

Innovation, Intellectual Property and Technologies for Addressing Antimicrobial Resistance in Wastewater



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Glossary of terms

Activated carbon: A highly porous material used to remove antibiotics and other pollutants from water by trapping them on its surface.

Activated sludge: A wastewater treatment process that uses microorganisms and aeration to break down organic matter and reduce contaminants.

Adsorption: A process in which substances in water attach to the surface of a material, such as activated carbon or biochar.

Advanced oxidation process (AOP): A treatment method that generates highly reactive substances, such as reactive oxygen species, to break down difficult-to-remove pollutants in water.

Anaerobic digestion: A biological treatment process in which microorganisms break down organic matter in the absence of oxygen. It can also produce biogas.

Antimicrobial: A substance used to prevent or treat infections caused by microorganisms. Antimicrobials include antibiotics, antifungals, antivirals and antiparasitic medicines.

Antimicrobial residue: An antimicrobial compound, or part of it, that remains in wastewater or the environment following use, manufacture or disposal.

Antimicrobial resistance (AMR): The ability of microorganisms to survive or continue to grow despite treatment with antimicrobials to which they were previously susceptible.

Antimicrobial resistance gene (ARG): A gene that gives a microorganism the ability to resist the effects of one or more antimicrobials.

Antimicrobial-resistant bacteria (ARB): Bacteria that are able to survive or grow in the presence of one or more antibiotics that would normally inhibit or kill them.

Biochar: A carbon-rich material made by heating organic matter that can remove pollutants from wastewater by trapping them on its surface. It may provide a lower-cost alternative to activated carbon where locally validated.

Biosensor: A device that combines a biological recognition element with a sensor to detect a specific substance, microorganism or genetic target. Some biosensors can provide rapid or near-real-time results.

Constructed wetland: A nature-based wastewater treatment system that uses plants, microorganisms and soil or other substrates to filter and break down contaminants.

Copyright and related rights: Rights that protect literary and artistic works and other forms of creative expression. In the technologies discussed in this report, copyright may apply to software, databases, technical documentation and user interfaces.

Current assignee: The entity recorded as holding the rights to a patent at the time of analysis. It may differ from the original applicant or assignee named when the patent was filed.

Effluent: Wastewater leaving a facility, production process or wastewater treatment system.

Enzyme-linked immunosorbent assay (ELISA): A laboratory test that uses antibodies and a measurable signal, often a color change, to detect and measure specific substances.

Exclusive license: A license giving one licensee the sole right to use specified intellectual property within the agreed scope, excluding other parties and, within that scope, the IP owner.

High-performance liquid chromatography (HPLC): A laboratory technique that separates chemicals in a liquid sample so they can be identified and measured.

High-strength wastewater: Wastewater containing relatively high concentrations of pollutants, such as organic matter, nutrients, pharmaceutical compounds or other contaminants.

Hotspot: A location where monitoring identifies relatively high levels of antimicrobial residues, resistant organisms, resistance genes or other AMR-related risks.

Industrial design: Protection for the ornamental or aesthetic aspects of a product, such as its shape, configuration, pattern or surface appearance.

Influent: Wastewater entering a treatment system or treatment process.

Intellectual property (IP): Creations and innovations that may be protected through legal rights such as patents, copyright, industrial designs and trade secrets.

Intellectual property (IP) audit: A systematic review of an organization's intellectual assets, such as inventions, designs, software, data, brand names and know-how, and their ownership and protection status.

Knowledge and technology transfer (K/TT): The process through which technology, technical knowledge, skills, software, data, documentation or know-how are shared or transferred so that another organization or partner can use, adapt or apply them.

Lateral flow test (LFT): A rapid strip-based test that detects a specific target in a sample, similar to a home pregnancy test.

Licensing: An arrangement in which an IP owner gives another party permission to use specified IP under agreed conditions without transferring ownership of the IP.

Membrane bioreactor (MBR): A wastewater treatment system that combines biological treatment with membrane filtration to remove contaminants.

Metagenomics: An approach that analyses genetic material from the microorganisms present in a sample without targeting only predetermined organisms or genes. It can be used to characterize the resistome and microbial community in wastewater.

Non-exclusive license: A license that allows the IP owner to grant the same or similar rights to more than one licensee and to continue using the IP.

One Health: An approach that recognizes that human, animal, food production and environmental health are interconnected and that health risks, such as AMR, require coordinated action across these areas.

Over the counter (OTC): Medicines that can be purchased without a prescription.

Patent: An exclusive right granted for an invention that allows the patent owner to prevent others from making, using or selling the patented invention without authorization for a limited period, subject to applicable law.

Patent family: A group of related patent applications or grants covering the same or closely related invention across different countries or jurisdictions.

Patent landscape: An analysis of patent information used to understand patterns of innovation, including trends in technologies, applicants or assignees and geographic activity.

Phenotypic resistance: Observable resistance of a microorganism to an antimicrobial, usually determined by testing the response of a viable organism to the antimicrobial.

Polishing: An additional treatment step used after the main wastewater treatment process to remove contaminants that remain in the treated water.

Predicted no-effect concentration (PNEC): An estimated concentration below which an antimicrobial is not expected to create a specified adverse environmental effect. In the report, PNECs are discussed particularly in relation to thresholds for AMR selection.

Quality assurance: Procedures used to help ensure that sampling, testing, analysis and reporting produce reliable and comparable results.

Quantitative polymerase chain reaction (qPCR): A laboratory technique that copies and measures specific genetic material in real time.

Resistome: The collection of antimicrobial resistance genes present in a microorganism, microbial community or environmental sample.

Selective pressure: Environmental conditions that favor the survival or growth of resistant microorganisms, for example through exposure to antimicrobial residues.

Sentinel surveillance: Monitoring conducted at selected sites or facilities to identify trends, hotspots or early signals that may warrant further investigation.

Sole license: A license under which only one licensee is granted the specified rights, while the IP owner retains the right to use the IP.

Source control: Measures that prevent or reduce pollutants entering wastewater at their point of origin, rather than relying only on downstream treatment.

Technology maturity: The stage a technology has reached in its development and application, ranging from early research or prototype stages to validated and operational use.

Technology transfer: The transfer of technology and associated rights, knowledge, skills or know-how from one organization or entity to another to enable its use, adaptation, manufacture or deployment.

Trade secret: Confidential technical or commercial information that has value because it is not generally known and is subject to reasonable measures to keep it secret.

Treatment train: A sequence of two or more treatment processes used together to address different contaminants or treatment objectives.

Ultrafiltration/nanofiltration/reverse osmosis (UF/NF/RO): Pressure-driven membrane filtration methods that remove different types and sizes of contaminants from wastewater.

Validation: The process of demonstrating that a technology, analytical method or system performs adequately for its intended purpose and conditions of use.

Voluntary licensing: A contractual arrangement in which an IP owner voluntarily grants another party the right to use specified IP under agreed terms while retaining ownership.

Wastewater-based surveillance: The monitoring and analysis of wastewater to identify biological, chemical or other indicators that can provide information on health or environmental risks.

Wastewater matrix: The composition and characteristics of a wastewater sample, which can affect the performance and interpretation of analytical or treatment methods.

Abbreviations and acronyms

AGF	artificial ground freezing
AI	artificial intelligence
ALT	active layer thickness
AMOC	Atlantic Meridional Overturning Circulation
AUV	autonomous underwater vehicle
BAER	burned area emergency rehabilitation
BDA	beaver dam analogue
BGT	borehole ground temperature
CAMS	Copernicus Atmosphere Monitoring Service
CDR	carbon dioxide removal
CFR	community fish refuge
CO2	carbon dioxide
CRDS	(closed-path) cavity ring-down spectroscopy
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTCN	Climate Technology Centre and Network
CTD	conductivity, temperature, depth
DAF	dissolved air flotation
DHW	degree heating week
DRIFT	downstream response to imposed flow transformation
DTO	digital twin of the ocean
eCDR	electrochemical carbon dioxide removal
eDNA	environmental DNA
ELJ	engineered logjam
ERT	electrical resistivity tomography
ESA	European Space Agency
ESG	environmental, social and governance
EU	European Union
EWS	early warning system
FAO	United Nations Food and Agriculture Organization
FMNR	farmer-managed natural regeneration
GHG	greenhouse gas
GIS	geographic information system
GLIMS	Global Land Ice Measurements from Space
GLOF	glacial lake outburst flood
GNSS	global navigation satellite system
GPS	global positioning system

ICRI	International Coral Reef Initiative
InSAR	interferometric synthetic aperture radar
IoT	internet of things
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
JPL	Jet Propulsion Laboratory
LiDAR	light detection and ranging
L-VOD	L-band vegetation optical depth
MAR	managed aquifer recharge
mCDR	marine carbon dioxide removal
MENA	Middle East and North Africa
MHW	marine heatwave
MIT	Massachusetts Institute of Technology
MRV	monitoring, reporting and verification
MTBS	Monitoring Trends in Burn Severity
NASA	National Aeronautics and Space Administration
NBR	normalized burn ratio
NbS	nature-based solution
NFM	natural flood management
NOAA	National Oceanic and Atmospheric Administration
N2O	nitrous oxide
OA	ocean acidification
OAE	ocean alkalinity enhancement
OIEau	Office International de l'Eau
pCO2	partial pressure of CO2
PES	payment for ecosystem services
RaaS	robotics-as-a service
ROV	remotely operated vehicle
SaaS	software-as-a-service
SAR	synthetic aperture radar
SDG	Sustainable Development Goal
SST	sea surface temperature
TNDF	Taskforce on Nature-related Financial Disclosures
TRL	technology readiness level
UAV	uncrewed aerial vehicle
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
USV	uncrewed surface vessel
VCM	voluntary carbon market
WGMS	World Glacier Monitoring Service
WIPO	World Intellectual Property Organization
WIPPS	WMO Integrated Processing and Prediction System
WMO	World Meteorological Organization
WRI	World Resources Institute
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research

Introduction

Antimicrobial resistance (AMR) is an escalating global challenge with significant implications for public health, food security and environmental sustainability. While AMR responses have traditionally focused on human and animal health, growing evidence highlights wastewater as a critical interface for the emergence, transmission and potential mitigation of AMR across One Health sectors. Wastewater systems concentrate antimicrobial residues, resistant microorganisms and resistance genes from multiple sources, creating both risks and strategic opportunities for surveillance and intervention.

Much of the global AMR response has focused on investment in research and development (R&D) to address growing drug resistance, alongside antimicrobial stewardship programs aimed at promoting the appropriate use of antibiotics and reducing unnecessary or excessive use. The environmental dimensions of AMR have received less attention than their human and animal health counterparts.[1] Wastewater is a critical interface across the One Health dimensions of AMR, receiving and transporting antimicrobial residues, resistant bacteria and resistance genes from human, animal, agricultural and industrial sources into environmental systems.[2] Intellectual property rights (IPRs) can encourage R&D and innovation in technologies relevant to detecting and managing AMR in wastewater by helping to define ownership, protect inventions and know-how, attract investment and structure collaboration, licensing and technology transfer.[3], [4]

This report examines wastewater technologies as a strategic entry point for addressing AMR within a One Health approach. It brings together two complementary components of technology deployment: (1) conditions that support innovation and technology transfer; and (2) technical and operational considerations involved in applying technologies in various settings.

Part 1 Innovation and intellectual property in wastewater technologies

Following an initial overview of the challenges posed by AMR and the potential for wastewater treatment to contribute to addressing a number of these challenges, Part 1 of the report focuses on the enabling environment through which technologies relevant for detecting and managing AMR in wastewater may be developed, adapted and brought into wider use. It is primarily intended for innovation agencies, technology developers, research institutions, manufacturers, investors, IP offices, technology transfer offices, policymakers and development partners.

1 United Nations Environment Programme (UNEP) (2023). *Bracing for Superbugs: Strengthening Environmental Action in the One Health Response to Antimicrobial Resistance*. Nairobi: UNEP. https://www.unep.org/resources/superbugs/environmental-action.
2 Al-Khalaifah, H., M.H. Rahman, T. Al-Surrayai, A. Al-Dhumair and M. Al-Hasan, M. (2025). A One-Health perspective of antimicrobial resistance (AMR): human, animals and environmental health. *Life*, 15(10), 1598. https://doi.org/10.3390/life15101598.
3 World Intellectual Property Organization (WIPO) (2017). *Innovation and Intellectual Property*. Geneva: WIPO. https://www.wipo.int/en/web/ipday/2017/innovation_and_intellectual_property.
4 Borges, C. (2025). *RAI explainer: How IP rights promote innovation*. Washington, D.C.: Center for Strategic and International Studies. https://www.csis.org/blogs/perspectives-innovation/rai-explainer-how-ip-rights-promote-innovation.

Part 1:

- highlights the rising spread of AMR in the environment across the One Health sectors and the global response
- uses patent landscape insights to illustrate innovation trends in AMR wastewater detection, monitoring and management technologies
- explores IP management, licensing, collaboration, knowledge and technology transfer approaches that can support local adaptation and scale-up
- discusses the wider enabling conditions for innovation, including financing, manufacturing, procurement, regulatory pathways and institutional capacity
- identifies policy entry points through which innovation, IP and technology transfer considerations can be incorporated into AMR planning.

Part 2: AMR Wastewater Technology Companion

The AMR Wastewater Technology Companion examines some technologies relevant to detecting and managing AMR in wastewater, with particular attention to innovation through adaptation, repurposing, integration and application in different settings. It is primarily intended to provide policymakers, regulators, public health and environmental authorities, laboratories, utilities, development banks and implementing partners with accessible technical background for policy and partnership discussions. It also summarizes some lessons learned from AMR wastewater treatment technology deployment, in the hope that these lessons will benefit future technology deployments.

The Companion:

- provides an overview of established and emerging AMR detection and treatment technologies across human, animal, industrial and environmental interfaces
- presents selected case studies showing how technologies are being developed, adapted, combined or applied in practice across selected developing countries
- discusses technology maturity and key implementation considerations, including infrastructure, validation, operational models, costs, skills and integration into existing systems
- highlights portable, decentralized, hybrid, digital and locally adaptable approaches, while recognizing that innovation may also lie in the application of an existing technology in addition to a wholly new invention
- connects technical application and implementation to the innovation, IP, licensing and technology transfer pathways discussed in Part 1.

As the technical areas covered in the Companion extend beyond WIPO's specialized mandate, it was prepared in close partnership with technical and subject-matter experts whose institutional responsibilities and work cover AMR, wastewater surveillance, environmental health, wastewater management and treatment.

The Companion places relevant technological information at the disposal of policymakers and other stakeholders and supports broader discussion of technologies and approaches for detecting and managing AMR in wastewater. It is designed as a policy and discussion resource rather than as a technical manual, engineering guide or procurement tool. It does not prescribe particular technologies, treatment configurations, surveillance methods or implementation models.

The technologies and case studies included in the report are illustrative and do not constitute endorsement by WIPO or the technical contributors. Reported performance is specific to the wastewater source, study design, technology configuration, operating conditions and analytical methods concerned. Technology selection and implementation should be guided by local priorities, applicable laws and standards, infrastructure, resources, technical capacity and guidance from the relevant national authorities and technical experts.

Following an overview of the AMR challenges, Parts 1 and 2 provide a linked pathway from innovation to application. Each component may be consulted independently, but they are intended to show how innovation, IP and technology transfer arrangements connect with the technical and operational conditions required for sustainable implementation of AMR wastewater technologies.

Overview: the challenge of AMR and AMR in wastewater



Wastewater connects human, animal and environmental health, making it an important part of the One Health response to antimicrobial resistance (AMR). It offers opportunities to monitor the spread of resistance, identify emerging risks and inform public health and environmental interventions.

Antimicrobial resistance in a One Health context

Antimicrobial resistance (AMR) is a major and evolving global health concern that occurs when microorganisms become resistant to treatments to which they were previously susceptible, making infectious diseases more difficult to treat and increasing morbidity and mortality.[1] In 2019, an estimated 1.27 million deaths were directly attributable to bacterial AMR.[2] New estimates predict that between 2025 and 2050, approximately 39 million cumulative deaths could be directly attributable to AMR, with a further 169 million deaths associated with resistant infections.[3] The causes of AMR are complex and interconnected, including inappropriate antimicrobial use in human medicine and agriculture and the discharge of untreated or poorly managed wastewater.[4]

Wastewater within the AMR system

Wastewater collects antimicrobial residues, resistant bacteria and resistance genes from hospitals, pharmaceutical factories, households, farms, livestock and aquaculture activities.[5] These pollutants can enter wastewater through medicine use, industrial discharge, agricultural runoff and poor sanitation systems. Studies have documented the discharge of substantial concentrations of antibiotic residues into the environment through untreated or inadequately treated industrial, hospital and municipal wastewater.

Wastewater frequently contains high concentrations of antibiotics, particularly near hospitals, pharmaceutical plants and livestock facilities, creating conditions that favor the evolution and spread of resistance.[6] The most commonly used monitoring indicator is the predicted no-effect concentration (PNEC), which indicates the threshold below which antibiotics are unlikely to spread resistant bacteria or resistance genes in the environment.[7] A global analysis found that 42.8 percent of hospital wastewater samples exceeded the PNEC for AMR selection, with ciprofloxacin and clarithromycin frequently detected above thresholds.[8] Case studies in India have highlighted pharmaceutical clusters where ciprofloxacin concentrations in treated effluents reached up to 31 mg/L, sufficient to treat tens of thousands of patients based on standard dosing.[9]

Antibiotics are widely used for non-therapeutic purposes (growth promotion, disease prevention) in the animal sector. Livestock wastewater remains a major reservoir of AMR, with

1 World Health Organization (WHO) (2026). *Antimicrobial Resistance*. Geneva: WHO. https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance.
2 Antimicrobial Resistance Collaborators (2022). Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. *The Lancet*, 399(10325), 629–655. https://doi.org/10.1016/S0140-6736(21)02724-0.
3 GBD 2021 Antimicrobial Resistance Collaborators (2024). Global burden of bacterial antimicrobial resistance 1990–2021: a systematic analysis with forecasts to 2050. *The Lancet*, 404(10459), 1199–1226. https://doi.org/10.1016/S0140-6736(24)01867-1.
4 World Health Organization (WHO) (2026). *Antimicrobial Resistance*. Geneva: WHO. https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance.
5 Bakon, S.K. and Z.A. Mohamad (2025). Flushed and forgotten: antimicrobial resistance from wastewater perspective. In Mustafa, G., Thoms-Rodriguez, C.-A., J. Mullings, P.E. Akpaka, K.J. Roye-Green and V. McIntosh-Morgan (eds), *Antimicrobial Resistance – New insights*. London: IntechOpen. https://doi.org/10.5772/intechopen.1009584.
6 Hanna, N., A.J. Tamhankar and C.S. Lundborg (2023) Antibiotic concentrations and antibiotic resistance in aquatic environments of the WHO Western Pacific and South-East Asia regions: a systematic review and probabilistic environmental hazard assessment. *The Lancet Planetary Health*, 7(1), e45–e54. https://doi.org/10.1016/S2542-5196(22)00254-6.
7 Berendonk, T.U., C.M. Manaia, C. Merlin *et al.* (2015). Tackling antibiotic resistance: the environmental framework. *Nature Reviews Microbiology,* 13(5), 310–317. https://doi.org/10.1038/nrmicro3439.
8 Booth, A., D.S. Aga and A.L. Wester (2020). Retrospective analysis of the global antibiotic residues that exceed the predicted no effect concentration for antimicrobial resistance in various environmental matrices. *Environment International*, 140, 105763. https://doi.org/10.1016/j.envint.2020.105796.
9 Joakim Larsson, D.G., C. de Pedro and N. Paxeus (2007). Effluent from drug manufactures contains extremely high levels of pharmaceuticals. *Journal of Hazardous Materials*, 148(3), 751–755. https://doi.org/10.1016/j.jhazmat.2007.07.008.

studies showing that effluents from swine and poultry operations can contain three to five orders of magnitude more antimicrobial resistance genes (ARGs) than hospital or municipal wastewater.[10] The overuse of antimicrobials in crops, livestock and aquaculture, combined with irrigation using untreated wastewater, contaminates food and water systems. Globally, of the 30,300 metric tons of antibiotics consumed annually, about 9,500 tons (31 percent) are discharged into surface waters, and 3,250 tons (11 percent) reach oceans or inland sinks.[11] Commonly detected antimicrobial classes in wastewater, their characteristics and relevance to AMR are summarized in Table 8 in Annex 2.

As conventional wastewater treatment plants are not always designed to remove them fully, some may remain in treated water and spread into rivers, soil and sediments. Wastewater can therefore provide useful information about antimicrobial use and resistance across different sectors.[12] It can also be used for surveillance, early warnings and targeted action to reduce the spread of antimicrobial resistance.

Global response

The discharge of untreated antibiotic residues into the environment is becoming a major contributor to the spread of AMR from the One Health sectors. European governments and multilateral procurement agencies are increasingly incorporating environmental and social criteria into antibiotic purchasing decisions, recognizing that pollution from manufacturing sites can drive AMR.[13] Notably, Nordic countries are revising their procurement frameworks to favor suppliers that demonstrate strong environmental performance, including responsible antibiotic production practices and effective wastewater management. For instance, Norway assigns a 30 percent weight to environmentally friendly production in supplier evaluations.[14] The United Kingdom (UK) is also adopting green procurement.

The AMR Industry Alliance has developed an Antibiotic Manufacturing Standard intended to ensure effective control of emissions from antibiotic manufacturing so that the antibiotic concentration in the aquatic environment does not exceed permissible concentration levels. The Alliance has partnered with the British Standards Institution (BSI) to develop an independent certification scheme to verify that an antibiotic is made in accordance with the requirements of the standard, including that the concentration of antibiotic in the environment is less than the PNEC.[15] The Alliance has updated its Standard to align with the World Health Organization (WHO)'s 2024 *Guidance on wastewater and solid waste management for manufacturing of antibiotics*.[16]

The One Health framework recognizes that antimicrobial compounds, resistant bacteria and ARGs circulate across human, animal and environmental systems. It therefore promotes coordinated action across these sectors, as reflected in international policy instruments, such as: the Quadripartite *One Health joint plan of action (2022–2026)* (OH JPA);[17] the World Bank's *Stopping the grand pandemic: a framework for action*;[18] the 2024 United Nations (UN) General

10 He, Y., Q. Yuan, J. Mathieu, L. Stadler, N. Senehi, R. Sun, and P.J.J. Alvarez (2020). Antibiotic resistance genes from livestock waste: occurrence, dissemination, and treatment. *npj Clean Water*, 3(4). https://doi.org/10.1038/s41545-020-0051-0.

11 Macedo, H.E., B. Lehner, J.A. Nicell, U. Khan and E.Y. Klein (2025). Antibiotics in the global river system arising from human consumption. *PNAS Nexus,* 4(4), pgaf096. https://doi.org/10.1093/pnasnexus/pgaf096.

