL^{-1}	Selective; label-free options	Receptor stability
Culture-based microbiology	Microorganisms	Single cell after enrichment	Definitive gold standard	Slow (24–48 h); misses VBNC

4.1. Electrochemical sensors

Electrochemical methods are particularly well suited to handheld, low-power deployment. Cyclic voltammetry, differential-pulse voltammetry and square-wave voltammetry, combined with nanomaterial-modified electrodes, allow direct or indirect quantification of organic analytes from pesticides to pharmaceuticals down to nanomolar concentrations [25,26]. Electrochemical impedance spectroscopy (EIS), in which a binding event modulates the interfacial charge-transfer resistance at a functionalised electrode, has become a popular transduction for both organic and microbial biosensors [27]. A representative example for bacterial detection is the membrane-based impedimetric nanobiosensor of Joung and co-workers, which reaches a detection limit of 22 CFU mL^{-1} for E. coli over five orders of magnitude of linear range and discriminates between viable and non-viable cells [27].

4.2. Optical methods: SERS, fluorescence and colorimetric assays

Surface-enhanced Raman scattering (SERS), first observed by Fleischmann and colleagues in 1974 [28], exploits the enormous enhancement of Raman scattering near plasmonic nanostructures — typically Au or Ag to produce molecule-specific fingerprints at very low concentration. Enhancement factors of 10^6 or more are now routine on well-designed substrates, and detection limits at the nanomolar level have been reported for dyes, pesticides and microbial markers [29]. Fluorescence detection, often built around carbon dots, quantum dots or fluorescent MOFs, complements SERS for analytes that can be made to quench or enhance the emission of the nanomaterial [17,30]. Colorimetric assays, based on aggregation of gold or silver nanoparticles or on the intrinsic peroxidase-like activity of bimetallic nanoplates, offer the simplest readout sometimes literally a visible colour change and are particularly attractive for low-resource settings; a recent bimetallic Ag/Pt nanoplate aptasensor for E. coli, for instance, achieves a detection limit of about 10 CFU mL^{-1} with a thirty-minute total assay time [31].

4.3. Bio-recognition: aptamers, antibodies and molecularly imprinted polymers

Bio-recognition adds selectivity. Aptamers short single-stranded oligonucleotides selected against a specific target can be raised against essentially any analyte from a small organic molecule to a whole bacterial cell. Immobilised on a nanomaterial surface, they convert the surface into a selective bioelectrode or SERS substrate [32]. Aptasensors for E. coli with detection limits of 22–37 CFU mL^{-1} on functionalised electrodes [27], and as low as 10 CFU mL^{-1} on Ag/Pt nanoplate colorimetric platforms [31], have been reported. Antibody-functionalised magnetic nanoparticles allow specific capture and concentration of target bacteria from large sample volumes [33]. Molecularly imprinted polymers (MIPs), in which a synthetic polymer is templated against a target organic molecule, provide an antibody-like recognition for small molecules at far lower cost and with greater chemical robustness; they are now routinely coupled to electrochemical, fluorescent and SERS transduction [34].

4.4. Nanomaterial-assisted preconcentration

A second analytical role for nanomaterials is to feed the classical instruments. Solid-phase extraction on magnetic carbon, MOF or functionalised silica nanoparticles concentrates trace organics from large water volumes before LC–MS or GC–MS quantification, easily lowering the working detection limit by two to three orders of magnitude and making sub-ng L^{-1} analysis of PFAS and pharmaceuticals practical [3,35]. The same chemistry that makes these materials good preconcentrators also makes them, downstream, good adsorbents the seam between detection and removal that the dual-function platforms exploit.

5. REMOVAL AND INACTIVATION MECHANISMS

5.1. Adsorption of organic pollutants

Adsorption remains the most economically attractive route for removing organic micropollutants from water. Activated carbon, GO, biochar and porous frameworks dominate the field [16,36]. The dominant interactions depend on the analyte: hydrophobic and π–π interactions for aromatic dyes and pharmaceuticals, hydrogen bonding for polar pesticides, electrostatic attraction or ion exchange for charged molecules at appropriate pH, and pore-filling in the case of microporous MOFs and COFs. Activated carbon retains dominance for many organics on cost grounds, but the literature on functionalised GO and MOFs reports far higher capacities at lower loadings, particularly for emerging pollutants such as PFAS for which conventional sorbents perform poorly. Equilibrium and kinetic models are summarised in Table 4.

Table 04: Common adsorption isotherm and kinetic models applied to the uptake of organic pollutants on nanomaterials.