12 Meradji, S., N.S. Basher, A. Sassi, N.A. Ibrahim, T. Idres and A. Touati (2025). The role of water as a reservoir for antibiotic-resistant bacteria. *Antibiotics,* 14(8), 763. https://doi.org/10.3390/antibiotics14080763.

13 Health Care Without Harm Europe (2023). *Procuring for Greener Pharma*. https://europe.noharm.org/sites/default/files/documents-files/7333/2023-02-08_HCWH-Europe_Procuring-greener-pharma.pdf.

14 Sykehusinnkjøp H.F. (2023). *Experience Report: Environmental Requirements for Pharmaceutical Procurements 2022–2023*. Vadsø: The Norwegian Hospital Procurement Trust (NHPT). https://www.sykehusinnkjop.no/4937c6/siteassets/bilder/nyheter/2024/miljokrav-legemidler-rapport/erfaringsrapport-miljo-2023_engelsk-versjon.pdf.

15 Antimicrobial Industry Alliance (n.d.). *New Certification System Could Promote Responsible Antibiotic Manufacturing*. Geneva: Antimicrobial Industry Alliance. https://www.amrindustryalliance.org/mediaroom/new-certification-system-could-promote-responsible-antibiotic-manufacturing.

16 World Health Organization (WHO) (2024) *Guidance on Wastewater and Solid Waste Management for Manufacturing of Antibiotics*. Geneva: WHO. https://www.who.int/publications/i/item/9789240097254.

17 Food and Agriculture Organization of the United Nations (FAO), United Nations Environment Programme (UNEP), World Health Organization (WHO) and World Organisation for Animal Health (WOAH) (2022). *One Health Joint Plan of Action (2022–2026): Working Together for the Health of Humans, Animals, Plants and the Environment*. FAO, UNEP, WHO, & WOAH. https://www.who.int/publications/i/item/9789240059139.

18 World Bank (2024). *Stopping the Grand Pandemic: A Framework for Action: Addressing Antimicrobial Resistance Through World Bank Operations.* Washington, D.C.: World Bank. https://www.worldbank.org/en/topic/health/brief/antimicrobial-resistance-amr.

Assembly Political Declaration on AMR;[19] and the UN Environment Programme report *Bracing for superbugs*.[20] Many of these AMR strategy and policy documents have begun to prioritize wastewater as a strategic entry point for tackling AMR across the One Health sectors. This report provides insights into a range of wastewater technologies and innovations and their application in hospitals, pharmaceutical sites, animal farms and agricultural settings through practical case studies.

Innovation pathways and enabling conditions

There are a number of emerging technologies available for detecting and managing AMR in wastewater. These include analytical platforms, laboratory methods, digital tools, treatment processes and integrated systems. Many are established technologies developed for clinical, industrial or environmental purposes and are now being adapted, repurposed or combined for AMR wastewater applications.[21] Innovation may therefore be a new invention, but it may also involve a lower-cost design, a portable or decentralized application, a hybrid treatment system, improved data analysis, local manufacture, or integration into an existing surveillance or wastewater system.

19 United Nations (UN) General Assembly (2024*). Political Declaration of the High-level Meeting on Antimicrobial Resistance*. New York: UN. https://documents.un.org/doc/undoc/ltd/n24/278/35/pdf/n2427835.pdf?_gl=1*1l7uzui*_ga*MzY3NzE5MTYxLjE3MjA5OTAzNzA.*_ga_TK9BQL5X7Z*MTczNTM0NzIzMy4yMC4wLjE3MzUzNDcyMzMuMC4wLjA.

20 United Nations Environment Programme (UNEP) (2023). *Bracing for Superbugs: Strengthening Environmental Action in the One Health Response to Antimicrobial Resistance*. Nairobi: UNEP. https://www.unep.org/resources/superbugs/environmental-action.

21 Hock, L., R. Luiken, E. Valério, M. Vargha, J. Vierheilig, S. Börjesson, T. Pitkänen and H. Schmitt (2026). Integrating AMR surveillance into wastewater monitoring systems in 2025: a position on the implementation of Article 17 of the Urban Wastewater Treatment Directive (UWWTD). *Eurosurveillance,* 31(3). https://doi.org/10.2807/1560-7917.ES.2026.31.3.2500289.

Part 1: Innovation and intellectual property in AMR wastewater technologies



Innovation in technologies for detecting, monitoring and managing AMR in wastewater is growing, with contributions from universities, research institutions and industry. The section explores how intellectual property (IP), strategic IP management, licensing and partnerships can support technology development, transfer and wider use. It also considers how IP and voluntary technology transfer can be reflected in national AMR action plans.

Moving antimicrobial resistance (AMR) wastewater detection, monitoring and management technologies from research or pilot use into sustained application requires more than technical performance. It depends on appropriate protection and management of intellectual property (IP) and know-how; validation; finance; regulatory pathways; procurement; infrastructure; maintenance; skilled personnel; and institutions able to absorb and use the technology, to name a few examples. This part examines these enabling conditions, while the AMR Wastewater Technology Companion in Part 2 considers how technologies are applied in practice.

In 2017, WIPO published a global challenges report examining AMR and multidrug resistance from an innovation and IP perspective.[1] The report considered the role of patents, licensing, collaborative research and development models and other incentive mechanisms in the development of antibiotics, diagnostics and related health technologies. This present report examines a separate area of AMR innovation, focusing on technologies relevant to detecting and managing AMR in wastewater and the IP, licensing and knowledge and technology transfer considerations that may arise in their development, adaptation and application.

Why innovation and IP matter

IP can play a critical enabling role in the sustainable development and deployment of technologies addressing AMR, particularly in wastewater systems. For innovators, a well-functioning IP framework offers the legal certainty needed to invest in research, safeguard proprietary knowledge and establish structured mechanisms for responsible technology dissemination. Patents and trade secrets, among other IP tools, help define ownership, support commercialization and facilitate voluntary collaboration[2] across sectors. This is particularly important for AMR technologies, which often involve complex combinations of hardware, software and process innovation that require significant upfront investment and coordination across jurisdictions. For example, membrane bioreactor (MBR) systems may require physical infrastructure, pumps and filtration units (hardware), along with monitoring systems to regulate flow and pressure (software), and operational protocols to ensure effective bacterial removal (process). The technology may comprise a mix of patented and non-patented components.

IP rights enable licensing and technology transfers. Evidence suggests that weak IP protection can deter technology diffusion, as firms are less likely to license their technologies into jurisdictions with poor enforcement mechanisms or weak levels of protection. Broader analyses indicate that insufficient IP protections discourage investment and the trade of environmentally sound technologies across borders.[3] Innovators strategically file patents in countries with stronger IP systems and market potential, underscoring the importance of creating robust IP environments to attract AMR solutions.[4]

1 Jenner, A., N. Bhagwandin and S. Kowalski (2017). *Antimicrobial Resistance (AMR) and Multidrug Resistance (MDR): Overview of Current Approaches, Consortia and Intellectual Property Issues*. Geneva: WIPO. https://www.wipo.int/publications/en/details.jsp?id=4210.

2 World Intellectual Property Organization (WIPO) (2024). *WIPO GREEN: Facilitating Dissemination of Green Technology*. Geneva: WIPO. https://www.wipo.int/en/web/wipo-magazine/articles/wipo-green-facilitating-dissemination-of-green-technology-38134.

3 Lybecker, K.M. and S. Lohse (2015). *Innovation and Diffusion of Green Technologies: The Role of Intellectual Property and Other Enabling Factors (Global Challenges Report)*. Geneva: WIPO. https://www.wipo.int/edocs/pubdocs/en/wipo_rep_gc_2015_1.pdf.

4 Haščič, I. and M. Migotto (2015). Measuring Environmental Innovation Using Patent Data. *OECD Environment Working Papers No. 89*. Paris: OECD Publishing. https://dx.doi.org/10.1787/5js009kf48xw-en.

IP can serve as a key enabler for advancing AMR technologies, particularly in the context of wastewater treatment and the One Health approach. This section of the report contains three parts:

1. A patent landscaping analysis, offering insights into patent trends relating to technologies relevant to detecting and managing AMR in wastewater.
2. An examination of IP management strategies to advance these technologies, including some ways to protect early-stage innovations, manage risks and facilitate collaboration.
3. A consideration of IP licensing, highlighting how well-structured licensing arrangements can support technology transfer, local manufacturing and international scale-up.

Together, these elements illustrate how a strategic approach to IP can incentivize innovation while enabling the deployment of AMR solutions across sectors and borders.

Patent landscape and selected innovation trends

Addressing AMR in wastewater is not just a matter of scientific and technological innovation, it also requires a deep understanding of the IP landscape that governs the development, transfer and deployment of these technologies. Patent data offers a unique evidence base for policymakers and funders to identify where innovation is occurring, emerging technologies, key actors and the potential for broader technology uptake.

How the patent landscaping was conducted

The patent landscaping exercise was conducted by WIPO's IP Analytics Section using a commercial patent database, aiming to identify global innovation trends in wastewater treatment technologies relevant to AMR. The analysis targeted patent families published between 2010 and 2024 and was performed at the simple patent family level to avoid duplication across jurisdictions. A patent family is a group of interrelated patent applications or grants covering the same invention across different countries.

The technology landscape was conducted across selected detection categories: high-performance liquid chromatography (HPLC); enzyme-linked immunosorbent assays (ELISAs); lateral flow tests (LFTs); and quantitative polymerase chain reaction (qPCR). Selected wastewater treatment technology categories were also included: MBRs and advanced oxidation processes (AOPs); ultrafiltration/nanofiltration/reverse osmosis (UF/NF/RO); activated carbon; and biochar. These technologies are discussed in detail in the second part of the study.

The patent search strategy examined the titles, abstracts and claims of patents, specifically within the International Patent Classification (IPC) subclass C02F, which pertains to the treatment of water, wastewater, sewage or sludge. A comprehensive query was constructed to capture patents addressing AMR in water treatment systems, using search combinations related to AMR and wastewater treatment processes. Sensor-related technologies were excluded as a separate sub-category due to their ubiquity across the dataset. The core query included variations of the terms "antimicrobial resistance", "antibiotic resistance" and related pharmacological terms, combined with environmental water treatment terminology.

In parallel, a desk-based current assignee-level review was undertaken using publicly available patent data from a commercial patent database to track patenting activity associated with selected industry players. "Current assignee" refers to the entity recorded in the database as holding the patent rights at the time of analysis and may differ from the original assignee or applicant named on the patent document. This secondary search was not restricted to keyword criteria and aimed to provide complementary insights into corporate innovation trends in the AMR wastewater treatment space.

Unless otherwise stated, all patent analysis in this section was conducted based on current assignee, as recorded at the time of the search.

Scope limitations

The patent landscaping analysis was designed to identify innovation activity relevant to AMR and wastewater technologies using a combination of technical classification codes and keyword-based searching. While the search strategy was restricted to patents classified under a specific IPC subclass and further refined using AMR-related terminology, some technologies identified in the analysis – such as biochar, activated carbon, membrane systems and analytical platforms – have applications beyond wastewater treatment. As a result, certain patents captured may relate to broader industrial, manufacturing, environmental or research processes that are relevant to the AMR wastewater ecosystem but not necessarily directed exclusively toward wastewater treatment deployment. Patent documents do not always clearly distinguish the ultimate application of a technology, particularly where the same underlying technology is used across multiple sectors. Consequently, the results should be interpreted as an indicator of innovation activity associated with technologies relevant to AMR wastewater detection and treatment rather than a definitive count of patents exclusively directed to AMR and wastewater applications.

Overall trends and key findings

By publication year: The number of patent families relating to AMR in wastewater has been increasing steadily since 2018 (see Table 1), with an increase in the number of new technologies to address One Health AMR. This is broadly in line with the global increase in patenting levels across all technologies.

Geographic distribution by current assignee location: China accounts for the largest number of patent families based on the recorded location of the current assignee (see Table 2). This is followed by the United States, the Republic of Korea, Japan and Germany.

Table 1 Number of patent families relating to AMR in wastewater by publication year (2018–2024), highlighting an overall recent upward trend in patenting activity

Publication year	Number of patent families
2018	455
2019	498
2020	556
2021	601
2022	691
2023	776
2024	845

Source: WIPO IP Analytics Section, patent landscape analysis undertaken for this report (2025).

Table 2 Number of patent families relating to wastewater technologies addressing AMR, by geographic distribution of current assignees

Recorded location of current assignee	Number of patent families
China	4,584
United States	536
Republic of Korea	240
Japan	226
Germany	182

Source: WIPO IP Patent Analytics Section, patent landscape analysis undertaken for this report (2025).

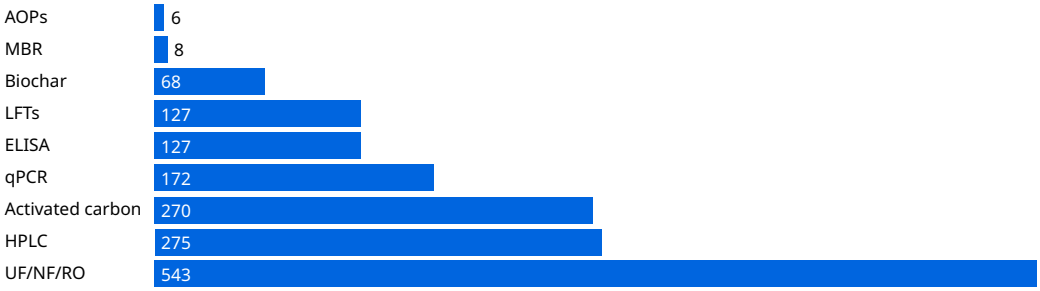
Top assignees: Xidian University in China had the largest number of patent families (82) identified in this landscape search, which accounts for around 1 percent of patents in this sector. This suggests that it is a fairly distributed sector where many assignees are active and hold relatively small patent portfolios. The Xidian University patents were also captured by the general AMR wastewater query rather than by the more specific technology-focused searches. This suggests that while Xidian University is active in filing broadly on AMR in wastewater, its patents may not directly claim the specific detection or treatment technologies highlighted in this report.

The broader landscape is highly fragmented, with most assignees holding relatively small portfolios. After Xidian University, the next tier of top assignees each hold between 28 and 59 patent families. These include innovators, technology providers and pharmaceutical companies. This distribution underscores the competitive, yet dispersed, nature of innovation in technologies relevant to detecting and managing AMR in wastewater, with no single entity exerting dominance and multiple players contributing incremental advances across sub-technologies. The detection technologies with the highest number of patent activity include HPLC, qPCR and ELISA.

Trends and findings by technology

Figure 1 shows the level of innovation across different wastewater technologies.

Figure 1 Number of patent families across AMR wastewater technologies



Source: WIPO IP Patent Analytics Section, patent landscape analysis undertaken for this report (2025).

Detection

HPLC: A laboratory technique that separates chemicals in a liquid sample so they can be identified and measured.

Findings: 275 patent families were identified as directly related to HPLC within AMR wastewater treatment. As with AMR-related patenting more generally, filings appear to have peaked in both 2012 and 2020. Based on the recorded location of the current assignee, the United States accounted for the largest number of identified patent families (130). The top assignees are not HPLC instrument manufacturers but large pharmaceutical and chemical companies that use HPLC in their R&D and production processes. The diversity of assignees suggests that HPLC may be viewed less as a niche innovation and more as a cross-cutting analytical platform with applications spanning pharmaceuticals, clinical diagnostics and environmental monitoring.

ELISA: A laboratory test that uses antibodies and a measurable signal, often a color change, to detect and measure specific substances.

Findings: 127 patent families are directly related to ELISA within AMR and wastewater treatment, with activity peaking in 2019 and 2020. The United States accounts for the largest number of identified patent families based on the recorded location of the current assignee, followed by smaller contributions from Europe and Asia. Patent ownership is relatively fragmented, with families distributed across multiple companies rather than concentrated in a few. Importantly, the top assignees produce ELISA test kits that are used primarily in veterinary and clinical diagnostics. This could reflect the role of ELISA as a widely available, low-cost technology that is being repurposed for environmental monitoring applications, rather than an area of proprietary test kit development.

LFTs: A rapid strip-based test that detects a specific target in a sample, similar to a home pregnancy test.

Findings: Patent activity for LFTs in AMR and wastewater stands at 127 patent families. Patent activity in this area is lower compared to HPLC and is fragmented across many small assignees. This distribution highlights the early-stage and exploratory nature of LFT innovation in the AMR wastewater space. Importantly, most of the assignees are pharmaceutical companies, biotech firms or research institutes that are using lateral flow platforms in adapted applications, rather than core LFT manufacturers.

qPCR: A laboratory technique that copies and measures specific genetic material in real time.

Findings: 172 patent families are directly related to qPCR within AMR in wastewater treatment. The peak was in 2019, reflecting growing adoption of molecular methods for resistome monitoring. Patent activity in qPCR within AMR and wastewater treatment is robust, with more than a hundred families filed globally. In qPCR, the patenting landscape reflects the assignee distribution of the underlying platform technologies themselves.

Treatment

MBR: A wastewater treatment system that combines biological treatment with membrane filtration to remove contaminants.

Findings: The search identified 8 patent families relating to MBRs in the AMR and wastewater context between 2010 and 2024. This suggests relatively modest patent activity captured by the search in this category. Activity has been sporadic with no clear peak years. This pattern may suggest steady but low-volume innovation, often tied to specific project or site applications rather than broad surges of R&D.

AOPs: A treatment method that generates highly reactive substances, such as reactive oxygen species, to break down difficult-to-remove pollutants in water.

Findings: Patent activity in AOPs within AMR and wastewater treatment is limited with 6 patent families found. The earliest peak occurred in 2012 (3 families), followed by sporadic filings in 2013 (1 family) and, most recently, a renewed cluster in 2024 (2 families). This pattern suggests AOP innovation is tied to specific research cycles or project needs rather than continuous R&D momentum. The assignee landscape is also highly fragmented: some assignees from universities and companies each hold just one family. Unlike qPCR or MBR, where leading technology developers dominate, the AOP landscape reflects one-off patents from a mix of individuals, universities, pharmaceutical firms and industrial suppliers. This fragmentation could indicate that while AOP is recognized as a promising treatment pathway, especially for removing active pharmaceutical ingredients (APIs) and resistant organisms in high-load effluents, there is no single dominant technology provider. Instead, AOP patents may be capturing niche innovations (e.g., new catalysts, ultraviolet (UV)/ozone configurations or reactor designs) developed across diverse sectors.

UF/NF/RO: Pressure-driven membrane filtration methods that remove different types and sizes of contaminants from wastewater.

Findings: 543 patent families are directly related to UF/NF/RO within AMR and wastewater treatment, making this the largest sub-technology area. Activity peaked in 2012, a spike significantly higher than any other year. Based on the recorded location of the current assignees, the United States accounted for the largest number of identified patent families in this sub-technology area. However, the identified patent families were distributed across many different assignees. This mix could suggest and underscore the technology's role as both an enabling platform for pharma and biotech processes and a core treatment technology for wastewater.

Activated carbon: A highly porous material that removes antibiotics and other pollutants from water by adsorbing them on its surface.

Findings: 270 patent families were identified as directly related to activated carbon within AMR and wastewater treatment. Patent activity showed notable peaks in 2020 and 2024, reflecting growing attention on activated carbon as a polishing step for antibiotic removal. Based on the recorded location of the current assignees, China accounted for the largest number of identified patent families in this sub-technology area. The landscape appears to be distributed across a range of assignees, including research institutions, universities and other technology actors, with no single assignee holding a dominant share. This distribution could suggest that activated carbon remains a research-driven and application-oriented area of material innovation, with potential relevance for wastewater treatment approaches addressing AMR.

Biochar: A carbon-rich material, made by heating organic matter, that can remove pollutants from wastewater by adsorbing them on its surface, often providing a lower-cost alternative to activated carbon.

Findings: A total of 68 patent families were identified as directly related to biochar within AMR and wastewater treatment. Based on the recorded location of the current assignees, a substantial share of the identified patent families was associated with assignees located in China. This may reflect broader research activity in biomass conversion, low-cost treatment materials and water treatment applications. The patent landscape appears fragmented, with the identified patent families distributed across universities, research institutions, technology actors and individual inventors. No single assignee holds a dominant share. This could suggest that biochar remains an emerging and exploratory area of innovation, with potential relevance as a low-cost and locally adaptable wastewater treatment approach for AMR mitigation.

The patent activity appears to reflect interest in biochar-related materials and water treatment applications. Given the potential availability of agricultural residues and biomass feedstocks in many settings, biochar may warrant further investigation as a low-cost and locally adaptable treatment approach for AMR mitigation, particularly in low- and middle-income countries (LMICs).

Conclusion of patent landscaping study

The observed trends in patent filings provide compelling evidence that innovation in AMR-related wastewater treatment technologies is both active and evolving. The data reflects sustained global R&D interest across a diverse range of technology types. The fact that no single assignee, company or academic institution dominates the space, and that activity is spread across many small portfolios, shows the vibrant nature of this innovation ecosystem. Such trends highlight the critical role IP plays, not only as a marker of innovation, but also as a mechanism to incentivize investment, protect technical know-how, and structure collaborations among innovators, funders and implementers.

Understanding where patent activity is concentrated and how technologies are distributed across regions and assignees allows policymakers, funders and development partners to make more informed decisions. IP landscaping can help identify technological gaps, assess readiness for scaling and pinpoint potential partners for voluntary licensing. For emerging areas such as AMR mitigation in wastewater, this insight is crucial. It ensures that scientific advances do not remain siloed but are translated into accessible, deployable solutions through well-defined IP frameworks that facilitate responsible dissemination and adoption. In this context, patent data is not merely a record of innovation.

This patent landscaping study is accurate as of July 2025 when the search was conducted.

Managing IP and other intangible assets

In the context of One Health where AMR challenges span human, animal and environmental domains, IP protection can enable technologies to move more efficiently across sectors and borders. Whether applied to wastewater diagnostics, treatment systems or surveillance platforms, an IP framework helps to ensure that innovations are not only developed but also adapted and scaled responsibly. This ultimately supports faster, more sustainable deployment of AMR solutions in diverse real-world settings.

Significant innovation in the AMR wastewater sector is taking place across universities, wastewater technology companies, pharmaceutical companies and diagnostic companies. Some of these innovators may not yet be fully aware of how IP can support the protection, commercialization and wider application of their technologies in addressing the environmental dimensions of AMR. The next section provides an overview of the various IP instruments that can be deployed by wastewater innovators to help scale up their technologies.

IP audits and inventories

Before choosing specific forms of IP protection, companies can first consider identifying the full inventory of products, services and outputs that could be protected, such as detection kits, digital tools, processes, platform technologies, etc. Companies can then consider conducting an IP audit or inventory check, which involves systematically identifying all existing and potential intellectual assets, inventions, designs, brand names, data and know-how and checking their protection status.[5] An IP audit reveals gaps (for example, a novel biosensor technique that isn't yet patented) and ensures the company actually owns critical IP (for example, confirming that employee inventions are assigned to the company). By taking stock of IP assets, an AMR wastewater-tech firm can decide which innovations to patent, which to keep as trade secrets, and where to shore up agreements or registrations. This proactive inventory is especially crucial in high-tech AMR solutions, which often combine hardware, software and biochemical innovations. It also helps to facilitate commercial negotiations and IP strategies when moving to deploy these solutions.

Conducting an IP audit not only helps identify what needs protection, it also supports strategic decisions that accelerate deployment. By clarifying ownership and protection status early, companies can avoid legal delays and facilitate smoother regulatory, procurement and partnership processes. This upstream clarity enables faster and more sustainable deployment of AMR technologies, particularly in cross-border and resource-constrained settings.[6]

Examples of IP protection that could benefit the development and deployment of AMR in wastewater detection, monitoring and management technologies are patents, copyright, trademark, designs and trade secrets.

Patents

A patent is an exclusive right granted for an invention. Patents benefit inventors by providing them with legal protection against copying of their inventions by competitors.[7] Companies and innovators working on AMR-related technologies could consider filing patents to secure exclusive rights over their inventions. Patents can serve as a powerful incentive mechanism by granting innovators exclusive rights for a limited period (usually for 20 years), enabling them to recover research and development costs, attract investment and commercialize the protected technologies, either themselves or by licensing them to other market players.[8] Many innovators and start-ups are using IP protection to attract investors as patents can prove the innovation is new, thereby serving as a form of collateral for venture capital. Furthermore, patent protection can help ensure that novel solutions addressing AMR are commercially viable, particularly when deployed through licensing models that align with global health needs.

Patents are fundamental IP protection for novel and inventive technical innovations. The right to exclude granted for an invention under patent law allows the owner to prevent others from making, using or selling the invention without authorization. In the AMR wastewater context, patents can protect new devices or processes. Beyond protecting technical innovations, patents strengthen a company's IP portfolio in ways that support structured technology development. In commercial negotiations, patents provide the legal clarity that defines ownership and the scope of rights being shared. This enables transparent, equitable agreements that facilitate the diffusion of AMR technologies while preserving the integrity of the invention. Patents can help

5 World Intellectual Property Organization (WIPO) (n.d.). *Uncovering IP Risks and Potential: IP Audit*. Geneva: WIPO. https://www.wipo.int/en/web/business/ip-audit.
6 World Intellectual Property Organization (WIPO) (n.d.). *IP Audit – Description and Toolkit*. Geneva: WIPO. https://www.wipo.int/documents/d/tisc/docs-en-tisc-toolkit-ip-audit-description.pdf.
7 World Intellectual Property Organization (WIPO) (n.d.). *Patents*. Geneva: WIPO. https://www.wipo.int/en/web/patents.
8 World Intellectual Property Organization (WIPO) (2023). *News – Global Health: Intellectual Property and Global Health News*. Geneva: WIPO. https://www.wipo.int/en/web/global-health/w/news/2023/news_0016.

operationalize innovation by supporting responsible use, ensuring quality control and fostering trust between partners.[9]

For example, a developer of a wastewater treatment system designed to remove resistant bacteria may file a patent for its novel filtration chamber function and integrated UV-reactor mechanism. This protects the invention from being copied, allowing the developer to license the technology to other partners. By doing so, the company retains exclusive rights while enabling broader deployment in regions facing high AMR burdens, demonstrating how patents can both incentivize innovation and support public health goals.

For AMR innovations that include software implementation of digital dashboards, machine learning models for microbial detection, or treatment optimization algorithms, these innovations could also be patented in certain jurisdictions.

Copyright and related rights

"Copyright and related rights" is a legal term used to describe the rights that creators and rights holders have in their literary and artistic works. Works covered by copyright and related rights range from books, music, paintings, sculpture and films to computer programs, databases, advertisements, maps and technical drawings.[10] For AMR innovations that include software implementation of digital dashboards, machine learning models for microbial detection, or treatment optimization algorithms, copyright protection plays a crucial role. Innovators should take steps to secure rights over the code, databases and user interfaces they develop.

While copyright arises automatically upon creation,[11] it is important to document authorship and consider registering rights, where appropriate, to strengthen enforcement options. Copyright and related rights can be foundational tools for enabling commercial partnerships while protecting against unauthorized copying or redistribution.

For example, a company developing an optical fiber biosensor platform for detecting antibiotic residues in wastewater may rely on copyright to protect the software interface used for visualizing detection data and generating automated reports. While the biosensor's hardware and detection mechanism may be patented, the source code for the visualization software, the structure of its underlying database, and the non-functional design of the user dashboard could be protected by copyright (although this varies by country and jurisdiction). This ensures that collaborators in different countries can adapt and use the platform under license while preserving the tool's original structure, usability and analytical outputs.

While patents protect functional aspects, copyright safeguards the specific expression of ideas thereby complementing other IP tools to create a comprehensive IP strategy. This enables innovators to license their tools responsibly, prevent unauthorized replication and maintain quality and integrity as technologies are adapted across different contexts. In addition, protecting the copyright of the manuals and databases that often accompany AMR technologies supports consistent, scalable training and implementation. In this way, copyright not only recognizes creative effort but also facilitates the secure and effective dissemination of technology.[12]

Trade secrets and know-how

Trade secrets are IP rights on confidential information that may be sold or licensed because it has commercial value due to its secrecy.[13] Trade secrets refer to confidential technical

9 Lybecker, K.M. and S. Lohse (2015). *Innovation and Diffusion of Green Technologies: The Role of Intellectual Property and Other Enabling Factors (Global Challenges Report)*. Geneva: WIPO. https://www.wipo.int/edocs/pubdocs/en/wipo_rep_gc_2015_1.pdf.
10 World Intellectual Property Organization (WIPO) (n.d.). *Copyright*. Geneva: WIPO. https://www.wipo.int/en/web/copyright.
11 World Intellectual Property Organization (WIPO) (n.d.). *Copyright Registration Systems*. Geneva: WIPO. https://www.wipo.int/en/web/copyright/activities/copyright-registration/index.
12 El Saghir, M. (n.d.). *Software and Database Protection* [PowerPoint slides]. Geneva: WIPO. https://www.wipo.int/edocs/mdocs/mdocs/en/wipo_ssc_cai_13/wipo_ssc_cai_13_topic_9_el_saghir.pptx.
13 World Intellectual Property Organization (WIPO) (n.d.). *Trade Secrets*. Geneva: WIPO. https://www.wipo.int/en/web/trade-secrets.

or commercially sensitive information that derives value from not being generally known and is subject to reasonable steps to maintain secrecy. Trade secret protection against misappropriation lasts only as long as the information is held in secrecy. In cases where patenting is not feasible, or not desired, due to subject-matter eligibility, cost, timelines or strategic considerations, innovators can protect key technical details, confidential know-how, processes or formulations through trade secrets. Companies should establish internal protocols such as non-disclosure agreements (NDAs), document management systems, access restrictions and information technology (IT) measures, and information management systems to safeguard proprietary insights, including production techniques or detection thresholds. This form of IP protection is particularly valuable for maintaining a competitive edge while avoiding disclosure through the patent system.[14]

In the context of AMR technologies, particularly in wastewater systems, trade secrets offer a valuable complement to other forms of IP protection by enabling innovators to safeguard proprietary knowledge that may not be suited for patenting. Unlike patents, trade secrets require no formal registration and can potentially remain protected indefinitely, provided confidentiality is maintained. However, trade secret protection depends on the holder taking reasonable steps to preserve secrecy, such as using confidentiality agreements, access controls, internal information management protocols and other safeguards.

Where trade secrets are unlawfully acquired, used or disclosed, legal recourse may be available depending on the jurisdiction, contractual obligations and/or specific trade secret legislation where such legislation exists.[15] At the same time, trade secrets are not an equivalent alternative to patent protection. Trade secret protection has inherent limitations as it generally does not prevent a competitor from independently discovering or legitimately reverse engineering the protected information.[16]

Trade secret protection plays an enabling role in technology commercialization by giving technology holders the confidence to engage in licensing, joint development or pilot deployment agreements without fully disclosing sensitive elements of their innovations in public. When used responsibly, trade secrets allow technologies to be transferred to implementation partners while still safeguarding key know-how.[17]

For example, a developer of a wastewater treatment system might patent the physical architecture of its bioreactor while keeping the microbial or enzymatic formulation confidential as a trade secret. Similarly, a company producing an AMR detection biosensor may license its device but retain the calibration algorithm or chemical coating process as undisclosed know-how. By combining patents and trade secrets, companies can protect critical components while enabling the controlled and scalable deployment of their technologies in diverse field settings.

By providing a means to protect proprietary know-how without public disclosure, trade secrets can help accelerate the responsible diffusion of AMR technologies by enabling innovators to engage confidently in collaborative deployment arrangements.

Designs

Industrial designs protect the ornamental or aesthetic aspects of a product, including features such as shape, configuration, pattern, color or surface appearance.[18] In the context of AMR in wastewater detection, monitoring and management technologies, industrial design protection may apply to the visual appearance of wastewater treatment devices, purification systems, biosensor housings, monitoring interfaces or modular treatment units. Beyond protecting product appearance, industrial designs may also form part of a broader branding and commercialization strategy alongside trademarks, helping innovators differentiate their technologies, strengthen market recognition and support technology deployment across different jurisdictions.

14 World Intellectual Property Organization (WIPO) (n.d.). *Trade Secrets*. Geneva: WIPO. https://www.wipo.int/en/web/trade-secrets.
15 World Intellectual Property Organization (WIPO) (n.d.). *Trade Secrets*. Geneva: WIPO. https://www.wipo.int/en/web/trade-secrets.
16 World Intellectual Property Organization (WIPO) (2024). *WIPO Guide to Trade Secrets and Innovation*. Geneva: WIPO. https://doi.org/10.34667/TIND.49735.
17 World Intellectual Property Organization (WIPO) (2024). *WIPO Guide to Trade Secrets and Innovation*. Geneva: WIPO. https://doi.org/10.34667/TIND.49735.
18 World Intellectual Property Organization (WIPO) (n.d.). *Industrial Designs*. Geneva: WIPO. https://www.wipo.int/en/web/designs.

Licensing, collaboration, knowledge and technology transfer

As AMR-related technologies move from research to real-world applications, strategic use of IP can help support their efficient, equitable and scalable deployment. However, IP tools represent only one component of a broader voluntary knowledge and technology transfer (K/TT) ecosystem, which also encompasses technology readiness, institutional and absorptive capacity, market adoption pathways, and downstream deployment considerations. Within this wider framework, a range of IP-based mechanisms can be leveraged to support the broader deployment and uptake of technologies while maintaining incentives for innovation. These considerations are especially important in the context of One Health, where wastewater detection tools, diagnostic platforms and treatment systems may need to be transferred, adapted and deployed across multiple sectors and jurisdictions.

Detection technologies: innovation and IP protection

Detection technologies for AMR often combine advanced scientific principles with engineering and data analytics. This creates multiple layers of innovation eligible for IP protection.[19] Innovations may include proprietary biosensor designs, microfluidic channels, novel detection chemistries, optical configurations, and signal amplification methods, each of which may be protected through patents.

In parallel, software components, such as machine learning algorithms for resistance profiling, data interpretation dashboards and user interfaces, may be protected by copyright.

Trademarks can also play a role in branding validated diagnostic kits or platforms, while trade secrets and NDAs safeguard calibration processes, source data or field validation protocols.

In K/TT, these layers are often transferred through different mechanisms. Patent-protected software or hardware or platform components may be licensed; software and data analytics tools may be deployed under voluntary licenses, including controlled use agreements; and calibration methods, datasets and field validation protocols are frequently retained as know-how and supported through training or ongoing technical assistance. Together, these IP tools help innovators secure investment, enable voluntary technology transfer and scale deployment while maintaining quality and trust.

Treatment technologies: innovation and IP protection

Innovations in wastewater treatment relevant to AMR include advanced remediation processes and targeted bacteriophage- or enzyme-based approaches designed to reduce antimicrobial residues, resistant bacteria or resistance genes.[20] Patentable elements may include: novel wastewater treatment processes; reactor designs; filtration systems; treatment materials; catalysts; microbial formulations; or integrated treatment configurations that improve the removal or inactivation of antimicrobial residues, resistant bacteria or resistance genes. Process innovations, such as enzyme-based treatment methods, bioaugmentation using selected or engineered microbial strains, and hybrid biological, physical or chemical treatment systems, may also be protectable, although patentable subject matter differs between jurisdictions.

Software used to model treatment performance, optimize operating parameters, control aeration or chemical dosing, monitor contaminant removal or track system performance may be protected by copyright and, where applicable, other forms of IP. Trade secrets may also be relevant for protecting confidential operating parameters, microbial strains, formulations, calibration methods and manufacturing processes. NDAs can support the controlled exchange of technical information during research collaboration, joint development, validation and pilot deployment.

19 Yamin, D., V. Uskoković, A.M. Wakil *et al.* (2023). Current and future technologies for the detection of antibiotic-resistant bacteria. *Diagnostics*, 13(20), 3246. https://doi.org/10.3390/diagnostics13203246.

20 Pham, M.N., F. Nishimura, J.C.W. Lan and K.S. Khoo (2024). Recent advancement of eliminating antibiotic-resistant bacteria and antibiotic resistance genes in livestock waste: a review. *Environmental Technology & Innovation,* 36, 103751. https://doi.org/10.1016/j.eti.2024.103751.

The commercialization and wider deployment of wastewater treatment technologies may also require local performance validation; environmental and regulatory approvals; suitable infrastructure; reliable maintenance and supplies; and sustained technical and operator capacity.

Voluntary licensing and partnerships for scale-up

Once a patent is granted, the technology inventor can either manufacture and sell the product individually or by entering into a business partnership through licensing the technology to another partner. Voluntary licensing is a contractual arrangement where the owner of IP grants another party the right to use the IP under agreed terms, without transferring ownership. This enables IP holders to commercialize their assets, generate revenue, expand into new markets and form strategic partnerships while retaining control over their IP.[21]

In practice, voluntary licensing is often a midpoint rather than an endpoint. While it enables the authorized use and deployment of protected technologies, effective market entry frequently also depends on post-license support, regulatory alignment and the development of local user and operator capabilities. For this reason, voluntary licensing is best understood as one component of a broader K/TT pathway through which wastewater AMR technologies can reach the market and achieve sustained impact.

Voluntary licensing agreements can also differ based on the scope of rights granted:

- An **exclusive license** gives a single licensee the sole right to use the IP within a specified scope, excluding all others, including the IP owner.
- A **non-exclusive license** allows the IP owner to grant the same rights to multiple licensees and to use the IP themselves.
- A **sole license** permits only one licensee to use the IP, but the owner retains the right to use it too.

Each voluntary licensing agreement should carefully define the territory, duration, financial terms (e.g., royalties) and scope of rights to ensure clear expectations and legal certainty. When executed effectively, voluntary licensing promotes the dissemination of innovation, facilitates global business expansion and unlocks the commercial value of intangible assets. The agreement types outlined below in Table 3 are presented for illustrative purposes only. They may not be equally applicable across all AMR wastewater and environmental technologies, with their relevance depending on the nature of the technology, its stage of development and the intended deployment context.

Table 3 Types of voluntary licensing agreement

Type of agreement	Summary
Technology licensing agreement	Grants the right to use patented or proprietary technology, enabling broader commercialization and innovation for both the technology owner and the user.
Trademark licensing agreement	Allows a business to use another company's trademark, leveraging brand recognition to enhance market reach and consumer trust.
Copyright licensing agreement	Permits the use of creative works protected by copyright, offering legal access to content like software, music or literature.
Merchandise licensing agreement	Authorizes the use of IP such as trademarks or characters on consumer products, enhancing market appeal and creating new revenue streams.
Franchising agreement	Provides the right to operate under a proven business model, bundling IP rights and operational know-how for market replication.

Source: WIPO synthesis for this report, based on WIPO's IP Assignment and Licensing guidance available at: https://www.wipo.int/en/web/business/assignment-licensing (2026).

21 World Intellectual Property Organization (WIPO) (n.d.). *IP Assignment and Licensing*. Geneva: WIPO. https://www.wipo.int/en/web/business/assignment-licensing.

Case study: university–industry technology transfer in wastewater treatment (Mexico)

Background

After the Second World War, Mexico's wastewater treatment infrastructure struggled to keep up with the country's rapid population and industrial growth.[22]

In 1986, to address Mexican treatment plants' lack of experience with efficient anaerobic processes, the Metropolitan Autonomous University (UAM) and the French National Research Institute for Sustainable Development (IRD) formed a research team, which was joined a year later by the Engineering Institute of the National Autonomous University of Mexico (UNAM), contributing expertise in public–private sector collaboration.[23]

IP strategy and key outcomes

The developed technology was licensed to nine Mexican companies through non-exclusive licenses granted for 10 years. In addition to the patented technologies, the licensing package included computer software, engineering manuals, a trademark and technical assistance for the implementation of initial projects.[24]

In 1994, an early evaluation of the technology transfer revealed that the licensees did not promote the technologies actively and adequately. While this approach enabled early dissemination of the technology, it also illustrated a common K/TT challenge: licensing alone did not ensure active uptake, market development or sustained promotion by licensees. It was therefore decided to adopt a new commercialization approach: the creation of a spin-off company called Integración Biotecnológica S.A. de C.V. (IB Tech®), led by a group of Mexican academics and entrepreneurs.

During its start-up phase, IB Tech operated within the Incubator System for Technology and Science-based Companies (SIECyT) of the UNAM. This model offered a more agile and mission-aligned complement to the earlier licensing arrangement, which on its own had proven less effective in scaling anaerobic treatment innovations due to limited technical handholding and weak industry uptake. By embedding researchers within a dedicated commercial vehicle, the spin-off approach allowed for closer collaboration with end users, iterative product refinement and more effective deployment of the technology in the field. The spin-off provided a vehicle for technical translation, sustained user engagement and operational credibility, addressing gaps that contractual licensing alone could not fill.

When IB Tech had its first important project contract signed, it graduated from the incubator system and started operating outside the university campus. IB Tech specializes in technologies for the treatment of wastewater mainly from industrial sources. The company manages every stage required in turnkey projects of treatment plants for municipalities and industries, from the characterization of the wastewater to be treated to the start-up of the plant. It continues to collaborate closely with the UNAM's Engineering Institute both by hiring academic personnel and applying technologies developed by the Institute.

Lessons learned

This case study highlights several K/TT design principles that are relevant to AMR-related technologies, particularly in wastewater and environmental contexts.

Voluntary licensing, particularly when embedded within public–private partnerships, can be an effective entry point for technology diffusion. However, its impact depends on how it is

22 McCulligh, C. and D. Tetreault (2017). Water management in Mexico: from concrete-heavy persistence to community-based resistance. *Water Alternatives*, 10(2), 341–369. https://www.water-alternatives.org/index.php/alldoc/articles/vol10/v10issue2/359-a10-2-9/file.

23 World Intellectual Property Organization (WIPO) (2010). *University–Industry Link: The Case of UNAM–IB Tech*. Geneva: WIPO. https://www.wipo.int/en/web/ip-advantage/w/stories/university-industry-link-the-case-of-unam-ib-tech.

24 World Intellectual Property Organization (WIPO) (2010). *University–Industry Link: The Case of UNAM–IB Tech*. Geneva: WIPO. https://www.wipo.int/en/web/ip-advantage/w/stories/university-industry-link-the-case-of-unam-ib-tech.

sequenced and supported within a broader K/TT strategy. For institutions seeking to transfer AMR-relevant technologies, this underscores the importance of aligning institutional strategy, partner selection and the sequencing of transfer mechanisms around go-to-market realities rather than IP transactions alone. More broadly, successful deployment depends on a range of complementary factors, including financing, infrastructure, regulatory systems, manufacturing capacity, technical expertise and local absorptive capacity. IP can facilitate technology transfer and collaboration, but it is only one component of the wider ecosystem required to translate innovation into sustainable impact.

While IB Tech's focus was not on AMR-specific wastewater treatment, its experience offers transferable lessons for the AMR innovation ecosystem. The strategic use of IP through non-exclusive licensing, bundled asset transfer and, ultimately, the creation of a mission-driven spin-off demonstrates how thoughtful commercialization pathways can overcome barriers to technology uptake. By combining robust IP strategies with mechanisms that consider the uniqueness of the jurisdiction and demand, similar models can be applied to accelerate the deployment of AMR-relevant technologies, such as diagnostic tools, biosensors and environmental surveillance systems.

The effectiveness of such models also depends on institutional financing and capability, including technology transfer offices, public procurers and regulatory bodies to coordinate licensing, implementation support and market uptake.

Policy entry points in national AMR action plans

National action plans (NAPs) increasingly recognize that AMR responses depend not only on stewardship, surveillance and infection prevention, but also on the ability to develop, adapt, supply and scale relevant tools. IP-related considerations are beginning to appear within AMR NAPs as part of the policy architecture for AMR innovation. References to research outputs, patenting, licensing models, innovation incentives, geographical diversification of manufacturing, sustainable supply, data systems and traditional knowledge indicate a growing recognition that AMR responses depend not only on generating new knowledge, but also on creating the conditions for that knowledge to be protected, transferred, adapted and deployed.

For wastewater-based AMR detection and treatment, these issues are practical rather than theoretical. A biosensor may involve patented components, copyrighted software, protected data structures, confidential calibration protocols and trademarked test kits. A treatment technology may depend on proprietary process designs, trade secrets, servicing arrangements, imported components or locally adapted materials. IP can help organize these assets into practical pathways for collaboration, licensing, local adaptation, quality assurance and scale-up. National AMR policy frameworks that already recognize these issues can therefore provide useful entry points for integrating IP and technology transfer considerations into AMR implementation planning. This helps promising AMR technologies move from research and pilot settings into sustained use across health, environmental and industrial systems.

Table 4 provides examples of where AMR policy frameworks already contain several entry points for IP and technology transfer, even when they do not always use technical IP language. Future AMR planning could build on these entry points by giving more systematic attention to ownership of research outputs, patenting, licensing, data governance, local production and technology transfer, particularly where countries are seeking to move AMR-related technologies from pilots to sustained implementation. Table 4 groups these provisions into broad policy entry points, while Table 6 in Annex 1 provides more detailed country-level examples of how IP and IP-related considerations are reflected in national AMR action plans.