Model	Category	Underlying assumption	Information obtained
Langmuir	Isotherm	Monolayer adsorption on energetically uniform sites; saturating	Maximum capacity q_{max}; affinity; favourability (R_L)
Freundlich	Isotherm	Heterogeneous surface; empirical power law	Heterogeneity/intensity (n); relative capacity (K_f)
Temkin	Isotherm	Heat of adsorption decreases linearly	Adsorption-energy (heat) parameter

		with coverage	
Dubinin–Radushkevich	Isotherm	Pore-filling on a heterogeneous surface	Mean free energy E (physisorption vs chemisorption)
Pseudo-first-order	Kinetic	Rate proportional to number of unoccupied sites	Rate constant k_1; physisorption-leaning uptake
Pseudo-second-order	Kinetic	Rate proportional to the square of unoccupied sites	Rate constant k_2 and q_e; often read as chemisorption
Intraparticle diffusion (Weber–Morris)	Kinetic	Uptake varies with √t when pore diffusion controls	Diffusion rate; rate-limiting step
Elovich	Kinetic	Chemisorption on energetically heterogeneous surface	Initial sorption rate; desorption constant

5.2. Photocatalytic degradation

Photocatalysis is the most distinctive transformation that nanomaterials add to the toolkit. On illumination, a semiconductor photocatalyst absorbs a photon, promoting an electron from the valence band to the conduction band and leaving a hole behind. Both species can react with surface-bound water or oxygen to generate reactive oxygen species predominantly hydroxyl radicals (•OH) and superoxide anion radicals (O_2•$^-$) which then attack any adsorbed organic pollutant in a sequence of oxidation steps that typically ends in CO_2, water and small inorganic ions [12,42] (Figure 2). The classical photocatalyst is anatase TiO_2; degradation efficiencies of 93–98% for methylene blue under solar or UV irradiation are routinely reported [13,43], and incorporation of activated carbon or reduced GO into TiO_2 composites pushes this to 98.3 and 97% respectively under solar irradiation, with substantially improved kinetics and reusability over multiple cycles [13]. g-C_3N_4 extends activity into the visible region with comparable performance against dyes, pesticides and antibiotics, and the additional advantage of metal-free composition [14]. Photocatalytic disinfection using the same ROS chemistry to kill bacteria and viruses is a natural extension of the same surface chemistry. Representative degradation studies are gathered in Table 5.

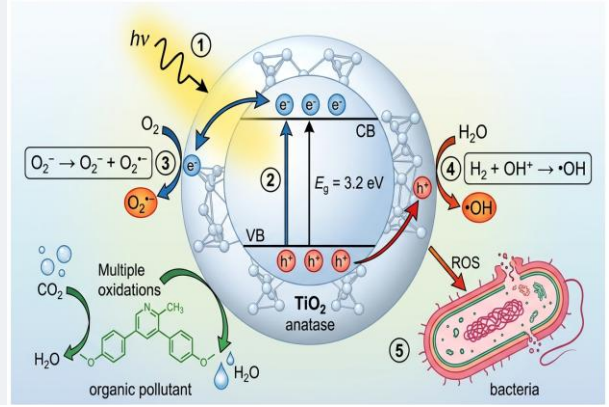

Figure 02: Illustration of the photocatalytic mechanism at a semiconductor nanoparticle surface, with reactive oxygen species attacking adsorbed organic pollutants or microbial cells.

Table 05: Representative photocatalytic degradation studies of organic pollutants on advanced nanomaterials (values are condition-dependent and indicative).

Photocatalyst	Target pollutant	Light source	Efficiency	Time	Ref.
TiO_2 (anatase)	Methylene blue	UV / solar	93–98%	~140 min	[13, 43]
TiO_2 / activated carbon	Methylene blue	Solar	98.3%	138 min	[13]
TiO_2 / reduced GO	Methylene blue	Solar	97%	~140 min	[13]
g-C_3N_4 (metal-free)	Dyes; antibiotics	Visible	80–95%	60–180 min	[14]
Cu_2O / g-C_3N_4 (Z-scheme)	Methyl orange	Visible	98.3%	90 min	[51]
Fe-NU-1003 MOF	Chloramphenicol	Visible	~100% (61% mineralised)	30 min	[49]
ZnO / Fe_3O_4 composite	Pesticides	UV-visible	80–95%	60–120 min	[36]