Table 4 Examples of AMR policy frameworks that contain entry points for IP and technology transfer

Policy entry point for IP	Examples of country NAPs where IP appears
Protecting research outputs and new inventions	
Protection of AMR-related research outputs, institutional developments, inventions or IP rights	Argentina, the Republic of Côte d'Ivoire, Madagascar, Rwanda, Uganda
Patenting and institutional innovation	
Patenting, patent filings or registration of new AMR-related institutional innovations	Algeria, Argentina, Madagascar, Rwanda, Uganda, United Kingdom
Licensing and authorized use	
Licensing conditions, licensing models, approvals, authorization or regulated use of AMR-related products and technologies	Germany, Rwanda, Switzerland
Research translation and commercialization	
Movement of AMR research, diagnostics, therapeutics, vaccines, surveillance tools or innovations toward practical use or commercialization	Algeria, Argentina, Canada, Japan, Uganda, United Kingdom, United States
Local production and supply capacity	
Domestic production, manufacturing capacity, supply security, product availability or engagement with manufacturers	France, Japan, Rwanda, United Kingdom
Data, software and knowledge management	
AMR data systems, databases, surveillance platforms, research outputs, dashboards or knowledge-sharing mechanisms	Canada, Japan, Madagascar, United States
Local innovation and traditional knowledge	
Traditional knowledge, indigenous knowledge, locally developed solutions or local innovation capacity	The Republic of Côte d'Ivoire, Madagascar, Uganda
Incentives to sustain innovation and access	
Incentives, market-entry approaches, procurement measures, subscription models, grants, prizes or policies to maintain the availability of important products	Canada, France, Germany, Japan, Netherlands, Switzerland, United Kingdom

Source: WIPO analysis of publicly available national AMR action plans accessed online (2026).

Effective IP strategies can play a critical role in supporting the development, deployment and uptake of AMR-related technologies, especially in LMICs. Several low-cost innovative diagnostic and detection technologies are being developed by innovators, companies and universities. Patents, trade secrets and voluntary licensing mechanisms can help them to commercialize and scale up their technologies to address the One Health dimensions of AMR. Building public sector capacity, knowledge of IP rights and the ability to undertake voluntary licensing are essential to aligning innovation ecosystems with One Health goals.

From innovation and IP to technology application

The analysis in Part 1 shows that IP can provide legal clarity, support investment and structure collaboration. However, IP is only one component of the wider pathway through which technologies are developed, transferred, adapted and brought into sustained use. Effective K/TT may also require access to software, data, technical documentation and confidential know-how, together with training, validation, servicing, financing and institutional capacity.

Patent information can help identify areas of innovation activity and potential technology partners. However, the existence of a patent does not demonstrate that a technology is technically suitable, commercially available, affordable or ready for implementation. Decisions on adoption must also consider: the intended use; evidence of performance; technology maturity; infrastructure and operating requirements; costs; local capacity; and integration with existing wastewater, laboratory and surveillance systems.

These technical and implementation considerations are examined in the AMR Wastewater Technology Companion in Part 2.

Part 2: AMR Wastewater Technology Companion



The Technology Companion explores available technologies for detecting, monitoring and managing AMR in wastewater, from accessible laboratory methods to advanced surveillance and treatment approaches. It introduces tiered surveillance and phased treatment options that can be adapted to local needs and capabilities, complemented by seven country case studies illustrating how different technologies are being developed and applied in practice.

Purpose and scope

The Antimicrobial Resistance (AMR) Wastewater Technology Companion provides a policy-oriented overview of established and emerging technologies relevant to detecting and managing AMR in wastewater. It focuses on innovation through adaptation, repurposing, integration and application, including portable, decentralized, hybrid, digital and locally adaptable approaches. The Companion also explains the practical conditions that shape technology uptake, including validation, infrastructure, operating models, costs, skills, quality assurance, maintenance and integration into existing systems.

The Companion (written in collaboration with partner experts) is intended to provide accessible technical background for policy and partnership discussions. It is not a technical design manual, procurement guide or substitute for site-specific engineering, laboratory or regulatory assessment. The tiered detection and phased treatment frameworks are illustrative tools for structured planning rather than standardized international models. Technology choices should be adapted to the intended use, local risks, national systems, applicable standards and available resources.

The technologies described in the Companion vary in maturity. Some are established in clinical, environmental or industrial settings but remain under adaptation for complex wastewater matrices. Others are at research, prototype, pilot or demonstration stage. Case study and efficacy results are therefore context-specific illustrative and should not be interpreted as standardized performance benchmarks.

Context and rationale

AMR, One Health and wastewater

AMR arises when microorganisms no longer respond to antimicrobial treatments, making infections more difficult to treat. A One Health approach recognizes that antimicrobial use and resistance are interconnected across human, animal, food production and environmental systems. Wastewater is one of the interfaces through which antimicrobial residues, resistant organisms and resistance genes can move between these systems.[1]

Wastewater systems receive inputs from healthcare facilities, households, pharmaceutical manufacturing, livestock, aquaculture and agriculture. Depending on the setting, these inputs may enter sewer networks, onsite sanitation, treatment plants, surface waters, soils or sediments.[2] Wastewater can therefore function both as a pathway for environmental dissemination and as a practical point for surveillance, source control and targeted treatment. Conventional wastewater treatment can reduce some AMR-relevant contaminants, but performance varies by process, wastewater characteristics and operating conditions.[3]

1 United Nations Environment Programme (UNEP) (2023). *Bracing for Superbugs: Strengthening Environmental Action in the One Health Response to Antimicrobial Resistance*. Nairobi: UNEP. https://www.unep.org/resources/superbugs/environmental-action.
2 Anand, U., B. Adelodun, C. Cabreros *et al.* Occurrence, transformation, bioaccumulation, risk and analysis of pharmaceutical and personal care products from wastewater: a review. *Environmental Chemistry Letters*, 20, 3883–3904 (2022). https://doi.org/10.1007/s10311-022-01498-7.
3 World Health Organization (WHO) (2024). *Guidance on Wastewater and Solid Waste Management for Manufacturing of Antibiotics*. Geneva: WHO. https://www.who.int/publications/i/item/9789240097254.

Wastewater and environmental surveillance

Wastewater and environmental surveillance can measure three broad categories of AMR-relevant indicators: (1) antimicrobial residues; (2) antimicrobial-resistant organisms; and (3) antimicrobial-resistant genes (ARGs). These indicators can support screening, hotspot identification, trend monitoring, treatment-performance assessment and, where methods and interpretation are sufficiently standardized, regulatory or public health decision-making.[4]

Unlike surveillance of a single pathogen, AMR signals in wastewater may originate from multiple human and non-human sources. Interpretation therefore depends on sampling design; wastewater flow and dilution; the target being measured; the analytical method; and the relationship between the sampling point and the population or activity represented. In settings with limited sewer coverage, relevant surveillance points may include hospital discharge; sanitation systems; industrial effluent; agricultural runoff; and environmental waters affected by wastewater.[5],[6]

Technology landscape: detection and treatment approaches

Selecting technologies according to purpose and context

Technology selection often begins with the decision or action the technology is expected to support. Technologies for detection and monitoring may support initial screening, hotspot identification, early warning, routine trend analysis, regulatory assessment and evaluation of treatment performance.[7] Within the broader area of management, wastewater treatment technologies may contribute to source-level control and to reducing antimicrobial residues, resistant bacteria and the presence or abundance of resistance genes.[8] The most appropriate option depends on: the wastewater source; what is being measured; evidence required; infrastructure; skills; cost; regulatory context; and intended scale of use.

Tiered detection framework for wastewater-based AMR surveillance

The following indicative three-tier framework organizes technologies according to analytical depth, infrastructure, skills and intended use (see Figure 2). It is a synthesis for policy and implementation discussion, not a formal ranking of technology quality or maturity. Countries may use technologies from several tiers simultaneously, with referral and confirmation pathways linking decentralized screening to reference-level analysis.

Tier 1: decentralized screening and sentinel surveillance

Tier 1 emphasizes rapid and relatively accessible screening at facility, district or sentinel sites. ELISA, selected LFTs, validated biosensors and simplified molecular tools can support hotspot identification and prioritization of samples or sites for further investigation.[9] Their use requires standardized sampling, basic quality assurance and clear referral pathways where results may trigger regulatory or public health action.

4 Malcom, H.B. and D.A. Bowes (2025). Use of wastewater to monitor antimicrobial resistance trends in communities and implications for wastewater-based epidemiology: a review of the recent literature. *Microorganisms,* 13(9), 2073. https://doi.org/10.3390/microorganisms13092073.

5 Balcázar, J.L. (2025). Could wastewater-based surveillance be key to combating antimicrobial resistance? *mBio*, 16, e02778-25. https://doi.org/10.1128/mbio.02778-25.

6 Foxman, B., E. Salzman *et al.* (2025). Wastewater surveillance of antibiotic-resistant bacteria for public health action: potential and challenges. *American Journal of Epidemiology*, 194(5), 1192–1199. https://doi.org/10.1093/aje/kwae419.

7 Kamarul Aryffin, H.A., M.A. Bin Sahbudin, S. Ali Pitchay, A.H. Abhalim and I. Sahbudin (2025). Technological trends in epidemic intelligence for infectious disease surveillance: a systematic literature review. *PeerJ Computer Science,* 11, e2874. https://doi.org/10.7717/peerj-cs.2874.

8 Sambaza, S.S. and N. Naicker (2023). Contribution of wastewater to antimicrobial resistance: a review article. *Journal of Global Antimicrobial Resistance*, 34, 23–29. https://doi.org/10.1016/j.jgar.2023.05.010.

9 Centers for Disease Control and Prevention (CDC) (2024). *Wastewater Surveillance: A New Frontier for Public Health*. Atlanta: CDC. https://www.cdc.gov/advanced-molecular-detection/php/success-stories/wastewater-surveillance.html.

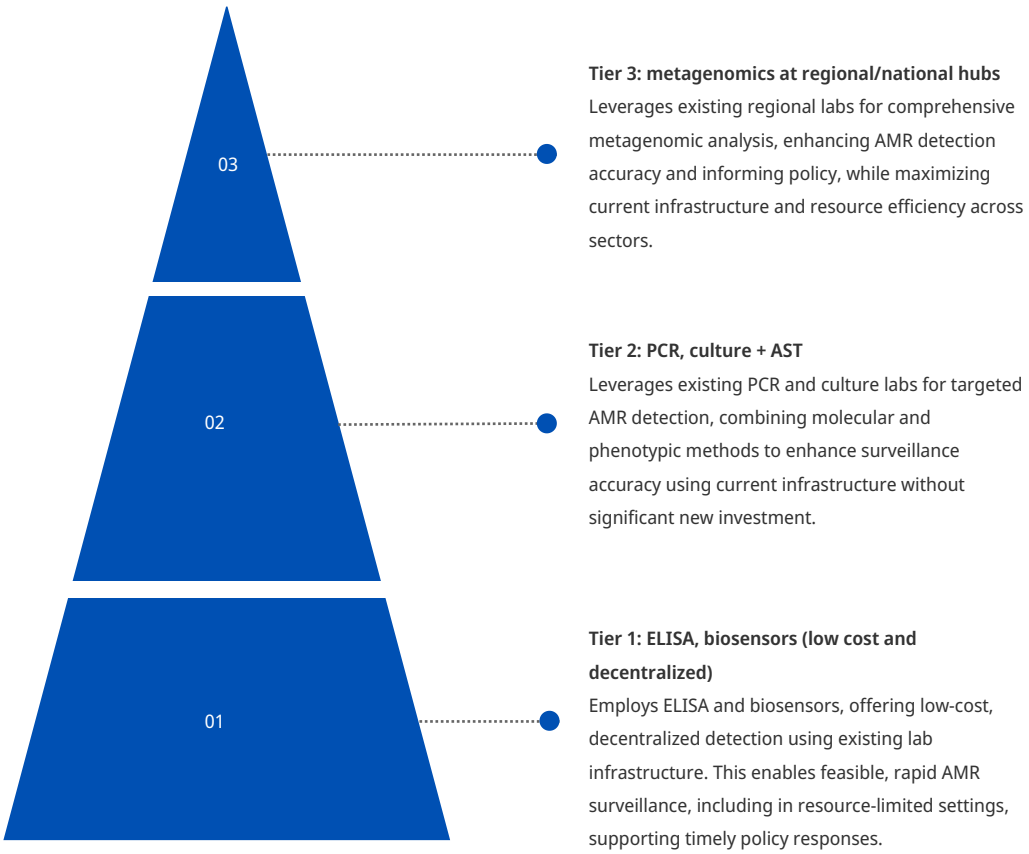
Tier 2: targeted molecular and phenotypic analysis

Tier 2 supports routine targeted monitoring through qPCR, digital PCR, high-throughput qPCR arrays, culture and antimicrobial susceptibility testing (AST). Wastewater applications require protocols that address sample concentration, nucleic-acid preservation, inhibitors, contamination controls and matrix-specific quality assurance. These methods can support quantitative trend monitoring and comparison across sites when embedded in established laboratory systems.[10],[11]

Tier 3: advanced genomic and analytical platforms

Tier 3 comprises advanced reference methods such as metagenomic or whole-genome sequencing and liquid chromatography–mass spectrometry (LC–MS). These platforms support detailed resistome characterization, identification of emerging signals, confirmation of lower-tier findings and trace measurement of antimicrobial residues. They require advanced instrumentation, bioinformatics or analytical chemistry expertise, reference materials, strong quality systems and sustainable financing.[12]

Figure 2 Tiered detection framework for wastewater-based AMR surveillance



Source: WIPO (2026). Framework developed based on technology complexity and informed by WHO's tiered laboratory network model (Figure 4.2), available at: https://tbksp.who.int/en/node/3121#Fig4.2.

Countries may operate technologies from several tiers at the same time. Tier 1 tools can extend geographic coverage and identify priority sites; Tier 2 methods can support routine

10 Oon Y.-L., Y.-S. Oon, M. Ayaz, M. Deng, L. Li and K. Song (2023) Waterborne pathogens detection technologies: advances, challenges, and future perspectives. *Frontiers in Microbiology.*, 14:1286923. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1286923/full.

11 World Health Organization (WHO) (2025). *Wastewater and Environmental Surveillance: Summary for Antimicrobial Resistance*. Geneva: WHO. https://www.who.int/publications/m/item/wastewater-and-environmental-surveillance--summary-for-antimicrobial-resistance.

12 Oon Y.-L., Y.-S. Oon, M. Ayaz, M. Deng, L. Li and K. Song (2023) Waterborne pathogens detection technologies: advances, challenges, and future perspectives. *Frontiers in Microbiology*, 14:1286923. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1286923/full.

targeted surveillance; and Tier 3 capacity can provide confirmation, deeper characterization and reference support. Results should be comparable across sites through harmonized sampling, quality assurance, data standards and clearly defined referral pathways.

See Table 7 in Annex 2 for a summary of the principal detection technologies, their main surveillance roles, likely deployment settings and key limitations.

Emerging detection technologies and rapid assessment

Emerging detection approaches illustrate how innovation is expanding the practical reach of wastewater surveillance through new tools and the adaptation of established platforms for environmental use. Next-generation biosensors are being developed for rapid detection of selected antibiotics, resistant organisms or resistance markers; clustered regularly interspaced short palindromic repeats (CRISPR)-based assays offer highly specific nucleic-acid detection; and portable sequencing platforms may support preliminary genomic assessment in time-sensitive settings.[13],[14] Innovation in these tools is not limited to the underlying technology, but also includes making these tools more portable, rapid, affordable and suitable for decentralized use. These approaches may strengthen Tier 1 or Tier 2 capacity, but they generally require further validation in complex wastewater matrices and confirmation through established reference methods.[15]

Field-adapted tools may be particularly useful during hospital outbreaks, investigations of pharmaceutical or industrial discharge, sanitation disruptions or other high-risk situations where early environmental signals can guide targeted sampling and risk prioritization.[16] Their primary value lies in extending surveillance closer to the point of need, while complementing, rather than replacing, accredited laboratory analysis.[17]

Integration with public health and environmental data systems

Wastewater indicators are most useful when they complement, rather than operate separately from, clinical, veterinary, antimicrobial-use and environmental information. Existing laboratory networks, digital reporting platforms and surveillance cycles can provide a starting point for integration, provided that wastewater-specific sampling, biosafety, quality assurance and interpretation requirements are addressed.[18]

Integration can support geographic and sector-specific hotspot identification, trend monitoring, stewardship evaluation, environmental oversight and early warning. It also reduces duplication by building on PCR, culture, sequencing, analytical chemistry, water-quality and pathogen-surveillance capacity already available in many systems.[19]

13 Wu, F., Q. Zhu, L. Zhang, W. Shen, J. Gong, H.K. Lee and S. Tang (2025). Recent progress of biosensing techniques for environmental antibiotic resistance genes. *TrAC Trends in Analytical Chemistry*. 191, 118380. https://doi.org/10.1016/j.trac.2025.118380.

14 Khan, M.U., M.M. Rahman, N. Zahan, M.K. Masud, S. Sarker and M.H. Haque (2025). Electrochemical biosensing for antibiotic-resistant bacteria: advances, challenges, and future directions. *Micromachines*, 16(9), 986. https://doi.org/10.3390/mi16090986.

15 Wu, F., Q. Zhu, L. Zhang, W. Shen, J. Gong, H.K. Lee and S. Tang (2025). Recent progress of biosensing techniques for environmental antibiotic resistance genes. *TrAC Trends in Analytical Chemistry*. 191, 118380. https://doi.org/10.1016/j.trac.2025.118380.

16 World Health Organization (WHO) (2024). *Wastewater and Environmental Surveillance for One or More Pathogens: Guidance on Prioritization, Implementation and Integration: Pilot Version*. Geneva: WHO. https://www.who.int/publications/m/item/wastewater-and-environmental-surveillance-for-one-or-more-pathogens--guidance-on-prioritization--implementation-and-integration.

17 Zhou, Z., I.-H. Cho and U.S. Kadam (2025). CRISPR-Cas-based diagnostics in biomedicine: principles, applications, and future trajectories. *Biosensors*, 15(10), 660. https://doi.org/10.3390/bios15100660.

18 Hock, L., R. Luiken, E. Valério, M. Vargha, J. Vierheilig, S. Börjesson, T. Pitkänen and H. Schmitt (2026). Integrating AMR surveillance into wastewater monitoring systems in 2025: a position on the implementation of Article 17 of the Urban Wastewater Treatment Directive (UWWTD). *Eurosurveillance,* 31(3). https://doi.org/10.2807/1560-7917.ES.2026.31.3.2500289.

19 Hock, L., R. Luiken, E. Valério, M. Vargha, J. Vierheilig, S. Börjesson, T. Pitkänen and H. Schmitt (2026). Integrating AMR surveillance into wastewater monitoring systems in 2025: a position on the implementation of Article 17 of the Urban Wastewater Treatment Directive (UWWTD). *Eurosurveillance,* 31(3). https://doi.org/10.2807/1560-7917.ES.2026.31.3.2500289.

Phased framework for treatment and mitigation

Detection technologies help identify antimicrobial residues, resistant organisms and resistance genes in wastewater. Treatment technologies can then be applied to reduce these contaminants and limit their release into receiving environments.[20] The following illustrative phased framework (Table 5) organizes treatment options according to increasing levels of intervention. It does not replace site-specific engineering design or national technical guidance.

Table 5 Phased approaches to wastewater treatment relevant to AMR

Phase	Primary focus	Indicative approaches	When it may be appropriate
Phase 1: source control and optimization of existing treatment [1, 2, 3, 4, 5]	Reduce avoidable antimicrobial loading and improve the performance of systems already in place.	Source segregation and pollution prevention; optimization of activated sludge, anaerobic digestion, lagoons, constructed wetlands and other biological or nature-based systems; improved operation, maintenance and monitoring.	Initial action across most settings, particularly where existing systems are underperforming or resources are limited. Establishes a performance baseline and identifies residual risks.
Phase 2: targeted barrier strengthening and polishing [4, 6, 7, 8]	Address priority contaminants or organisms that persist after conventional treatment.	Membrane bioreactors (MBRs), ultrafiltration or nanofiltration; granular activated carbon and, where locally validated, biochar-based adsorption; validated chemical or UV disinfection; localized point-of-source treatment; combinations of biological treatment with adsorption or physical separation.	Where monitoring identifies persistent residues or resistant organisms, discharge requirements are more stringent, or high-risk facilities require additional barriers.
Phase 3: advanced, hybrid or responsive treatment at high-risk sites [1, 4, 7, 9]	Treat high-concentration or complex waste streams and improve performance across several AMR-relevant endpoints.	AOPs; electrochemical or photocatalytic treatment; hybrid multi-barrier systems; monitoring-informed or automated process control, where validated; and carefully validated emerging approaches.	At pharmaceutical, healthcare, livestock or other priority sites where risk assessment and monitoring justify higher investment and where specialist operation, energy, maintenance and regulatory oversight can be sustained.

Notes: 1 World Health Organization (WHO), 2024.2 World Health Organization (WHO), Food and Agriculture Organization of the United Nations (FAO) and World Organisation for Animal Health (WOAH), 2020. 3 United Nations Environment Programme (UNEP), 2023. 4 Bairán, G. et al., 2020. 5 Londong, J. et al., e, 2023. 6 Hiller, C.X. et al., 2019. 7 Pham, M.N. et al., 2024. 8 Werkneh, A. A. and M. A. Islam, 2023. 9 World Health Organization (WHO), 2025.

Sources: As shown above.

This phased approach is an indicative synthesis of international guidance and the wastewater-treatment literature. It is not intended as a fixed sequence or technology hierarchy. Appropriate measures should be selected on the basis of source characteristics; locally identified AMR risks; treatment objectives; infrastructure; available capacity; lifecycle costs; and regulatory requirements. Technologies should be evaluated against relevant endpoints, including antimicrobial residues, antimicrobial-resistant organisms and resistance genes.

The phases may be combined within a treatment train. Monitoring can help determine whether existing treatment is adequate, whether an additional barrier or polishing step is needed, or whether advanced treatment is justified at a high-risk discharge point.[21] Decisions should consider: the wastewater matrix; target contaminants; treatment objectives; energy and consumables; operator capacity; maintenance; by-products; and applicable discharge or reuse requirements.

20 Bairán, G., G. Rebollar-Pérez, E. Chávez-Bravo and E. Torres (2020). Treatment processes for microbial resistance mitigation: the technological contribution to tackle the problem of antibiotic resistance. *International Journal of Environmental Research and Public Health,* 17(23), 8866. https://doi.org/10.3390/ijerph17238866.

21 Sampeney, E.T., I.M. Bryant, R.K. Sam, G.S. Botchway, P.K. Yeboah-Danso, P. Dotsey, I. Yaala and D.O. Agyei (2025). Revolutionizing industrial wastewater management in Ghana: sustainable innovations for a cleaner future. *Desalination and Water Treatment*, 324, 101589. https://doi.org/10.1016/j.dwt.2025.101589.

Treatment technologies across the phases

Conventional and established treatment approaches

Biological treatment: Activated sludge systems and related biological processes form the foundation of municipal wastewater treatment globally. Although originally designed to remove organic matter, nutrients and pathogens, these systems can also reduce total microbial loads and partially decrease resistance markers and antibiotic concentrations.[22] Performance varies according to influent composition, system design and operational conditions. In many settings, optimizing existing biological systems represents the first and most cost-effective step in addressing AMR-relevant endpoints.[23] This approach aligns with phased implementation strategies and allows incremental improvement without major infrastructure replacement.

Nature-based treatment systems: These systems, including constructed wetlands, waste stabilization ponds and soil- or plant-based filtration systems, use microbial activity, sedimentation, plant uptake, sunlight exposure and natural filtration to reduce microbial loads, nutrients and selected antimicrobial residues.[24] These systems may be particularly relevant for decentralized, rural or resource-constrained settings, although performance against AMR-specific targets, such as resistant bacteria and resistance genes, remains variable and is dependent on site-specific design and monitoring.[25]

Membrane systems: These systems, including MBRs, ultrafiltration and nanofiltration, provide improved removal of microorganisms and particulate-associated resistance genes.[26] These are particularly relevant where effluent standards are stringent or where pharmaceutical discharge concentrations are elevated.[27] Their deployment is typically considered in higher-capacity facilities or industrial zones where environmental risk assessments justify additional investment.

Chemical disinfection and advanced oxidation processes (AOPs): These processes, including ozonation, photo-Fenton reactions, heterogeneous photocatalysis and electrochemical oxidation, are increasingly being evaluated for their ability to degrade persistent pharmaceutical compounds and reduce genetic material in treated effluent. These processes are often implemented as tertiary treatment stages in high-capacity municipal facilities or industrial settings.[28] Adoption of advanced processes is generally guided by regulatory triggers, environmental thresholds or pharmaceutical discharge assessments rather than universal application.

Adsorption and hybrid systems: adsorptive materials, including granular activated carbon (GAC) and biochar, are used to remove organic micropollutants, including certain antibiotics.[29] Hybrid, multi-barrier treatment configurations that combine biological, physical and chemical processes are being evaluated to determine their ability to improve overall performance across multiple AMR-related indicators.[30] Such configurations may be appropriate in settings where risk assessments indicate persistent residue levels after conventional treatment.

22 Rizzo, L., C. Manaia, C. Merlin, T. Schwartz, C. Dagot, M.C. Ploy, I. Michael and D. Fatta-Kassinos (2013). Urban wastewater treatment plants as hotspots for antibiotic resistant bacteria and genes spread into the environment: a review. *Science of the Total Environment*, 447, 345–360. https://doi.org/10.1016/j.scitotenv.2013.01.032.

23 Zhang, S., T. Xu, C. Zhang, H. Zhou, T. Liu and H.-L. Song (2025). A review of antibiotic resistance generation and control in wastewater and solid waste system. *Journal of Environmental Chemical Engineering,* 13(5), 118014. https://doi.org/10.1016/j.jece.2025.118014.

24 Kaur, A., S. Arora, A. Kumar, A. Karnwal and R. Singh, (2026). Nature-based wastewater treatment technologies: a comprehensive review of constructed wetlands and vermifiltration. *Cleaner Water*, 5, 100204. https://doi.org/10.1016/j.clwat.2026.100204.

25 Zhang, S., T. Xu, C. Zhang, H. Zhou, T. Liu and H.-L. Song (2025). A review of antibiotic resistance generation and control in wastewater and solid waste system. *Journal of Environmental Chemical Engineering,* 13(5), 118014. https://doi.org/10.1016/j.jece.2025.118014.

26 Gong, W., L. Bai and H. Liang (2024). Membrane-based technologies for removing emerging contaminants in urban water systems: limitations, successes, and future improvements. *Desalination*, 590, 117974. https://doi.org/10.1016/j.desal.2024.117974.

27 Zhang, S., T. Xu, C. Zhang, H. Zhou, T. Liu and H.-L. Song (2025). A review of antibiotic resistance generation and control in wastewater and solid waste system. *Journal of Environmental Chemical Engineering,* 13(5), 118014. https://doi.org/10.1016/j.jece.2025.118014.

28 Rizzo, L., C. Manaia, C. Merlin, T. Schwartz, C. Dagot, M.C. Ploy, I. Michael and D. Fatta-Kassinos (2013). Urban wastewater treatment plants as hotspots for antibiotic resistant bacteria and genes spread into the environment: a review. *Science of the Total Environment*, 447, 345–360. https://doi.org/10.1016/j.scitotenv.2013.01.032.

29 Rizzo, L., C. Manaia, C. Merlin, T. Schwartz, C. Dagot, M.C. Ploy, I. Michael and D. Fatta-Kassinos (2013). Urban wastewater treatment plants as hotspots for antibiotic resistant bacteria and genes spread into the environment: a review. *Science of the Total Environment*, 447, 345–360. https://doi.org/10.1016/j.scitotenv.2013.01.032.

30 Lin, K., N. Wu, S. Liu, J. Yao, H. You, S. Heng, X. Wang, J. Huang, P. Pullammanappallil and S. Yang (2026). Advanced treatment and disinfection of hospital wastewater: progress, monitoring gaps, and trends. *Water*, 18(5), 605. https://doi.org/10.3390/w18050605.

Emerging wastewater treatment technologies

Innovation in wastewater treatment relevant to AMR ranges from incremental improvements to established processes, to potentially breakthrough approaches based on new materials, biological mechanisms and targeted gene technologies.[31] Incremental innovation may involve improving the performance of existing treatment systems, combining established processes into more effective treatment trains, using locally available materials or adapting technologies for decentralized and lower-resource settings. More transformative innovation is being explored through nanotechnology, bacteriophages and CRISPR-based approaches that aim to act more selectively on resistant organisms or resistance genes.[32]

In addition to established biological, membrane and oxidation processes, several emerging treatment approaches are being explored to address antimicrobial residues, resistant bacteria and ARGs that may persist after conventional treatment. These technologies are largely at pilot or research stage and are being evaluated for performance, scalability, cost and environmental safety.

Nanotechnology-based systems: Engineered nanomaterials, such as metal oxides or carbon-based nanomaterials, are used to enhance antimicrobial activity and adsorption capacity. Compared with conventional filtration, nanostructured membranes and reactive surfaces aim to improve removal or inactivation of resistant organisms and reduce the abundance of antimicrobial resistance genes (ARGs).[33] These systems may eventually support advanced tertiary treatment, particularly in higher-capacity facilities, subject to evaluation of long-term environmental safety and regulatory approval.

Phage-based approaches: These represent a potentially more targeted form of biological innovation. They use bacteriophages – viruses that infect bacteria – to selectively target and reduce resistant bacterial populations .[34] Unlike broad-spectrum disinfection methods, phages can be directed at specific bacteria and may eventually be integrated into biological treatment systems. Their use in wastewater remains experimental, with ongoing assessment of stability, ecological impact and operational feasibility.[35]

CRISPR-based strategies: These represent a more disruptive research direction. They are being investigated for targeted removal or disruption of resistance genes within microbial communities.[36] While CRISPR technologies are more established in diagnostics, their application in environmental treatment is at an early research stage.[37] Potential delivery mechanisms include engineered phages or nanoparticles, but practical use would require careful consideration of biosafety, ecological impacts, containment and regulatory oversight.[38]

Algal–bacterial consortia: These combine microalgae and bacterial systems to enhance nutrient removal, antibiotic degradation and pathogen reduction within low-energy treatment configurations. These systems are being explored as part of circular or resource-recovery

31 Saeed, U., R.A. Insaf, Z.Z. Piracha *et al.* (2023). Crisis averted: a world united against the menace of multiple drug-resistant superbugs – pioneering anti-AMR vaccines, RNA interference, nanomedicine, CRISPR-based antimicrobials, bacteriophage therapies, and clinical artificial intelligence strategies to safeguard the global antimicrobial arsenal. *Frontiers in Microbiology*, 14, 1270018. https://doi.org/10.3389/fmicb.2023.1270018.

32 Saeed, U., R.A. Insaf, Z.Z. Piracha *et al.* (2023). Crisis averted: a world united against the menace of multiple drug-resistant superbugs – pioneering anti-AMR vaccines, RNA interference, nanomedicine, CRISPR-based antimicrobials, bacteriophage therapies, and clinical artificial intelligence strategies to safeguard the global antimicrobial arsenal. *Frontiers in Microbiology*, 14, 1270018. https://doi.org/10.3389/fmicb.2023.1270018.

33 Xu, Z., D. Zhao, J. Lu, J. Liu, G. Dao, B. Chen, B. Huang and X. Pan (2023). Multiple roles of nanomaterials along with their based nanotechnologies in the elimination and dissemination of antibiotic resistance. *Chemical Engineering Journal*, 455 (Part 2), 140927. https://doi.org/10.1016/j.cej.2022.140927.

34 World Health Organization (WHO) Regional Office for Europe (2025). *Bacteriophages and Their Use in Combating Antimicrobial Resistance*. Geneva: WHO. https://www.who.int/europe/news-room/fact-sheets/item/bacteriophages-and-their-use-in-combating-antimicrobial-resistance.

35 Huang, W., F. Wang, Y. Su, H. Huang and J. Luo (2025). Underestimated roles of phages in biological wastewater treatment systems: recent advances and challenges. *Journal of Hazardous Materials*, 495, 139007. https://doi.org/10.1016/j.jhazmat.2025.139007.

36 Nuevo J.J.M., J.A.G. Fortaleza, K.S.P. Cabuhat, C.J.N. Ong, A.C. Jalova, F.A. Mortel and G.D. Bacalzo (2026) CRISPR-driven strategies to disrupt methicillin-resistant Staphylococcus aureus biofilms: a review. *Frontiers in Cellular and Infection Microbiology*, 16, 1784529. https://doi.org/10.3389/fcimb.2026.1784529.

37 Pursey, E., D. Sünderhauf, W.H. Gaze, E.R. Westra and G. van Houte (2018). CRISPR-Cas antimicrobials: challenges and future prospects. *PLoS Pathogens*, 14(6), e1006990. https://doi.org/10.1371/journal.ppat.1006990.

38 Gao, Z., Y. Gao, S. Wang, X. Li *et al.* (2025). Application progress and biosafety challenges of gene editing and synthetic biotechnology in diagnosis, treatment and prevention of infectious diseases. *Biosafety and Health*, 7(5), 312–322. https://doi.org/10.1016/j.bsheal.2025.09.002.

models and may be relevant for decentralized or resource-constrained settings.[39] Their innovative value lies primarily in combining biological functions with resource-recovery and circular-economy models. They may be relevant for decentralized or resource-constrained settings, subject to local validation and operational feasibility.[40]

Biochar-based adsorption systems: These systems illustrate incremental and locally adaptable innovation that represent a lower-cost emerging option. Biochar produced from agricultural residues can adsorb certain antibiotics and may contribute to reducing microbial loads. Innovation may involve selecting local feedstocks, modifying the material to improve adsorption, integrating it into existing treatment systems or developing lower-cost replacement and regeneration models.[41],[42] Its relative affordability and adaptability make it potentially suitable for decentralized or rural treatment applications, pending further validation of performance and longevity.[43]

Across these approaches, innovation does not always depend on inventing an entirely new treatment technology. It may also arise through adaptation, new materials, process integration, improved delivery, local manufacture or the combination of existing technologies into more effective treatment systems.[44] Phased piloting, comparison with established performance benchmarks and alignment with environmental and regulatory requirements will be important in determining whether these emerging approaches can address residual AMR-related contaminants in high-risk or high-concentration wastewater settings.[45]

Innovations in wastewater treatment systems

Emerging wastewater treatment innovations increasingly incorporate sensor-driven control and adaptive process optimization. Rather than operating at fixed treatment settings, "smart" systems use real-time monitoring of parameters, such as antibiotic concentrations, microbial load and organic content, to dynamically adjust aeration, oxidation intensity or chemical dosing. Coupled with digital and artificial intelligence (AI)-driven control platforms, these adaptive systems can optimize removal efficiency while reducing energy and chemical use. In high-risk settings, such as hospitals or pharmaceutical facilities, responsive treatment adjustments may help limit selective pressure during periods of elevated antimicrobial discharge.

Although still developing in many contexts, smart treatment configurations illustrate a shift from static infrastructure toward responsive environmental risk management. By linking detection with automated operational adjustments, such systems integrate surveillance and mitigation within a single treatment architecture, strengthening pollution prevention under a One Health framework.

Source: A.K. Worku, D.W. Ayele, M.A. Teshager, M. Omar, P. Poursafari Yerkrang, R. Elgaddafi and M.A. Alemu (2025). Recent advances in wastewater treatment technologies: innovations and new insights. *Energy Reviews*, 4(4), 100164. https://doi.org/10.1016/j.enrev.2025.100164.

39 Muñoz, R. and B. Guieysse (2006). Algal–bacterial processes for the treatment of hazardous contaminants: a review. *Water Research*, 40(15), 2799–2815. https://doi.org/10.1016/j.watres.2006.06.011.
40 Muñoz, R. and B. Guieysse (2006). Algal–bacterial processes for the treatment of hazardous contaminants: a review. *Water Research*, 40(15), 2799–2815. https://doi.org/10.1016/j.watres.2006.06.011.
41 Sridevi, H., V. Gosu and R. Juturu (2026) Recent advances in biochar from lignocellulosic and non-lignocellulosic feedstocks for heavy metal remediation. *Discover Applied Sciences*, 8, 819. https://doi.org/10.1007/s42452-026-08853-1.
42 Foong, S.Y., B.L.F. Chin, S.S.M. Lock *et al.* (2024). Enhancing wastewater treatment with engineered biochar from microwave-assisted approach – a comprehensive review. *Environmental Technology & Innovation*, 36, 103835. https://doi.org/10.1016/j.eti.2024.103835.
43 Rahman, A., M.M. Rahman, M.A. Haque, P. Shinu, M.M. Rahman, A.A. Khan and S. Rushd (2026). Biochar-based catalysts for sustainable wastewater treatment: advances, mechanisms, and future perspectives. *Catalysts*, 16(6), 538. https://doi.org/10.3390/catal16060538.
44 Anadon, L.D., G. Chan, A.G. Harley, K. Matus, S. Moon, S.L. Murthy and W.C. Clark (2016). Making technological innovation work for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America,* 113(35), 9682–9690. https://doi.org/10.1073/pnas.1525004113.
45 Anadon, L.D., G. Chan, A.G. Harley, K. Matus, S. Moon, S.L. Murthy and W.C. Clark (2016). Making technological innovation work for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America,* 113(35), 9682–9690. https://doi.org/10.1073/pnas.1525004113.

Application across wastewater sources and One Health interfaces

The following case studies illustrate different forms of technological innovation and application across healthcare, municipal, pharmaceutical, agricultural and environmental settings. They include research applications, pilots, operational treatment upgrades and coordinated surveillance networks. Each case study is linked to an indicative detection tier or treatment phase to show how the framework may be applied, in the hope that learning from them will contribute to future successful AMR wastewater treatment technology deployment. The placement is illustrative and should be considered alongside technology maturity, intended use, evidence base and local implementation conditions. The case studies demonstrate the practical use of wastewater detection and treatment technologies in developing countries and low-resource settings to address the environmental dimensions of AMR.

Disclaimer: The case studies presented in this report are based on publicly available information and do not necessarily reflect the views of the companies concerned, as the relevant stakeholders were not interviewed directly.

Healthcare-associated effluent

Healthcare facilities represent concentrated AMR interfaces where antimicrobial use is intensive and resistant pathogens are prevalent. Effluent from hospitals may contain antimicrobial residues, resistant bacteria and ARGs. Where treatment systems are not specifically designed to address pharmaceutical residues, hospital discharge may contribute elevated resistance signals in receiving systems.[46]

The following case studies from Qatar and Uganda demonstrate how wastewater-based approaches can be applied at the healthcare interface, combining facility-level surveillance with targeted treatment to support AMR monitoring and reduce environmental contamination.

Case study: Qatar – high-throughput qPCR-based hospital wastewater surveillance

Context

Qatar's National AMR Plan (2024–2030) prioritizes multisectoral coordination and strengthened surveillance across clinical, environmental and agricultural domains.[47] During the COVID-19 pandemic, researchers initiated hospital-based wastewater surveillance to evaluate whether molecular signals in effluent could provide a real-time window into antimicrobial use, infection control practices and resistance dynamics within healthcare facilities. The objective was to assess the feasibility of embedding wastewater-based epidemiology into national laboratory systems as an early warning tool capable of strengthening AMR surveillance, informing stewardship strategies and expanding environmental monitoring within a One Health framework.[48]

Technology and application

Wastewater samples were collected from COVID-19 and non-COVID facilities, including patient care and non-patient areas. Standard water quality parameters and microbial loads were assessed. High-throughput qPCR arrays were used to screen for priority ARG categories spanning major antibiotic classes. Parallel microbial community profiling characterized bacterial diversity and ecological composition. This integrated design enabled simultaneous assessment of resistance genes and microbial communities across facilities.

46 Lan, L., Y. Wang, Y. Chen, T. Wang, J. Zhang and B. Tan (2025). A review on the prevalence and treatment of antibiotic resistance genes in hospital wastewater. *Toxics*, 13(4), 263. https://doi.org/10.3390/toxics13040263.
47 Ministry of Public Health – Qatar (2024). *Qatar: National Antimicrobial Resistance Action Plan 2024–2030*. Geneva: WHO. https://www.who.int/publications/m/item/qatar--national-antimicrobial-resistance-action-plan-2024-2030.
48 Johar, A.A., M.A. Salih, H.A. Abdelrahman, H. Al Mana, H.A. Hadi and N.O. Eltai (2023). Wastewater-based epidemiology for tracking bacterial diversity and antibiotic resistance in COVID-19 isolation hospitals in Qatar. *Journal of Hospital Infection*, 141, 209–220. https://doi.org/10.1016/j.jhin.2023.08.011.

Technical findings and performance

Hospital wastewater contained diverse microbial populations, including clinically relevant organisms such as *Escherichia coli*, *enterococcus* species and *Clostridioides difficile*. A broad range of resistance genes were detected, including markers associated with beta-lactams, macrolides, aminoglycosides, fluoroquinolones and carbapenems. Several resistance markers were consistently observed across hospitals, indicating stable resistance signals within healthcare effluent. Carbapenem resistance genes were identified in multiple facilities. Higher resistance gene diversity was observed in patient-care areas of COVID-designated hospitals compared to non-patient sites, suggesting that antimicrobial use intensity may influence wastewater resistance profiles.

Implementation characteristics

The pilot demonstrated that high-throughput qPCR can be incorporated into hospital wastewater monitoring using existing molecular laboratory infrastructure. The approach enabled rapid, multi-target detection without requiring organism isolation. Implementation relied on standardized sampling, laboratory quality assurance and structured data management. Interpretation was strengthened when wastewater findings were analyzed alongside antimicrobial consumption and clinical resistance data. The study also illustrated how pandemic-era molecular diagnostic capacity can be leveraged for routine AMR surveillance.

Innovation and application significance

The Qatar pilot demonstrates how hospital wastewater surveillance can complement clinical AMR systems by generating facility-level resistance indicators linked to antimicrobial use, infection control practices and healthcare-associated risk. By applying high-throughput qPCR to hospital effluent, the study showed how molecular tools can detect resistance markers across multiple antibiotic classes and provide early signals of resistance patterns within healthcare settings.

The case study also illustrates the value of integrating wastewater data with antimicrobial consumption and clinical resistance information. This combined approach can strengthen situational awareness, support facility-level risk assessment and provide evidence for stewardship, infection prevention and environmental monitoring. Its use of existing molecular laboratory capacity further shows how pandemic-era diagnostic infrastructure can be adapted for longer-term AMR surveillance when supported by standardized sampling, quality assurance and data interpretation systems.

Within a One Health framework, the Qatar case study highlights how healthcare wastewater can function as an intelligence point between clinical practice and environmental exposure. It demonstrates the relevance of facility-level surveillance for understanding resistance dynamics beyond patient-level reporting and for linking hospital AMR control with broader environmental monitoring systems.

The Qatar case study focuses on surveillance, demonstrating how molecular analysis of hospital wastewater can generate facility-level resistance indicators. The Uganda case study below complements this by showing how decentralized treatment can reduce antimicrobial residues and resistant organisms at the point of discharge.

Case study: Uganda – MBR and GAC treatment of hospital wastewater

Context

Hospital wastewater contained organic loads, antimicrobial residues and resistant organisms associated with inpatient and surgical care. In Uganda, most facilities rely on septic systems that are not designed to remove pharmaceutical residues.[49] Environmental monitoring capacity is expanding nationally, but healthcare wastewater treatment infrastructure remains limited. Lubaga Hospital piloted a decentralized treatment upgrade to evaluate whether pharmaceutical contaminants could be reduced within existing urban constraints while promoting sustainability and innovation. The purpose of the pilot was to develop and showcase a cost-effective, robust and locally adaptable wastewater treatment solution capable of producing non-potable reusable water for toilet flushing, cleaning and irrigation.[50]

Technology and application

The pilot was installed downstream of the hospital's existing septic and biogas infrastructure. Wastewater first passed through an MBR, which provided biological treatment and solid–liquid separation. The MBR effluent was then directed to a GAC polishing unit, designed to adsorb residual pharmaceuticals and other micropollutants that were not sufficiently removed during MBR treatment. A solar photovoltaic system supported operation in a setting with intermittent grid power, with grid and generator backup available when needed.

Technical performance

The MBR component showed progressive improvement in organic matter removal, reaching approximately 70 percent after sludge acclimation. Nitrification remained stable at around 80 percent, while denitrification was limited by low influent carbon availability. However, the MBR alone provided only partial removal of pharmaceutical residues, making the downstream GAC unit important for final polishing. Initial GAC performance under field conditions was modest, but after redesign and optimization under controlled conditions, removal of selected micropollutants reached approximately 90 percent. Over time, GAC removal efficiency declined to approximately 25 percent, highlighting the need for planned media replacement, regeneration or operational optimization.

The solar energy system supplied approximately 43 percent of annual energy demand and met full daily requirements under favorable conditions. Treated effluent met discharge requirements and was reused onsite for toilet flushing, cleaning and irrigation, reducing reliance on municipal water supplies.

Implementation characteristics

The system required a capital investment of approximately €40,000, with annual operating costs of nearly €2,000. Reduced municipal water purchases and solar offset generated estimated annual savings of €7,000. While pilot-scale payback exceeded seven years, projected costs suggest shorter recovery periods with broader deployment. The potential for locally produced activated carbon, including from agricultural residues such as cassava peels, indicates opportunities for cost adaptation.

Innovation and application significance

The Uganda pilot demonstrates how decentralized, layered wastewater treatment can reduce AMR-relevant contaminants in healthcare effluent. By combining MBR treatment with GAC polishing, the system addressed both microbial load and selected pharmaceutical residues at the point of discharge. Its integration with solar energy and onsite water reuse also shows how wastewater treatment can be linked to sustainability, operational resilience and resource efficiency.

49 Gwenzi, W., T.T. Simbanegavi and P. Rzymski (2023). Household disposal of pharmaceuticals in low-income settings: practices, health hazards, and research needs. *Water*, 15(3), 476. https://doi.org/10.3390/w15030476.

50 De, S., M. Coutard and J. Hoinkis (2024) Solar powered membrane bioreactor (MBR) treating wastewater for reuse at a hospital in Kampala, Uganda – results of pilot-scale trials. *Environmental Challenges*, 16, 100986. https://doi.org/10.1016/j.envc.2024.100986.