5.3. Antimicrobial action

The antimicrobial action of nanomaterials operates through several overlapping mechanisms (Table 6). Silver nanoparticles release Ag^+ ions, which bind sulfur- and phosphorus-containing biomolecules in the cell wall and respiratory chain, disrupt energy metabolism and ultimately cause cell death; the released ions can also interact with bacterial DNA [18,19]. ROS generation, either light-driven (TiO_2, g-C_3N_4, ZnO) or surface-driven (CuO, MnO_2, GO), inflicts oxidative dam-

age on cell membranes and intracellular biomolecules and is the dominant mechanism for photocatalytic disinfection [44]. Direct physical interaction with the cell membrane graphene oxide sheets acting as molecular blades that puncture or wrap the cell, and the sharp edges of MXene flakes inserting into the membrane has been documented experimentally and reproduced in computational studies [45,46]. The synergy between Ag^+ release and GO membrane interaction in GO–Ag nanocomposites typically give the highest antibacterial efficiencies, with reductions in viable count exceeding 99% routinely achieved against E. coli and Staphylococcus aureus [45,47]. Photothermal inactivation, exploiting the localised heating around plasmonic gold or copper-sulfide nanoparticles under near-infrared illumination, adds a fourth distinct route, particularly useful against biofilms.

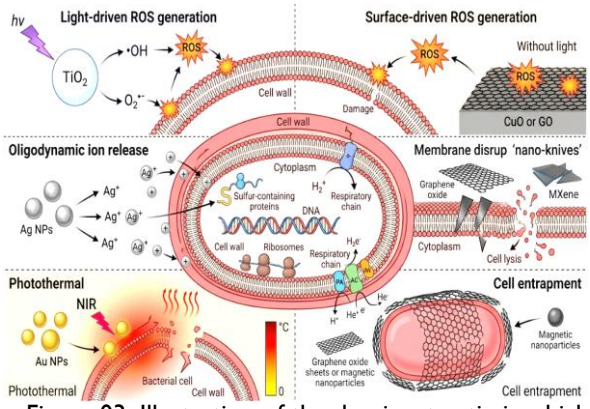

Figure 03: Illustration of the dominant antimicrobial mechanisms operating at a functionalised nanomaterial surface.

Table 06: Principal mechanisms of antimicrobial action of nanomaterials and the surface features that drive them.

Mechanism	Representative materials	Target structures	Outcome
ROS generation (light-driven)	TiO_2, ZnO, g-C_3N_4, $BiVO_4$	Membrane, DNA, proteins	Oxidative damage; cell death
ROS generation (surface-driven)	CuO, GO, MnO_2	Membrane lipids and biomolecules	Oxidative damage; growth inhibition
Oligodynamic ion release	Ag, Cu nanoparticles	S/P biomolecules; DNA; respiratory chain	Metabolic disruption; cell death
Membrane disruption (“nano-knives”)	GO sheets, MXene flakes	Bacterial lipid bilayer	Loss of membrane integrity; lysis
Cell entrapment / wrapping	Larger GO sheets, Fe_3O_4@Au@aptamer	Whole cells	Physical isolation and inactivation
Photothermal	Au, CuS, plasmonic nanoparticles	Whole cells; biofilms	Heat-induced lysis
Electrostatic interaction	Cationic NPs; functionalised surfaces	Negatively charged bacterial wall	Membrane permeabilisation

5.4. Operating factors

Performance in all these modes depends on a handful of operating variables. Solution pH governs surface charge and the protonation state of analyte and surface functional groups, and so controls adsorption and the speciation of generated radicals. Light intensity, wavelength and catalyst loading determine the rate of photocatalysis; oxygen concentration controls $O_2^{\bullet-}$ availability; ionic strength and natural organic matter compete for sites and can scavenge radicals. The recyclability of the material over how many cycles a catalyst or adsorbent can be regenerated without losing activity is, from an engineering standpoint, every bit as important as the headline efficiency. Several of the dual-function platforms discussed in Section 6 now report stable performance across at least five and in some cases more than two hundred consecutive cycles [13,42], which is the kind of robustness real deployment will require.

6. THE SAME SURFACE: DUAL-FUNCTION DETECTION-AND-REMOVAL PLATFORMS

If a single thread runs through the preceding sections, it is that the surface features that make a nanomaterial a sensitive sensor for organic or microbial pollutants are very largely the features that make it an effective remediator. High specific area, accessible binding groups, designable pores and photoactive band structures serve both ends. It is therefore natural-almost overdue-to ask whether one material, one surface, can do both jobs at once for these pollutants. A rapidly growing body of work answers yes, and this same-surface convergence is the conceptual core of the present review (Figure 04).