The case study addresses a practical implementation challenge common in many urban and resource-constrained settings: healthcare facilities may rely on septic or decentralized systems that are not designed to remove pharmaceutical residues or resistant organisms. The pilot shows how targeted treatment upgrades can be incorporated into existing hospital infrastructure without relying on large-scale centralized wastewater expansion. The potential use of locally produced activated carbon further illustrates opportunities for cost adaptation and local innovation.

Within a One Health framework, the Uganda case study highlights the role of healthcare facilities as priority intervention points for environmental AMR mitigation. It shows how treatment at high-risk discharge points can complement surveillance, reduce environmental loading and support prevention-oriented AMR strategies in settings with limited wastewater infrastructure.

Pharmaceutical manufacturing and industrial discharge

Pharmaceutical manufacturing hubs may represent high-concentration AMR interfaces. APIs may be discharged at levels substantially exceeding those typically observed in hospital or municipal wastewater. These environments may create localized selection pressure, making tailored monitoring and treatment approaches particularly relevant.

The following case studies from Brazil and Mexico illustrate how diverse technological pathways within a tiered wastewater AMR response can be operationalized across different sectors and governance contexts. Together, they demonstrate how advanced treatment systems, locally developed detection technologies and nationally coordinated surveillance networks can reduce antimicrobial emissions, strengthen environmental monitoring and institutionalize wastewater intelligence within broader AMR prevention and control frameworks. Importantly, the Brazil case study highlights the strategic impact of nationally designed systems in building sustainable surveillance capacity, supporting innovation ecosystems and reinforcing long-term AMR resilience.

Case study: Brazil – ReViRAE national liquid chromatography–mass spectrometry (LC–MS) surveillance network

Context

Brazil's National Action Plan for the Prevention and Control of Antimicrobial Resistance (PAN-BR) prioritizes integrated surveillance across human, animal and environmental sectors.[51] Building on wastewater monitoring capacity expanded during the COVID-19 pandemic, Brazilian institutions established the "Rede de Vigilância da Resistência Antimicrobiana no Esgotos" (ReViRAE) initiative to assess antimicrobial residues and resistant bacteria in municipal and hospital wastewater. The initiative reflects coordinated engagement among universities, public health institutions, sanitation agencies and regulatory authorities.[52]

Technology and application

The ReViRAE network operates across 10 major cities, sampling wastewater treatment plants and sentinel hospitals using harmonized protocols and composite sampling methods. Its analytical framework combines targeted LC–MS for quantification of selected antimicrobial residues, non-targeted high-resolution mass spectrometry for identification of additional or emerging compounds and culture-based methods to isolate clinically relevant resistant organisms, including extended-spectrum beta-lactamases (ESBLs) and carbapenemase-producing strains. National standard operating procedures and inter-laboratory harmonization support data consistency and comparability across regions.

51 Ministério da Saúde (2019). *Plano de Ação Nacional de Prevenção e Controle da Resistência aos Antimicrobianos no Âmbito da Saúde Única 2018–2022 (PAN-BR)*. Brasília: Ministério da Saúde. https://www.gov.br/saude/pt-br/centrais-de-conteudo/publicacoes/svsa/antimicrobianos/plano-nacional-antimicrobianos-pan-br-14fev19-isbn.pdf/view.

52 ReViRAE. *About Us*. ReViRae. https://revirae.com.br/sobre-nos.

Technical findings and performance

Early analyses confirmed widespread detection of antimicrobial residues and resistant bacteria in both municipal and hospital wastewater. Frequently detected antibiotic classes corresponded to those commonly used in clinical practice, reinforcing the link between antimicrobial consumption patterns and environmental indicators. Culture-based testing identified ESBL- and carbapenemase-producing organisms, patterns consistent with trends observed in Brazil's clinical surveillance systems. Although wastewater data do not directly measure clinical prevalence, they provided complementary indicators of resistance circulation at community and facility levels, strengthening situational awareness across sectors.

Implementation characteristics

ReViRAE demonstrates how advanced analytical infrastructure can be coordinated within a national wastewater surveillance framework. The combined use of targeted and non-targeted mass spectrometry with microbiological testing enables both quantitative monitoring of known compounds and broader detection of emerging contaminants. Integration within existing laboratory and public health institutions has been supported by standardized methodologies, cross-institutional coordination and alignment with national AMR reporting structures.

Innovation and application significance

The Brazil case study demonstrates how wastewater-based AMR monitoring can move from pilot activity toward coordinated national surveillance infrastructure. By combining targeted LC–MS, non-targeted high-resolution mass spectrometry and culture-based testing across multiple regions, ReViRAE provides a model for integrating advanced analytical platforms into national AMR and public health systems.

The case study addresses the challenge of generating comparable environmental AMR data across diverse sites and regions. Harmonized sampling methods, standard operating procedures and inter-laboratory coordination support data quality and enable environmental indicators to be interpreted alongside clinical and public health information. This strengthens the role of wastewater surveillance as a complementary source of evidence for AMR monitoring, regulatory planning and public health decision-making.

Within a One Health framework, the Brazil case study highlights the importance of institutional coordination among public health authorities, sanitation agencies, universities, laboratories and regulators. It shows how wastewater-based intelligence can be embedded within national systems, while also highlighting the importance of adapting sampling strategies in settings with limited sewer coverage.

Building on these surveillance approaches, the Mexico case study that follows turns to intervention, showing how advanced treatment and adsorption technologies can be applied to reduce antimicrobial residues in high-strength wastewater streams.

Case study: Mexico – AOPs for antimicrobial removal

Context

Mexico is a major pharmaceutical producer in Latin America and relies extensively on treated and untreated wastewater for agricultural use.[53],[54] Antibiotic residues and resistant bacteria have been detected in hospital and municipal effluents, and evidence indicates persistence of APIs following conventional treatment. National water and AMR strategies provide a framework for improving wastewater management, although pharmaceutical residues and resistance determinants are not uniformly incorporated into discharge standards.[55],[56]

Technology and application

To address concentrated industrial discharges, pilot initiatives evaluated AOPs for high-strength wastewater streams. In the city of Toluca, a photo-Fenton process combining hydrogen peroxide, iron salts and UV light was applied to pharmaceutical effluent. The system achieved approximately 90 percent reduction in chemical oxygen demand and more than 80 percent removal of selected APIs, alongside substantial reductions in toxicity indicators.[57]

At a pharmaceutical production facility, ozonation combined with activated carbon polishing was deployed in a containerized treatment unit. Target compounds were fully oxidized within minutes under operational conditions and the system enabled continuous, automated treatment prior to discharge into municipal systems.[58]

Researchers also assessed biochar derived from agave bagasse, a fibrous by-product of agave processing, as a locally sourced adsorbent. Removal efficiencies ranged between 50 percent and 90 percent for conventional pollutants and approximately 60 percent for selected pharmaceutical residues. Although commercial activated carbon achieved higher removal rates, biochar provided a lower-cost, locally adaptable option, with performance declining over time and requiring regeneration.[59]

Implementation characteristics

These pilots demonstrate that advanced oxidation and adsorption technologies can be deployed at the point of origin to address concentrated pharmaceutical waste streams before dilution into municipal systems. Modular and containerized designs enable integration within existing industrial infrastructure, reducing the need for large-scale retrofits. Effective deployment, however, depends on reliable energy supply, technical oversight and structured monitoring protocols to ensure consistent performance and regulatory compliance.

The application of AOPs and adsorption-based polishing at discharge points illustrates how high-risk industrial effluent can be targeted within a tiered wastewater AMR framework. Performance outcomes suggest that high-efficiency oxidation technologies are particularly suited to industrial discharge contexts, while lower-cost adsorption materials may support incremental system upgrades in resource-constrained settings.

53 Wisconsin Economic Development Corporation (WEDC) (2022). *Mexico's Pharmaceutical Industry Grows*. Madison: WEDC. https://wedc.org/market-intelligence/posts/mexicos-pharmaceutical-industry-grows.
54 Garduño-Jiménez, A.-L., J.-C. Durán-Álvarez, C.A. Ortori, S. Abdelrazig, D.A. Barrett and R.L. Gomes (2023). Delivering on sustainable development goals in wastewater reuse for agriculture: initial prioritization of emerging pollutants in the Tula Valley, Mexico. *Water Research*, 238, 119903. https://doi.org/10.1016/j.watres.2023.119903.
55 Contreras, J.D. *et al.* (2017). Health risks from exposure to untreated wastewater used for irrigation in the Mezquital Valley, Mexico: a 25-year update. *Water Research*, 123, 834–850. https://doi.org/10.1016/j.watres.2017.06.058.
56 Urzua-Abad, M.M. *et al.* (2024). Detection of carbapenemases in *Enterobacterales* and other Gram-negative bacilli recovered from hospital and municipal wastewater in Mexico City. *Scientific Reports*, 14(1), 26576. https://doi.org/10.1038/s41598-024-76824-w.
57 Novoa-Luna, K.A., A. Mendoza-Zepeda, R. Natividad, R. Romero, M. Galar-Martínez and L.M. Gómez-Oliván (2016). Biological hazard evaluation of a pharmaceutical effluent before and after a photo-Fenton treatment. *Science of the Total Environment,* 569–570, 830–840. https://doi.org/10.1016/j.scitotenv.2016.06.086.
58 Billenkamp, E., J. Straub, M. Studer Hoffmann and J. Türk (n.d.). *Elimination of Pharmaceuticals from the Wastewater of a Pharmaceutical Plant*. PharmaFocus Asia. https://www.pharmafocusasia.com/advertorials/elimination-pharmaceuticals-wastewater-pharmaceutical-plant.
59 Medina-Esparza, W.N. *et al.* (2025). Efficiency of a new biochar made from agave bagasse to remove conventional pollutants in samples from Laguna de Bustillos, Chihuahua, Mexico, and pharmaceutical derivatives in synthetic water. *Processes*, 13(6), 1861. https://doi.org/10.3390/pr13061861.

Innovation and application significance

The Mexico case study demonstrates how advanced oxidation and adsorption technologies can be used to reduce pharmaceutical residues in high-strength wastewater streams before they enter wider municipal or environmental systems. By applying photo-Fenton treatment, ozonation, activated carbon polishing and locally sourced biochar, the examples illustrate a range of treatment options for managing concentrated industrial and pharmaceutical discharge risks.

The case study addresses the implementation challenge of treating persistent pharmaceutical compounds that may not be adequately removed through conventional wastewater processes. Modular and containerized treatment configurations show how advanced treatment can be integrated into existing industrial infrastructure, while locally sourced adsorption materials point to opportunities for lower-cost and context-adapted system upgrades.

By focusing on concentrated waste streams, these technologies reduce pharmaceutical loading at source, thereby lowering downstream selective pressure in receiving environments. The use of sustainable and locally sourced materials, such as biochar, further demonstrate alignment between AMR mitigation, circular economy principles and resource efficiency strategies.

Within a One Health framework, the Mexico case study highlights the importance of source-level intervention for reducing downstream environmental loading and selective pressure. It also shows how treatment strategies can be connected with circular economy approaches, resource efficiency and broader wastewater governance, particularly in contexts where treated or untreated wastewater may be reused in agriculture or discharged into shared water systems.

Environmental and agricultural interfaces extend wastewater-based AMR action beyond hospitals and industrial discharge points. The following case studies from Benin and China show how surveillance and treatment approaches can be adapted for surface waters, hospital effluent and livestock wastewater.

Environmental and agricultural interfaces

Livestock production systems and untreated surface waters represent critical environmental interfaces in the transmission and amplification of antimicrobial resistance. In animal agriculture, substantial volumes of unmetabolized veterinary antibiotics enter manure and wastewater streams, creating high-risk effluent characterized by concentrated residues and resistance determinants.[60] At the same time, surface waters receiving hospital discharge and municipal runoff can accumulate antimicrobial residues and resistant organisms, particularly in settings with limited wastewater treatment coverage.

These environmental pathways point to the value of combining targeted treatment interventions at high-risk discharge points with scalable surveillance tools capable of detecting antimicrobial contamination across diverse water matrices. Common treatment processes and their relevance for AMR mitigation in livestock wastewater are summarized in Table 9 in Annex 2.

The Benin case study illustrates complementary strategies for managing environmental AMR risk: cost-effective immunoassay-based monitoring to detect antimicrobial contamination in surface waters and hospital effluent and AOPs to reduce veterinary antibiotic residues in livestock wastewater. Together, they demonstrate how surveillance and mitigation approaches can extend beyond centralized urban treatment systems and strengthen environmental components of national AMR responses.

60 Mulchandani, R., Y. Wang, M. Gilbert and T.P. Van Boeckel (2023). Global trends and projections of antimicrobial use in food animals: 2020 to 2030. *PLOS Global Public Health*, 3(3), e0001305. https://doi.org/10.1371/journal.pgph.0001305.

Case study: Benin – ELISA-based environmental surveillance

Context

Benin has documented a substantial burden of AMR, with NAPs prioritizing strengthened surveillance, laboratory capacity, infection prevention and antimicrobial stewardship. Expanding surveillance beyond clinical settings has become an increasing focus, particularly given concerns regarding untreated hospital effluent and contamination of rivers and lakes.[61]

To better understand environmental contributions to AMR risk, two nationwide studies assessed antimicrobial residues, resistant bacteria and associated contaminants in surface waters and hospital wastewater across northern and southern Benin. These investigations generated foundational baseline data on environmental antibiotic contamination and resistance circulation, supporting integration of environmental monitoring within national AMR strategies.

Technology design and application

The studies employed a combined microbiological and chemical analytical framework. Microbiological culture and AST were used to isolate and characterize resistant organisms. Chemical analysis relied on commercial ELISA kits to detect seven widely used antibiotics, including amoxicillin, ciprofloxacin, metronidazole and sulfamethoxazole.[62,63]

ELISA enabled residue detection in surface waters and hospital effluent without requiring advanced instrumentation such as LC–MS. As a standardized immunoassay platform, it provided a cost-adapted method suitable for decentralized environmental screening in resource-constrained laboratory environments.

Technical findings and performance

Bacterial isolates included *Klebsiella pneumoniae* and *Acinetobacter* species, with high levels of multidrug resistance observed in susceptibility testing. Antibiotic residues were widely detected in both hospital effluent and surface waters. Ciprofloxacin and metronidazole exceeded internationally referenced environmental risk thresholds in multiple locations. Sulfamethoxazole and chloramphenicol were also frequently identified, with regional variation reflecting differing antimicrobial usage patterns.

Heavy metals, including cadmium, nickel and lead, were detected in several samples. Elevated conductivity and total dissolved solids in hospital effluents indicated broader wastewater quality concerns and potential co-selection pressures contributing to resistance persistence in aquatic environments.

Implementation characteristics

The Benin case study demonstrates how cost-adapted surveillance tools can strengthen the environmental pillar of AMR monitoring in resource-constrained settings. By using ELISA-based screening alongside microbiological testing, the studies generated baseline data on antibiotic residues, resistant bacteria and co-contaminants in hospital effluent and surface waters.

The case study addresses the challenge of expanding environmental AMR surveillance where advanced analytical platforms such as LC–MS may not be readily available for broad geographic monitoring. ELISA offers a practical entry-tier tool for rapid screening, hotspot identification and prioritization of sites for further investigation. Confirmatory testing or expanded compound profiling can then be supported by more advanced analytical capacity at reference laboratories.

61 Deguenon, E. *et al.* (2022). Hospital effluents as sources of antibiotics residues, resistant bacteria and heavy metals in Benin. *SN Applied Sciences*, 4(8), 206. https://doi.org/10.1007/s42452-022-05095-9.
62 Gbotche, E. *et al.* (2023). National survey of stream water quality revealing threats to antibiotic-resistant bacteria, antibiotic residues and heavy metals in Benin. *Pollution*, 9(2), 678–692. https://doi.org/10.22059/poll.2022.348629.1629.
63 Deguenon, E. *et al.* (2022). Hospital effluents as sources of antibiotics residues, resistant bacteria and heavy metals in Benin. *SN Applied Sciences*, 4(8), 206. https://doi.org/10.1007/s42452-022-05095-9.

Within a One Health framework, the Benin case study highlights the importance of environmental waters as surveillance points, particularly where sewer coverage is limited or where communities interact directly with surface water systems. It shows how decentralized screening can support national AMR strategies by making environmental contamination more visible and actionable across health, water and environmental sectors.

Integration into national systems is supported by standardized sampling protocols, quality assurance procedures and structured data reporting mechanisms.

Innovation and application significance

Benin's experience illustrates how cost-adapted, decentralized detection tools can strengthen the environmental pillar of national AMR strategies by extending surveillance beyond clinical settings. By generating baseline data on antibiotic residues and resistant bacteria in hospital effluent and surface waters, the studies enhanced situational awareness of environmental contamination pathways.

Within a tiered wastewater AMR framework, ELISA-based screening functions as a scalable first-line surveillance approach, supporting geographic expansion, risk mapping and prioritization of regulatory or infrastructure interventions. When embedded within national laboratory networks and linked to confirmatory testing capacity, such tools contribute to institutionalizing environmental intelligence within broader AMR governance systems.

The Benin case study demonstrates how cost-adapted surveillance tools can identify antimicrobial contamination and resistance patterns across water systems. The case studies from China and India complement this by showing how hybrid treatment systems can reduce contaminant loads at agricultural sources.

Hybrid, decentralized and locally adaptable approaches

Innovation in wastewater technologies for addressing AMR is developing across both treatment and detection pathways. These innovations are not limited to advanced centralized wastewater treatment plants, but also include hybrid systems, low-cost monitoring tools and context-specific approaches designed for different sectors and infrastructure settings. The following case studies from China and India illustrate this diversity.

Case study: China – hybrid livestock wastewater treatment systems

Context

China is the world's largest livestock producer and a major consumer of veterinary antibiotics. Intensive pig and poultry production systems generate wastewater streams containing antibiotic residues, resistant bacteria and ARGs, reflecting the scale of antimicrobial use in animal agriculture.[64] Recognizing the environmental dimension of AMR, national strategies have progressively incorporated a One Health framework, including restrictions on non-therapeutic antimicrobial use and strengthened agricultural waste management policies.[65]

Despite regulatory reforms, land application of untreated manure and uneven treatment coverage continue to pose environmental risks, particularly in regions with high farm density.[66] In response, researchers piloted hybrid wastewater treatment systems designed not only to reduce nutrient loads and organic pollution, but also to limit antimicrobial residues and environmental conditions conducive to resistance selection and horizontal gene transfer.

64 Elbehiry, A. and E. Marzouk (2025). From farm to fork: antimicrobial-resistant bacterial pathogens in livestock production and the food chain. *Veterinary Sciences*, 12(9), 862. https://doi.org/10.3390/vetsci12090862.
65 Cai Z., H. He, H. Wu, J. Zhao, G. Zhang and J. Xing (2026) Governing antimicrobial resistance through One Health: a comparative analysis of public health governance in China and the United Kingdom. *Frontiers in Public Health*, 14:1883787. https://doi.org/10.3389/fpubh.2026.1883787.
66 Lu, Z., G. Liu, H. Xie, Y. Zhai, Y. and X. Li (2024). Advances and solutions in biological treatment for antibiotic wastewater with resistance genes: a review. *Journal of Environmental Management*, 368, 122115. https://doi.org/10.1016/j.jenvman.2024.122115.

Technology design and application

To address antimicrobial and nutrient loading from intensive livestock production, researchers in China piloted hybrid wastewater treatment systems to reduce pollutants from intensive livestock production. At a pig farm in south China, anaerobic digestion was combined with a microalgal electroactive wetland to improve nutrient removal and produce biogas.[67] In poultry farms in north China, a Fenton oxidation–algal cultivation system combined advanced oxidation with algal growth to degrade pollutants while producing lipid-rich biomass.[68]

Together, these approaches demonstrated how hybrid technologies can reduce environmental pollution, mitigate AMR-related risks and support circular economy objectives within a One Health framework.

Anaerobic digestion + microalgal electroactive wetland (swine farm): A full-scale pilot on a swine farm in south China integrated anaerobic digestion with a microalgal electroactive wetland. The anaerobic digestion stage stabilized manure-rich wastewater, reduced pathogen loads and generated biogas for energy recovery. The wetland polishing stage combined algae and electroactive bacteria to remove residual nitrogen and phosphorus while supporting further organic degradation.[69]

The system achieved 95 percent to 98 percent removal of chemical oxygen demand, 92 percent to 98 percent ammonium reduction, approximately 95 percent total nitrogen removal and 91 percent phosphorus removal across seasonal conditions. The estimated operating cost was approximately USD 0.118 per m^3, positioning the system as a cost-competitive option for medium-scale farms.

Fenton oxidation + algal cultivation (poultry farm): In north China poultry farms, a combined Fenton oxidation–algal cultivation system was piloted for high-strength flushing wastewater. Fenton oxidation served as a pretreatment step, generating hydroxyl radicals to degrade organic contaminants and reduce ammonia and turbidity. This stage achieved reductions of approximately 70 percent total nitrogen, 96 percent ammonium, 86 percent total phosphorus and 96 percent chemical oxygen demand.[70]

The treated effluent supported cultivation of *Chlorella sorokiniana*, which removed over 98 percent of remaining nutrients while generating biomass suitable for lipid extraction. In semi-continuous photobioreactors, biomass productivity approached 1,000 mg/L/day, with lipid fractions appropriate for biodiesel production, linking treatment with resource recovery.

Implementation characteristics

These pilots demonstrate how hybrid biological and chemical systems can simultaneously address multiple agricultural wastewater drivers. Biological stabilization reduced organic loading and pathogen presence, while oxidation and algal assimilation further decreased nutrient concentrations and degraded residual contaminants. By lowering nutrient-rich conditions and reducing contaminant loads, these systems helped mitigate environmental factors that facilitate bacterial proliferation and gene exchange.

The integration of biogas production and algal biomass recovery also linked wastewater treatment with renewable energy generation and circular economy objectives. Stable year-round performance in the electroactive wetland system addressed seasonal variability commonly observed in conventional lagoon-based systems, strengthening operational reliability.

67 Wang, T., Z. Ni, B. Kuang, L. Zhou, X. Chen, Z. Lin, B. Guo, G. Zhu and J. Jia (2022). Two-stage hybrid microalgal electroactive wetland-coupled anaerobic digestion for swine wastewater treatment in South China: full-scale verification. *Science of the Total Environment*, 820, 153312. https://doi.org/10.1016/j.scitotenv.2022.153312.

68 Cui H., J. Yu, X. Zhu, Y. Cui, C. Ji, C. Zhang, J. Xue, X. Jia, S. Qin and R. Li (2021) Advanced treatment of chicken farm flushing wastewater by integrating Fenton oxidation and algal cultivation process for algal growth and nutrients removal. *Journal of Environmental Management*, 298, 113543. https://doi.org/10.1016/j.jenvman.2021.113543.

69 Wang, T., Z. Ni, B. Kuang, L. Zhou, X. Chen, Z. Lin, B. Guo, G. Zhu and J. Jia (2022). Two-stage hybrid microalgal electroactive wetland-coupled anaerobic digestion for swine wastewater treatment in South China: full-scale verification. *Science of the Total Environment*, 820, 153312. https://doi.org/10.1016/j.scitotenv.2022.153312.

70 Cui H., J. Yu, X. Zhu, Y. Cui, C. Ji, C. Zhang, J. Xue, X. Jia, S. Qin and R. Li (2021) Advanced treatment of chicken farm flushing wastewater by integrating Fenton oxidation and algal cultivation process for algal growth and nutrients removal. *Journal of Environmental Management*, 298, 113543. https://doi.org/10.1016/j.jenvman.2021.113543.

Innovation and application significance

The China case study demonstrates how hybrid treatment systems can reduce environmental loading from intensive livestock wastewater. By combining anaerobic digestion, microalgal electroactive wetlands, Fenton oxidation and algal cultivation, the pilots addressed organic loads, nutrients and residual contaminants in high-strength agricultural waste streams.

The case study addresses the challenge of managing AMR-relevant risks in animal production systems, where veterinary antimicrobials, manure, nutrients and microbial contaminants may contribute to resistance persistence and amplification. The use of combined biological, chemical and algal processes illustrates how treatment systems can be designed to address multiple wastewater drivers while supporting resource recovery through biogas production and algal biomass generation.

Within a One Health framework, the China case study highlights the importance of upstream mitigation in agricultural systems. It shows how treatment interventions at livestock and poultry sources can complement environmental surveillance, reduce contaminant loads before land application or discharge, and support AMR strategies that extend beyond clinical and industrial settings.

Case study: India – fiber-optic biosensor for antimicrobial detection

Context

India is among the world's largest producers and consumers of antimicrobials, with extensive use across human medicine, animal health and pharmaceutical manufacturing. Studies have identified antibiotic residues and resistant organisms in hospital effluents, community sewage and surface waters, highlighting the importance of environmental AMR surveillance.[71,72]

In response to this need, Indian researchers developed a portable fiber-optic biosensor designed to detect low-concentration antibiotic residues and resistant bacteria in complex environmental matrices. Funded by the Indian governments Department of Biotechnology and co-developed with international academic partners, the platform represents a domestically driven innovation aimed at strengthening environmental AMR surveillance capacity while reducing dependence on high-cost, laboratory-intensive methods.[73]

Technology design and application

The biosensor utilizes an optical fiber coated with gold nanoparticles and functionalized with fluoroquinolone-specific antibodies. Binding of target residues, such as ciprofloxacin, generates a localized surface plasmon resonance (LSPR) signal measured at 520 nm. The device operates directly in complex matrices, including wastewater, serum and urine, without requiring extensive sample preprocessing. Laboratory validation demonstrated sensitivity to approximately 10 ng/mL and strong correlation with LC–MS reference methods.

Results are generated within approximately one hour and at substantially lower cost than conventional LC–MS analysis. The platform has also been adapted to detect resistant organisms such as *Escherichia coli* and *Klebsiella pneumoniae*, enabling combined antibiotic residue and microbial screening within a single portable device.

Technical findings and performance

71 Rathinavelu, S. *et al.* (2024). Mapping the scarcity of data on antibiotics in natural and engineered water environments across India. *Frontiers in Antibiotics*, 3, 1337261. https://doi.org/10.3389/frabi.2024.1337261.
72 Taneja, N. and M. Sharma (2019). Antimicrobial resistance in the environment: the Indian scenario. *Indian Journal of Medical Research,* 149(2), 119–128. https://doi.org/10.4103/ijmr.IJMR_331_18.
73 Mathai, T., T. Pal, N. Prakash and S. Mukherji (2023). Portable biosensor for the detection of enrofloxacin and ciprofloxacin antibiotic residues in food, body fluids, environmental and wastewater samples. *Biosensors & Bioelectronics*, 237, 115478. https://doi.org/10.1016/j.bios.2023.115478

Validation studies confirmed reliable detection across environmental and clinical samples, including mixed matrices containing potential interfering substances. Analytical performance showed strong agreement with LC–MS results, while resistance phenotypes aligned with conventional disk diffusion testing. The device demonstrated robustness under laboratory and pilot field conditions, supporting its suitability for decentralized screening applications.

Implementation characteristics

The application of LSPR-based optical sensing within a low-cost, field-deployable biosensor reflects strategic domestic innovation, translating advanced analytical science into a context-appropriate surveillance tool tailored to local environmental and infrastructure conditions. The platform is particularly suited for rapid screening, hotspot identification and preliminary risk assessment in settings where centralized analytical infrastructure is limited or inaccessible.

Effective integration into national systems is supported by standardized validation protocols, quality assurance frameworks and alignment with laboratory reporting structures. As with other decentralized tools, confirmatory testing through accredited reference laboratories remains essential for regulatory oversight and clinical decision-making, positioning the biosensor as a complementary tier within a broader, tiered AMR surveillance system.

Innovation and application significance

The India case study demonstrates how portable, lower-cost detection technologies can expand environmental AMR screening in settings where centralized analytical capacity is limited or difficult to access. The fiber-optic biosensor provides rapid detection of selected antibiotic residues and resistant organisms in complex matrices, supporting preliminary risk assessment and hotspot identification outside conventional laboratory settings.

The case study addresses a key implementation gap: environmental AMR monitoring often depends on high-cost analytical platforms that may not be widely available for routine or geographically distributed surveillance. By translating advanced optical sensing into a field-adapted platform, the biosensor illustrates how locally developed technologies can reduce costs and overcome implementation barriers while complementing confirmatory testing through reference laboratories.

Within a One Health framework, the India case study highlights the value of domestic innovation for strengthening environmental intelligence across clinical, industrial and community interfaces. It shows how context-adapted technologies can support tiered surveillance systems, reinforce local innovation ecosystems and expand monitoring capacity in high-use antimicrobial settings.

Taken together, the case studies show that relevant expertise, technologies and promising applications exist across a range of countries and institutional settings. They illustrate how technologies developed in different contexts can be adapted, combined and applied to different wastewater sources, infrastructure conditions and resource levels. Wider uptake will depend on continued validation, sustainable financing, institutional coordination, technical capacity and integration into national AMR, environmental and wastewater systems.

Implementation considerations for innovation uptake

Promising technologies do not move from research or demonstration into sustained use on technical performance alone. Adoption depends on a clear intended use; evidence generated under relevant local conditions; compatible infrastructure; trained personnel; reliable supplies and maintenance; quality-assurance systems; sustainable financing; and institutions able to act on the information produced.[74]

74 Greenhalgh, T., J. Wherton, C. Papoutsi, J. Lynch, G. Hughes, C. A'Court, S. Hinder, N. Fahy, R. Procter and S. Shaw (2017). Beyond adoption: a new framework for theorizing and evaluating nonadoption, abandonment, and challenges to the scale-up, spread, and sustainability of health and care technologies. *Journal of Medical Internet Research*, 19(11), e367. https://doi.org/10.2196/jmir.8775.

The case studies above illustrate that a range of technologies have produced useful or promising results in specific settings. Their suitability for wider application depends on local validation; technology maturity; operating requirements; costs; and integration into existing laboratory, wastewater and governance systems.

The following considerations can support phased and context-appropriate implementation. They highlight key areas for consideration by governments and partners seeking to facilitate effective and sustainable deployment of technologies relevant to detecting and managing AMR in wastewater within a One Health framework.

Integrate AMR in wastewater detection, monitoring and management technologies into AMR NAPs using a One Health approach

National AMR strategies could benefit from explicitly incorporating wastewater as a priority area for surveillance and intervention. Technologies relevant to detecting and managing AMR in wastewater intersect with human, agricultural and environmental health, but may not always be fully reflected in existing governance arrangements.[75] AMR coordination platforms could be strengthened by including environmental authorities and wastewater agencies to oversee cross-sectoral implementation. This integration is critical for monitoring resistant pathogens and deploying effective containment measures.[76]

Investment in scalable wastewater detection and treatment technologies

The case studies in this report illustrate that effective AMR detection and treatment technologies exist and can be applied in diverse settings. Consideration should be given to prioritizing funding for both piloting and scaling context-appropriate tools, including biosensors, filtration systems and diagnostic platforms. Investments should also extend to supporting infrastructure, local validation and technical training to ensure long-term sustainability and adaptability.

Sustainable funding mechanisms: Many AMR interventions, particularly those involving wastewater treatment and surveillance, require long-term financial commitment. Inconsistent or project-based funding can lead to interruptions in monitoring, technology maintenance and capacity-building efforts.[77] Sustainable financing models, including public–private partnerships, donor alignment and inclusion of AMR measures in national health budgets, are essential to ensure continuity and scalability.[78]

Human resource capacity and training needs: Successful adoption of AMR-related technologies often hinges on the availability of trained personnel. Countries may face gaps in the skilled technicians, microbiologists or data analysts required to operate and interpret the outputs of AMR detection systems. Investment in continuous training, certification programs and on-the-job capacity building are critical.[79] Beyond workforce development, sustained knowledge transfer and technical collaboration are also important to help embed long-term local capability. Partnerships between laboratories, who may have limited expertise, and institutions with established analytical expertise may therefore help support technology transfer, skills development, quality assurance and the gradual strengthening of local surveillance and testing capacity.[80]

75 Alem, K., M. Dagnew, M. Gizachew, B. Gelaw and F. Moges (2025). Environmental antimicrobial resistance: key drivers, hotspots, innovative strategies, and challenges in the fight against superbugs. *MicrobiologyOpen*, 14(5), e70067. https://doi.org/10.1002/mbo3.70067.

76 World Health Organization (WHO) (2024). *World Leaders Commit to Decisive Action on Antimicrobial Resistance*. Geneva: WHO. https://www.who.int/news/item/26-09-2024-world-leaders-commit-to-decisive-action-on-antimicrobial-resistance.

77 Åkerfeldt, K., A. Sjöblom and H. Aagaard (2025). *Unlocking AMR Financing: Optimizing International Resources for an Accelerated Response to Antibiotic Resistance*. Uppsala: ReAct Europe. https://www.reactgroup.org/wp-content/uploads/2025/10/ReAct-Policy-Brief-Unlocking-AMR-Financing-Optimizing-international-resources-for-an-accelerated-response-to-antibiotic-resistance-October-2025-Final.pdf.

78 Åkerfeldt, K., A. Sjöblom and H. Aagaard (2025). *Unlocking AMR Financing: Optimizing International Resources for an Accelerated Response to Antibiotic Resistance*. Uppsala: ReAct Europe. https://www.reactgroup.org/wp-content/uploads/2025/10/ReAct-Policy-Brief-Unlocking-AMR-Financing-Optimizing-international-resources-for-an-accelerated-response-to-antibiotic-resistance-October-2025-Final.pdf.

79 Parry, L., T. Leslie, S. Onasanya and S. Fenwick (2026). *Multi-Country Technical Assistance Approach for Strengthening AMR Surveillance in LMICs: Lessons from the Fleming Fund*. London: Fleming Fund. https://www.flemingfund.org/wp-content/uploads/293def9c0f0cef643a0503b65dd8738b.pdf.

80 Parry, L., T. Leslie, S. Onasanya and S. Fenwick (2026). *Multi-Country Technical Assistance Approach for Strengthening AMR Surveillance in LMICs: Lessons from the Fleming Fund*. London: Fleming Fund. https://www.flemingfund.org/wp-content/uploads/293def9c0f0cef643a0503b65dd8738b.pdf.

Technology procurement, licensing and transfer arrangements

Implementation may require licenses or other permissions to use protected hardware, software, databases or documentation, together with access to technical know-how, training, servicing, consumables and quality-assurance support. These arrangements should be considered during procurement and implementation planning. Part 1 discusses the relevant IP, licensing and knowledge and technology transfer (K/TT) considerations in greater detail.

Integration within AMR governance systems

Wastewater surveillance data, including antibiotic concentrations and ARG profiles, can be incorporated into existing AMR reporting platforms alongside clinical, animal health and antimicrobial use indicators. Using established digital infrastructure, data standards and reporting cycles can improve cross-sector comparability and situational awareness. Integration should also build on existing laboratory and environmental surveillance capacity (including PCR platforms, AST, genomic sequencing, water quality monitoring and pathogen surveillance systems) while adapting them to the specific requirements of wastewater and environmental samples through appropriate protocols, biosafety measures, quality assurance and data interpretation frameworks.[81] By defining standardized monitoring parameters, clarifying institutional responsibilities and aligning environmental indicators with public health objectives, wastewater surveillance can become part of routine national AMR oversight rather than a standalone initiative.[82]

Promoting risk-based environmental AMR governance and wastewater management

Risk-based environmental AMR governance connects wastewater surveillance, pollution prevention, wastewater management and One Health implementation across human health, animal health, food production, industry and environmental systems.[83] As wastewater-related AMR risks arise across multiple interfaces (including hospitals, municipal wastewater systems, pharmaceutical and industrial discharge points, livestock and aquaculture operations, agricultural runoff, sludge and contaminated surface waters), a risk-based approach helps prioritize action where environmental loading and exposure risks are highest. High-risk sites may include healthcare facilities with concentrated antimicrobial use; industrial production zones; livestock-intensive areas; wastewater treatment plants receiving mixed influents; and communities where untreated wastewater enters waters used for domestic, agricultural or recreational purposes. Surveillance can identify priority contaminants, resistance markers and exposure pathways, while treatment technologies can be targeted to the points most likely to reduce environmental loading and selective pressure.[84] Countries can build on existing water, sanitation, laboratory, environmental monitoring and public health systems, adapting sampling strategies to local infrastructure (including influent, effluent, sludge and wastewater treatment plant monitoring in sewered settings), and monitoring affected environmental waters in partially sewered or non-sewered settings.[85]

81 Kim, S., A. Zulli, E.M.G. Chan, D. Duong, R.Y. Linfield, C.E.M. McCormack, B.J. White, M.K. Wolfe, A.B. Boehm and A.J. Pickering (2026). Wastewater surveillance reveals patterns of antibiotic resistance across the United States. *Nature Communications*, 17, 4680. https://doi.org/10.1038/s41467-026-71195-4.

82 Hock, L., R. Luiken, E. Valério, M. Vargha, J. Vierheilig, S. Börjesson, T. Pitkänen and H. Schmitt (2026). Integrating AMR surveillance into wastewater monitoring systems in 2025: a position on the implementation of Article 17 of the Urban Wastewater Treatment Directive (UWWTD). *Eurosurveillance,* 31(3). https://doi.org/10.2807/1560-7917.ES.2026.31.3.2500289.

83 Al-Khalaifah, H., M.H. Rahman, T. Al-Surrayai, A. Al-Dhumair and M. Al-Hasan, M. (2025). A One-Health perspective of antimicrobial resistance (AMR): human, animals and environmental health. *Life*, 15(10), 1598. https://doi.org/10.3390/life15101598.

84 Alem, K., M. Dagnew, M. Gizachew, B. Gelaw and F. Moges (2025). Environmental antimicrobial resistance: key drivers, hotspots, innovative strategies, and challenges in the fight against superbugs. *MicrobiologyOpen*, 14(5), e70067. https://doi.org/10.1002/mbo3.70067.

85 Alem, K., M. Dagnew, M. Gizachew, B. Gelaw and F. Moges (2025). Environmental antimicrobial resistance: key drivers, hotspots, innovative strategies, and challenges in the fight against superbugs. *MicrobiologyOpen*, 14(5), e70067. https://doi.org/10.1002/mbo3.70067.

Strategic implications and the way forward

When seeking to deploy technologies in support of AMR wastewater monitoring and treatment, the analysis points to several priorities for policy and practice:

- integrating wastewater and environmental indicators into NAPs on AMR and surveillance systems;
- strengthening laboratory capacity and standardized monitoring frameworks;
- linking wastewater data with clinical, veterinary, antimicrobial use and environmental information; and
- aligning treatment interventions with identified risk points.

The analysis also points to the value of connecting AMR action with wider environmental priorities, including pollution prevention, wastewater and solid waste management, water reuse, sanitation planning and protection of receiving environments.

The strategic value of wastewater-based AMR action lies in its ability to connect evidence generation with practical intervention and technology deployment. Surveillance data can help identify where antimicrobial residues, resistant organisms and resistance genes are entering or persisting in the environment. Treatment technologies can then support source control, effluent improvement and reduction of environmental loading at priority sites. Together, these approaches help move environmental AMR action from general recognition toward targeted, measurable and prevention-oriented implementation that leverages innovation.

Implementation also depends on clear pathways for translating evidence into practice. Standardized sampling approaches, quality-assured laboratory methods, data-sharing arrangements and agreed monitoring parameters can improve comparability across sites and sectors. Where discharge standards, environmental thresholds or treatment performance expectations are being developed, wastewater surveillance can provide useful evidence for regulatory planning, procurement decisions and infrastructure investment. Emerging technical guidance and voluntary standards may also provide reference points for monitoring, treatment performance and responsible management of antimicrobial residues, when applied within broader national policy frameworks and One Health coordination systems.

The way forward also involves engagement across a wide range of public and private actors. Healthcare facilities, utilities, agricultural producers, aquaculture operators, pharmaceutical and other industrial manufacturers, technology developers, regulators and procurement agencies all influence how AMR-relevant waste streams are managed. Responsible production, supplier oversight, supply-chain accountability and transparent monitoring are particularly relevant for pharmaceutical manufacturing, livestock and aquaculture value chains. Similar principles of environmental stewardship and operational accountability apply across other sectors. These principles are also reflected in emerging legal and policy developments in some jurisdictions, including requirements for AMR monitoring in wastewater, environmental risk assessment of medicines, management of pharmaceutical residues and broader pollution prevention measures.

In low- and middle-income countries (LMICs), implementation is likely to be most effective when phased and adapted to existing capacity. Initial activities may include sentinel surveillance; low-cost screening tools; identification of priority discharge points; optimization of existing treatment systems; and targeted pilots. Over time, these activities can support routine monitoring; validated treatment upgrades; improved discharge controls; and integration into national AMR and environmental reporting systems. Development finance, technology transfer, capacity building and procurement incentives can support the adoption and deployment of context-appropriate solutions while promoting sustainable implementation.

Embedding wastewater within broader AMR governance systems can help strengthen prevention-oriented strategies, reduce environmental drivers of resistance and improve the overall effectiveness of multisectoral AMR responses. It also supports a more integrated approach to One Health implementation by connecting evidence generation, pollution prevention, infrastructure investment, responsible production and environmental stewardship across human, animal, industrial and environmental interfaces.

Evidence limitations and areas for further analysis

This report brings together evidence from different sectors, technology types and geographic settings. The evidence base remains uneven and dispersed, and the technologies and case studies included are illustrative rather than exhaustive. Study designs, target analytes, sampling methods and reported performance measures vary substantially, limiting direct comparison across technologies and settings.

The patent landscape covers selected detection and treatment categories and should be interpreted as an indicator of innovation activity rather than a definitive inventory of technologies exclusively developed for AMR and wastewater. Patent filings do not demonstrate technical performance, market availability, freedom to operate or readiness for implementation.

Detailed information on technology costs, savings, commercial terms, licensing arrangements and transfer packages was not consistently available and is often confidential or context-dependent. Further analysis would be valuable on life-cycle costs; implementation in low-resource settings; environmental standards; data governance; technology-provider and manufacturing landscapes; informal innovation ecosystems; and gender and equity considerations.

Case study results should not be treated as standardized benchmarks. Reported performance is specific to the wastewater source, technology configuration, operating conditions, sampling approach and analytical method used. Wider application requires local validation and monitoring under routine operating conditions.

Overall conclusion

Wastewater provides a practical entry point for strengthening the environmental dimension of One Health AMR action. It can generate evidence on antimicrobial residues, resistant organisms and resistance genes and can support targeted interventions at hospitals, pharmaceutical facilities, municipal systems, livestock and aquaculture operations and affected environmental waters.

There is no single technology solution. Countries and institutions need combinations of detection, surveillance and treatment approaches, selected according to the intended use, priority risks, available infrastructure, technical capacity and resources. Innovation may involve developing a new technology, but it may also involve adapting an existing platform, combining processes, using locally available materials, decentralizing testing or integrating data and treatment into existing systems.

Innovation, IP and technology transfer can help make appropriate technologies available and adaptable. However, sustained implementation also requires validation; regulation; financing; procurement; trained personnel; quality assurance; maintenance; and clear institutional responsibility. A phased approach that builds on existing systems and links surveillance evidence to practical intervention offers the strongest pathway from innovation to implementation.

Taken together, Parts 1 and 2 of this report show how enabling innovation and technology transfer pathways can be connected with context-appropriate technology choices to strengthen prevention-oriented, measurable and sustainable responses to AMR across One Health sectors.

Annex 1: IP mentions in AMR National Action Plans (NAPs)

Table 6 provides selected examples of how IP and IP-related considerations appear in national AMR action plans. It identifies where these issues arise in each plan and the context in which they are addressed, including research, patenting, licensing, innovation, local production and access.

Table 6 Examples of IP and IP-Related Provisions in National AMR Action Plans

WHO region	Country	Current / latest public NAP title	NAP period	Where IP or IP-related issues appear in the NAP	IP context
Africa	Algeria	National strategic plan against antimicrobial resistance 2024–2028	2024–2028	The NAP includes a patent-related indicator. Under Objective 5.2 on promoting operational research, activity 5.2.1 on orienting AMR research priorities with universities lists the Algerian National Institute of Industrial Property (INAPI) among partners and "Brevet" (patent) as the indicator/output for 2024–2025.	The NAP includes "Brevet" as an indicator or output under operational research. This appears in the context of strengthening AMR research by orienting research priorities with universities and relevant national institutions, including INAPI. The reference frames patents as an expected output of AMR-related operational research rather than as a detailed IP policy measure.
Africa	The Republic of Côte d'Ivoire	National multisectoral action plan against antimicrobial resistance 2021–2025	2021–2025	In the traditional medicine situation analysis section of the 2021–2025 PAN-RAM.	The NAP mentions IP directly through training for traditional medicine practitioners, including training on IP rights. The NAP frames IP as part of awareness and capacity-building for traditional medicine and local innovation.
Africa	Madagascar	National action plan to tackle antimicrobial resistance 2018	2018	Under Strategic Objective V, in the research and alternative solutions section, specifically the activity on creating a motivation system for research.	The NAP makes direct reference to protecting intellectual property: "Protéger la propriété intellectuelle". IP is framed as part of motivating AMR research and protecting outputs from research and alternative solutions, including traditional medicine and biodiversity-related work.
Africa	Rwanda	National action plan on antimicrobial resistance 2020–2024	2020–2024	Under the Research and Innovation Objective, Activity 5.1.1.5. Also, separately under supply-chain regulation activities.	The NAP refers to sensitizing researchers on IP rights and patenting. It also refers to strengthening licensing, approval, regulation and oversight of the antimicrobial supply chain. IP is framed mainly as research-capacity building, with licensing appearing in the supply-chain governance context.