Photoactive MOFs illustrate the idea particularly clearly. Liu and co-workers built a porphyrin-decorated Zr^{4+} MOF that detected the neonicotinoid insecticide nitenpyram by fluorescence turn-off, with a detection limit of 0.03 μg mL^{-1}, and on continued illumination acted as a visible-light photocatalyst to degrade the same insecticide with 95% efficiency [48]. Ran and colleagues encapsulated horseradish peroxidase inside an iron-functionalised mesoporous MOF (HRP@Fe-NU-

1003) and used it both to detect the antibiotic chloramphenicol and to drive its photocatalytic degradation: 50 μg mL^{-1} of the antibiotic was removed completely within 30 minutes under light, with 61% mineralisation, and the catalyst remained active over at least five cycles [49]. A conceptually similar Z-scheme heterojunction g-C_3N_4/ZnO/$NiFe_2O_4$ achieves real-time monitoring and concomitant photocatalytic removal of fluoroquinolone antibiotics on a single material [49].

Plasmonic SERS substrates married to photocatalysts give a second family of examples. A cobalt MOF sandwich-sheet showed both ultrasensitive SERS detection and photocatalytic degradation of the toxic pesticide intermediate 4-aminothiophenol on one surface [50]. A more recent Cu_2O/g-C_3N_4 p–n heterojunction reported by Liu and co-workers achieves a SERS enhancement factor of 2.43×10^6 for 4-aminothiophenol detection and a 98.3% photocatalytic degradation of methyl orange under visible light within 90 minutes, with the photocatalytic self-cleaning of the SERS substrate preserved across long-term operation about 93.7% of the initial activity is retained even after 216 days of storage [51]. The "self-cleaning" idea that the same illumination used between successive SERS measurements regenerates the substrate by destroying any residual analyte is one of the most practically appealing applications of the same-surface concept.

For microbial targets, the same-surface idea is realised somewhat differently. Magnetic capture followed by antimicrobial action on the same nanoparticle is one route: Fe_3O_4@Au@aptamer composites concentrate E. coli by magnetic separation and report the capture event electrochemically, while the gold shell provides plasmonic enhancement for an integrated SERS confirmation [33]. GO–Ag and related composites combine two simultaneous antimicrobial mechanisms (membrane disruption by GO sheets, Ag^+ release into the cell) on a surface that can also be exploited as a sensing platform [45,47]. The bimetallic Ag/Pt nanoplate aptasensor of Boroumand and co-workers detects E. coli colorimetrically at about 10 CFU mL^{-1} while the silver component of the same particle simultaneously delivers an intrinsic antimicrobial dose [31]. In every case the practical appeal is the same: a single material that signals the presence of a contaminant and then removes or inactivates it is operationally simpler than two separate steps, and the savings in instrumentation, sample handling and regeneration scale with deployment. Table 7 collects a representative selection of these dual-function platforms.

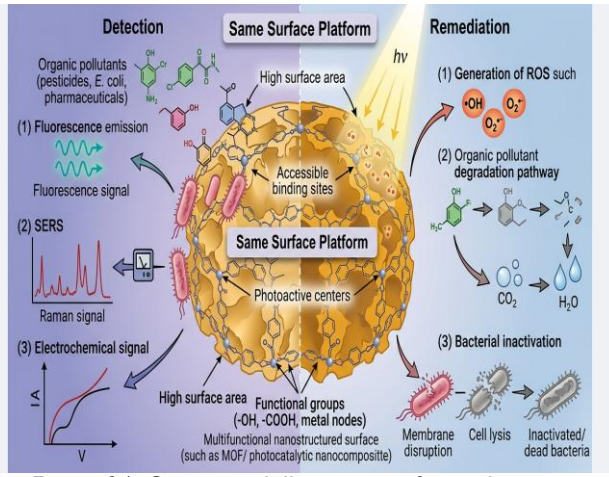

Figure 04: Conceptual illustration of a single same-surface platform performing simultaneous quantification and remediation of organic and microbial pollutants.

7. COMPARATIVE OVERVIEW OF SELECTED STUDIES

Pulling the literature together, a few patterns emerge. Photoactive semiconductors and their composites TiO_2, ZnO, g-C_3N_4, $BiVO_4$ and their heterojunctions dominate the high-removal-efficiency reports for organic micropollutants, with degradation efficiencies typically in the 90–99% range under realistic conditions and reasonable irradiation times [13,14,43]. MOFs and COFs are increasingly the platform of choice for selectivity and for dual-function applications, with the framework geometry providing both the binding pocket for recognition and the photoactive scaffold for degradation [48–50]. Carbon nanomaterials GO, biochar, activated carbon remain dominant on a pure capacity basis for adsorptive removal of dyes and pharmaceuticals.

For microbial targets, silver-containing nanocomposites consistently report the highest log-reduction values, but the practical case for them rests on the combination of Ag with a carrier (GO, MOF, magnetic core) that limits aggregation, controls release kinetics and adds complementary mechanisms [45,47]. Aptamer- and antibody-decorated platforms now reach detection limits well below the regulatory thresholds for E. coli, typically 10-40 CFU mL^{-1} on simple electrochemical or colorimetric formats [27,31,33]. Table 7 collects a representative selection of dual-function studies, with the emphasis deliberately placed on systems that report both functions detection and removal or inactivation on a single surface.

Table 07: Summary of selected dual-function (same-surface) nanomaterial platforms for the simultaneous detection and removal/inactivation of organic and microbial pollutants (previous studies).

Platform (same surface)	Functions	Target(s)	Key reported performance	Ref.
Cu_2O / g-C_3N_4 Z-scheme heterojunction	SERS detection + photocatalytic self-cleaning	4-aminothiophenol; methyl orange	EF ≈ 2.43 × 10^6 for 4-ATP; 98.3% MO degradation in 90 min; 93.7% activity after 216 days	[51]
Zr–porphyrin MOF	Fluorescence detection + photocatalysis	Nitenpyram (neonicotinoid)	LOD 0.03 μg mL^{-1}; ~95% degradation	[48]
HRP@Fe-NU-1003 MOF	Bioassay detection + photo-Fenton degradation	Chloramphenicol	Complete removal of 50 μg mL^{-1} in 30 min; 61% mineralisation; ≥5 cycles	[49]
Cobalt MOF sandwich-sheet	SERS detection + photocatalytic degradation	4-aminothiophenol	Ultrasensitive SERS + photocatalytic destruction	[50]
Fe_3O_4@Au@aptamer	Magnetic capture + electrochemical detection (+ SERS)	E. coli	Selective capture and quantification at low CFU	[33]
GO–Ag nanocomposites	Membrane disruption + Ag^+ release; sensor-compatible	E. coli, S. aureus	>99% bacterial inactivation; multiple cycles	[45, 47]
Ag/Pt bimetallic aptasensor	Colorimetric detection + intrinsic antimicrobial	E. coli	LOD ~10 CFU mL^{-1}; 30-min assay; built-in Ag action	[31]

8. CHALLENGES AND FUTURE PERSPECTIVES

Despite the clear conceptual appeal, several practical issues stand between the laboratory and field deployment. Real environmental matrices contain natural organic matter, competing ions, surfactants and particulate material that scavenge radicals, foul sensor surfaces and saturate adsorption sites; performance figures obtained in deionised water rarely survive translation to a wastewater or natural-water matrix without recalibration. Selectivity for the target organic or microbial species against a background of structurally similar compounds or competing microorganisms remains demanding outside aptamer- and MIP-based platforms. Long-term stability of photocatalysts, particularly composites that rely on a small fraction of an expensive component a noble metal, a fluorescent linker, an enzyme needs robust demonstration over hundreds of cycles rather than ten.

Cost remains a barrier for MOF/COF and MXene materials at scale; greener and lower-cost synthesis routes are an active research front. Toxicity of the nanomaterials themselves particularly the release of silver, copper or photocatalyst nanoparticles into the treated water deserves more attention than it usually receives in laboratory studies, and the regulatory framework for nanomaterial leaching in drinking water is still embryonic. Finally, the integration of detection and remediation in a single deployed device is more demanding than integration on a single laboratory surface: the practical engineering of flow cells, light delivery, magnetic separation and signal acquisition for routine use remains the next decade's work. The trajectory, however, is unambiguous; the surface-centred approach now spans organics, microbes and heavy metals on a single conceptual footing, and the same-surface concept is becoming the natural template for the next generation of water-quality technologies.

9. CONCLUSION

Advanced nanomaterials have moved the analytical and the treatment sides of water-quality work closer to-

gether than they have ever been. The same surface chemistry that enables sensitive electrochemical, optical or biorecognition detection of organic micropollutants and microbial cells also enables through adsorption, photocatalysis or contact-mediated antimicrobial action their removal or inactivation. The dual-function same-surface platforms reviewed here, MOFs and photoactive heterojunctions for organics and GO–Ag and aptamer-decorated magnetic composites for microbes, are now reaching the point at which a single material can plausibly serve both functions in a deployed device. Outstanding problems of real-matrix selectivity, long-term stability, cost and nanomaterial fate are real but tractable. The conceptual unification of detection and remediation around the reactive surface of an engineered nanomaterial is, on the present evidence, a productive way of organising the field and a likely template for the next generation of water-quality technologies.

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