WHO region	Country	Current / latest public NAP title	NAP period	Where IP or IP-related issues appear in the NAP	IP context
Africa	Uganda	Second antimicrobial resistance national action plan 2024/25–2028/29	2024/25–2028/29	In the monitoring, evaluation and learning framework for research and innovation in NAP-AMR II 2024/25–2028/29.	The NAP refers to patent filings and patent databases as evidence sources for tracking new AMR solutions developed and tested. The plan also has a broader research and innovation objective covering new diagnostics, therapeutics, technologies, indigenous technical knowledge, local antimicrobial production and diagnostic innovation.
Americas	Argentina	Strategy for the control of antimicrobial resistance	2015	In the section Development and implementation of new diagnostic methods, indicated as Section 2.4.4.	The NAP states: "Register the IP and/or patents of new institutional developments". This is in the context of developing new diagnostic methodologies for multidrug-resistant organisms, including providing inputs, allocating budget and establishing public–private partnerships.
Americas	Canada	Pan-Canadian action plan on antimicrobial resistance (2023–2028)	2023–2028	In the Research and Innovation pillar and actions supporting sustainable availability.	IP is not directly named in the NAP. The relevance of IP is implied in the NAP through innovation incentives, economic and regulatory tools, commercialization, market access and push/pull mechanisms for antimicrobials, diagnostics, vaccines and alternatives.
Americas	United States	Second national action plan for combating antibiotic-resistant bacteria 2020–2025	2020–2025	Under goals on diagnostics, therapeutics, vaccines, regulatory pathways, public–private partnerships and market sustainability.	IP is not directly discussed in the NAP. The relevance of IP is implied through federal research and development support, regulatory guidance, prizes, public–private partnerships, technology development, reimbursement and market sustainability measures.
Europe	France	National strategy for preventing infections and antibiotic resistance	2022–2025	In Priority 8, especially Measures 39 and 40 of the national strategy.	The NAP refers to protecting the existing therapeutic arsenal through incentives that ensure the continued availability of off-patent antibiotics, as well as schemes that help innovative products and technologies enter or remain on the market. The NAP therefore engages with patent status and the conditions affecting the continued supply and commercialization of products after patent expiry.
Europe	Germany	German antimicrobial resistance strategy DART 2030	To 2030	In Action Area 6 on research and development, including new diagnostics and new antibiotics.	The NAP refers to licensing and approval processes, reimbursement models, innovative economic models, industry partnerships and translation into practice. The relevance of IP arises through the conditions governing product development, market entry and commercialization.
Europe	The Kingdom of the Netherlands	Dutch national action plan on AMR	2024–2030	Under "Knowledge, insight and innovation", availability of antimicrobials, market push/pull incentives, data sharing and mission-driven innovation policy.	The NAP implies the relevance of IP through research translation, innovation funding, development of diagnostics and alternatives, market push/pull incentives, long-term availability of antimicrobials, data sharing, and collaboration with businesses, knowledge institutions and water companies.

WHO region	Country	Current / latest public NAP title	NAP period	Where IP or IP-related issues appear in the NAP	IP context
Europe	Switzerland	One Health action plan 2024–2030	2024–2030	In the Strategy on Antibiotic Resistance, especially measures on research coordination, new diagnostics, incentive models and antibiotic availability.	The NAP directly refers to examining financial incentives, economic models and IP to accelerate cooperation between industry, universities and the Confederation in developing and producing new antibiotics. It also refers to licensing conditions for improving availability of first-choice antibiotics and to market/incentive systems.
Europe	United Kingdom	Confronting antimicrobial resistance (2024–2029)	2024–2029	Under Theme 3 on innovation, product development, market incentives and the Open Innovation AMR case study.	The NAP refers to patent filings in the Open Innovation AMR case study, including patent filings linked to novel therapeutics and diagnostics and commercialization of rapid AST technology. It also uses subscription-style and market incentive approaches to support the sustained availability of antimicrobials and continued innovation.
Western Pacific	Japan	Second national action plan on antimicrobial resistance 2023–2027	2023–2027	In Goal 5, especially Strategy 5.6 on sustainable research and development of antimicrobials and stable supply, and related actions on incentives.	Japan does not directly name IP in the plan, but it discusses push/pull incentives, market incentives, priority review, stable supply, domestic production of raw materials and international research and development collaboration. It also cites examples such as exclusivity-period transfer and patent-term extension in explaining incentive models.

Source: WIPO synthesis for this report based on: World Health Organization, 2025; Oon, Y.-L., et al., 2023; Zhang, Y., et al., 2025

Annex 2: Summary of technologies

Table 7 summarizes the main detection technologies used, or emerging, for wastewater-based AMR surveillance. It focuses on what each technology is best suited to detect; how it can support surveillance; where it is most likely to be deployed; and the main limitations that policymakers or implementers may consider before adoption. Local validation remains essential, as performance varies by target, wastewater matrix, sampling approach, laboratory capacity and data interpretation requirements.

Table 7 Comparative overview of AMR detection technologies

Quantitative polymerase chain reaction (qPCR)	Selected antibiotic resistance genes (ARGs)	Targeted quantification of known ARGs for routine surveillance of priority markers	Established molecular laboratories, including regional or public health laboratories	Limited to pre-selected genes; susceptible to inhibition and primer/probe mismatch
Digital polymerase chain reaction (dPCR) / droplet digital polymerase chain reaction (ddPCR)	Selected ARGs	Absolute quantification of low-abundance targets; useful where inhibitors or low-copy targets complicate qPCR interpretation	Specialized molecular or reference laboratories	Lower throughput and higher cost than qPCR; still target-specific
High-throughput quantitative polymerase chain reaction (HT-qPCR)	Panels of ARGs, mobile genetic elements and bacterial markers	Broad targeted screening of many resistance markers in parallel; useful for comparing sites and trends	Centralized laboratories, national programs and research-supported surveillance networks	Requires predefined panels; data interpretation and standardization can be complex
Metagenomics	Resistome, microbial community, ARG diversity and mobile genetic elements	Untargeted profiling of known and potentially novel ARGs; supports resistome characterization and source/pathway analysis	Reference laboratories, research institutions and advanced surveillance programs	Cost; sequencing depth; bioinformatics capacity; database dependence; not easily expressed as a single limit of detection (LOD) or accuracy value
Enzyme-linked immunosorbent assay (ELISA)	Selected antibiotic residues or bacterial toxins	Low-cost screening of selected residues or toxins; useful where LC–MS/MS capacity is limited	Basic to intermediate laboratories, decentralized surveillance programs and screening studies	Cross-reactivity; matrix interference; limited target range; confirmatory testing may still be needed

Technology	Main target	Primary surveillance role	Typical deployment setting	Key limitation
Biosensors	Antibiotic residues, antibiotic-resistant bacteria (ARB) or ARGs depending on platform design	Rapid or near-real-time screening; supports hotspot identification and decentralized monitoring	Field, near-site or sentinel surveillance settings; still often pilot or early validation	Variable performance across targets and matrices; limited standardization and field validation
Lateral flow tests (LFTs)	Resistance enzymes, toxins or selected target products	Rapid screening or triage, especially for resistance enzymes such as carbapenemases; may complement culture-based workflows	Low-infrastructure laboratories, field-adapted screening and point-of-use settings	Often qualitative or semi-quantitative; AMR applications commonly require cultured isolates or sample preparation
Clustered regularly interspaced short palindromic repeats (CRISPR) diagnostics	Selected ARGs	Highly specific targeted detection of ARGs; potential for portable molecular screening when combined with isothermal amplification or lateral flow readout	Emerging field-adapted or near-site molecular platforms; currently mostly prototype to early validation	Not yet routine for wastewater AMR surveillance; requires assay design, sample preparation and validation for environmental matrices

Source: WIPO synthesis for report based on World Health Organization, 2025; Oon, Y.-L. et al., 2023; Zhang, Y. et al., 2025

Table 8 summarizes the antimicrobial classes commonly detected in wastewater, with examples of each class, their behavior in wastewater and their relevance to the development and spread of AMR.

Table 8 Commonly detected antimicrobial classes in wastewater

Antimicrobial Class	Examples	Key characteristics in wastewater	Environmental and AMR relevance
β-Lactams [1]	Amoxicillin, cefotaxime, ceftriaxone	Widely used; commonly detected in hospital and municipal wastewater; relatively biodegradable	High-volume use leads to continuous environmental loading and resistance selection
Fluoroquinolones [2]	Ciprofloxacin, norfloxacin, ofloxacin	Highly persistent; poorly removed by treatment; frequently detected in effluent and surface waters	Broad-spectrum activity and stability make them potent resistance drivers
Sulfonamides and trimethoprim [3]	Sulfamethoxazole, trimethoprim	Commonly co-prescribed; persist in municipal wastewater	Associated with mobile resistance genes such as sul1, sul2, dfrA
Macrolides [4]	Erythromycin, azithromycin, clarithromycin	Poorly removed during treatment; peak levels in winter; found in both water and sludge	Excreted in active form; persistent presence in effluent contributes to AMR
Tetracyclines [5]	Tetracycline, doxycycline, oxytetracycline	Heavily used in livestock; detected in runoff and wastewater	Strongly associated with tet(A) and tet(M) resistance genes
Carbapenems [6]	Imipenem, meropenem	Detected mostly in hospital wastewater; low ambient levels	Associated with emergence of carbapenem-resistant enterobacterales (CRE); critical due to limited treatment alternatives
Aminoglycosides [1]	Gentamicin, amikacin	Found in hospital wastewater; less frequently monitored	Contribute to selective pressure in clinical and environmental settings
Antifungals [7]	Fluconazole, ketoconazole	Frequently detected in wastewater and environmental waters due to outpatient/over-the-counter (OTC) use	Raise concerns about antifungal resistance, including among pathogenic fungi

Notes: 1 Rizzo, L. *et al*., 2013. 2 Kümmerer, K. 2009. 3 Karkman A. *et al*., 2017. 4 Gao, L. *et al*., 2012.5 Martinez, J.L., 2009. 6 Larsson, J. *et al*., 2018. 7 Wroński, M. *et al*., 2024.

Sources: As noted above.

Table 9 summarizes selected wastewater treatment processes used in livestock systems and their relevance for reducing antimicrobial residues, resistant bacteria and resistance genes. Their suitability depends on wastewater characteristics, treatment objectives, infrastructure and operational capacity.

Table 9 Wastewater treatment processes in livestock systems and their relevance for AMR mitigation

Process	How it works	Typical ARG removal	Strengths	Limitations
Anaerobic digestion	Microbial degradation in oxygen-free digesters	Variable (0–70%); antibiotic resistance genes (ARGs) persistence or enrichment may occur [1]	Reduces pathogens; generates biogas energy	Inconsistent ARG removal; may promote ARG persistence
Constructed wetlands	Plants, microbes and soil substrates filter and degrade contaminants	Moderate (40–80%); performance depends on design and season [2]	Low cost; nature-based; suitable for rural settings	Land-intensive; seasonal performance variability; incomplete removal of antibiotics
Activated sludge	Aerobic microbial treatment with aeration	Moderate (40–80%); removal varies with sludge age and operational conditions [3]	Effective organic load reduction; adaptable	Requires energy input; costly for small farms; ARGs may persist in effluent
Membrane bioreactors (MBRs)	Biological treatment combined with ultrafiltration membranes	High (>90%) for bacteria; variable for ARGs [4]	Strong removal of bacteria; compact footprint	High capital and operating cost; membrane fouling; limited adoption and suitability for use in low- and middle-income country (LMIC) farms
Advanced oxidation processes (AOPs)	Use of reactive oxygen species (ozonation, Fenton, photocatalysis)	Very high (>95%) for well-optimized systems [5]	Effective on bacteria, antibiotic residues and ARGs; rapid	Expensive but cost may be reduced when combined with a solar source; high energy/chemical input; potential formation of harmful transformation and byproducts if not properly managed; mostly pilot-scale in livestock wastewater

Notes: 1 Pourrostami, N. *et al.*, 2024. 2 Liu, X. *et al.*, 2019. 3 Cheng, X. *et al.*, 2021. 4 Ye, M., *et al.*, 2026. 5 Azuma, T., M. *et al.*, 2022.

Sources: As noted above.

Bibliography

Åkerfeldt, K., A. Sjöblom and H. Aagaard (2025). *Unlocking AMR Financing: Optimizing International Resources for an Accelerated Response to Antibiotic Resistance*. Uppsala: ReAct Europe. https://www.reactgroup.org/wp-content/uploads/2025/10/ReAct-Policy-Brief-Unlocking-AMR-Financing-Optimizing-international-resources-for-an-accelerated-response-to-antibiotic-resistance-October-2025-Final.pdf.

Alem, K., M. Dagnew, M. Gizachew, B. Gelaw and F. Moges (2025). Environmental antimicrobial resistance: key drivers, hotspots, innovative strategies, and challenges in the fight against superbugs. *MicrobiologyOpen*, 14(5), e70067. https://doi.org/10.1002/mbo3.70067.

Al-Khalaifah, H., M.H. Rahman, T. Al-Surrayai, A. Al-Dhumair and M. Al-Hasan, M. (2025). A One-Health perspective of antimicrobial resistance (AMR): human, animals and environmental health. *Life*, 15(10), 1598. https://doi.org/10.3390/life15101598.

Anadon, L.D., G. Chan, A.G. Harley, K. Matus, S. Moon, S.L. Murthy and W.C. Clark (2016). Making technological innovation work for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America,* 113(35), 9682–9690. https://doi.org/10.1073/pnas.1525004113.

Anand, U., B. Adelodun, C. Cabreros *et al.* Occurrence, transformation, bioaccumulation, risk and analysis of pharmaceutical and personal care products from wastewater: a review. *Environmental Chemistry Letters*, 20, 3883–3904 (2022). https://doi.org/10.1007/s10311-022-01498-7.

Antimicrobial Industry Alliance (n.d.). *New Certification System Could Promote Responsible Antibiotic Manufacturing*. Geneva: Antimicrobial Industry Alliance. https://www.amrindustryalliance.org/mediaroom/new-certification-system-could-promote-responsible-antibiotic-manufacturing.

Antimicrobial Resistance Collaborators (2022). Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. *The Lancet*, 399(10325), 629–655. https://doi.org/10.1016/S0140-6736(21)02724-0.

Azuma, T., M. Usui and T. Hayashi (2022). Inactivation of antibiotic-resistant bacteria in wastewater by ozone-based advanced water treatment processes. *Antibiotics,* 11(2), 210. https://doi.org/10.3390/antibiotics11020210.

Bairán, G., G. Rebollar-Pérez, E. Chávez-Bravo and E. Torres (2020). Treatment processes for microbial resistance mitigation: the technological contribution to tackle the problem of antibiotic resistance. *International Journal of Environmental Research and Public Health,* 17(23), 8866. https://doi.org/10.3390/ijerph17238866.

Bakon, S.K. and Z.A. Mohamad (2025). Flushed and forgotten: antimicrobial resistance from wastewater perspective. In Mustafa, G., Thoms-Rodriguez, C.-A., J. Mullings, P.E. Akpaka, K.J. Roye-Green and V. McIntosh-Morgan (eds), *Antimicrobial Resistance – New insights*. London: IntechOpen. https://doi.org/10.5772/intechopen.1009584.

Balcázar, J.L. (2025). Could wastewater-based surveillance be key to combating antimicrobial resistance? *mBio*, 16, e02778-25. https://doi.org/10.1128/mbio.02778-25.

Berendonk, T.U., C.M. Manaia, C. Merlin *et al.* (2015). Tackling antibiotic resistance: the environmental framework. *Nature Reviews Microbiology,* 13(5), 310–317. https://doi.org/10.1038/nrmicro3439.

Billenkamp, E., J. Straub, M. Studer Hoffmann and J. Türk (n.d.). *Elimination of Pharmaceuticals from the Wastewater of a Pharmaceutical Plant*. PharmaFocus Asia. https://www.pharmafocusasia.com/advertorials/elimination-pharmaceuticals-wastewater-pharmaceutical-plant.

Booth, A., D.S. Aga and A.L. Wester (2020). Retrospective analysis of the global antibiotic residues that exceed the predicted no effect concentration for antimicrobial resistance in various environmental matrices. *Environment International*, 140, 105763. https://doi.org/10.1016/j.envint.2020.105796.

Borges, C. (2025). *RAI explainer: How IP rights promote innovation*. Washington, D.C.: Center for Strategic and International Studies. https://www.csis.org/blogs/perspectives-innovation/rai-explainer-how-ip-rights-promote-innovation.

Cai Z., H. He, H. Wu, J. Zhao, G. Zhang and J. Xing (2026) Governing antimicrobial resistance through One Health: a comparative analysis of public health governance in China and the United Kingdom. *Frontiers in Public Health*, 14:1883787. https://doi.org/10.3389/fpubh.2026.1883787.

Centers for Disease Control and Prevention (CDC) (2024). *Wastewater Surveillance: A New Frontier for Public Health*. Atlanta: CDC. https://www.cdc.gov/advanced-molecular-detection/php/success-stories/wastewater-surveillance.html.

Cheng, X., J. Xu, G. Smith, N. Nirmalakhandan and Y. Zhang (2021). Metagenomic profiling of antibiotic resistance and virulence removal: activated sludge vs. algal wastewater treatment system. *Journal of Environmental Management*, 295, 113129. https://doi.org/10.1016/j.jenvman.2021.113129.

Contreras, J.D. *et al.* (2017). Health risks from exposure to untreated wastewater used for irrigation in the Mezquital Valley, Mexico: a 25-year update. *Water Research*, 123, 834–850. https://doi.org/10.1016/j.watres.2017.06.058.

Cui H., J. Yu, X. Zhu, Y. Cui, C. Ji, C. Zhang, J. Xue, X. Jia, S. Qin and R. Li (2021) Advanced treatment of chicken farm flushing wastewater by integrating Fenton oxidation and algal cultivation process for algal growth and nutrients removal. *Journal of Environmental Management*, 298, 113543. https://doi.org/10.1016/j.jenvman.2021.113543.

De, S., M. Coutard and J. Hoinkis (2024) Solar powered membrane bioreactor (MBR) treating wastewater for reuse at a hospital in Kampala, Uganda – results of pilot-scale trials. *Environmental Challenges*, 16, 100986. https://doi.org/10.1016/j.envc.2024.100986.

Deguenon, E. *et al.* (2022). Hospital effluents as sources of antibiotics residues, resistant bacteria and heavy metals in Benin. *SN Applied Sciences*, 4(8), 206. https://doi.org/10.1007/s42452-022-05095-9.

El Saghir, M. (n.d.). *Software and Database Protection* [PowerPoint slides]. Geneva: WIPO. https://www.wipo.int/edocs/mdocs/mdocs/en/wipo_ssc_cai_13/wipo_ssc_cai_13_topic_9_el_saghir.pptx.

Elbehiry, A. and E. Marzouk (2025). From farm to fork: antimicrobial-resistant bacterial pathogens in livestock production and the food chain. *Veterinary Sciences*, 12(9), 862. https://doi.org/10.3390/vetsci12090862.

Food and Agriculture Organization of the United Nations (FAO), United Nations Environment Programme (UNEP), World Health Organization (WHO) and World Organisation for Animal Health (WOAH) (2022). *One Health Joint Plan of Action (2022–2026): Working Together for the Health of Humans, Animals, Plants and the Environment*. FAO, UNEP, WHO, & WOAH. https://www.who.int/publications/i/item/9789240059139.

Foong, S.Y., B.L.F. Chin, S.S.M. Lock *et al.* (2024). Enhancing wastewater treatment with engineered biochar from microwave-assisted approach – a comprehensive review. *Environmental Technology & Innovation*, 36, 103835. https://doi.org/10.1016/j.eti.2024.103835.

Foxman, B., E. Salzman *et al.* (2025). Wastewater surveillance of antibiotic-resistant bacteria for public health action: potential and challenges. *American Journal of Epidemiology*, 194(5), 1192–1199. https://doi.org/10.1093/aje/kwae419.

Gao, L., Y. Shi, W. Li, J. Liu and Y. Cai (2012). Occurrence, distribution and bioaccumulation of antibiotics in the Haihe River in China. *Journal of Environmental Monitoring*, 14(4), 1247–1254. https://doi.org/10.1039/C2EM10916F.

Gao, Z., Y. Gao, S. Wang, X. Li *et al.* (2025). Application progress and biosafety challenges of gene editing and synthetic biotechnology in diagnosis, treatment and prevention of infectious diseases. *Biosafety and Health*, 7(5), 312–322. https://doi.org/10.1016/j.bsheal.2025.09.002.

Garduño-Jiménez, A.-L., J.-C. Durán-Álvarez, C.A. Ortori, S. Abdelrazig, D.A. Barrett and R.L. Gomes (2023). Delivering on sustainable development goals in wastewater reuse for agriculture: initial prioritization of emerging pollutants in the Tula Valley, Mexico. *Water Research*, 238, 119903. https://doi.org/10.1016/j.watres.2023.119903.

GBD 2021 Antimicrobial Resistance Collaborators (2024). Global burden of bacterial antimicrobial resistance 1990–2021: a systematic analysis with forecasts to 2050. *The Lancet*, 404(10459), 1199–1226. https://doi.org/10.1016/S0140-6736(24)01867-1.

Gbotche, E. *et al.* (2023). National survey of stream water quality revealing threats to antibiotic-resistant bacteria, antibiotic residues and heavy metals in Benin. *Pollution*, 9(2), 678–692. https://doi.org/10.22059/poll.2022.348629.1629.

Gong, W., L. Bai and H. Liang (2024). Membrane-based technologies for removing emerging contaminants in urban water systems: limitations, successes, and future improvements. *Desalination*, 590, 117974. https://doi.org/10.1016/j.desal.2024.117974.

Greenhalgh, T., J. Wherton, C. Papoutsi, J. Lynch, G. Hughes, C. A'Court, S. Hinder, N. Fahy, R. Procter and S. Shaw (2017). Beyond adoption: a new framework for theorizing and evaluating nonadoption, abandonment, and challenges to the scale-up, spread, and sustainability of health and care technologies. *Journal of Medical Internet Research*, 19(11), e367. https://doi.org/10.2196/jmir.8775.

Gwenzi, W., T.T. Simbanegavi and P. Rzymski (2023). Household disposal of pharmaceuticals in low-income settings: practices, health hazards, and research needs. *Water*, 15(3), 476. https://doi.org/10.3390/w15030476.

Hanna, N., A.J. Tamhankar and C.S. Lundborg (2023) Antibiotic concentrations and antibiotic resistance in aquatic environments of the WHO Western Pacific and South-East Asia regions: a systematic review and probabilistic environmental hazard assessment. *The Lancet Planetary Health*, 7(1), e45–e54. https://doi.org/10.1016/S2542-5196(22)00254-6.

Haščič, I. and M. Migotto (2015). Measuring Environmental Innovation Using Patent Data. *OECD Environment Working Papers No. 89*. Paris: OECD Publishing. https://dx.doi.org/10.1787/5js009kf48xw-en.

He, Y., Q. Yuan, J. Mathieu, L. Stadler, N. Senehi, R. Sun, and P.J.J. Alvarez (2020). Antibiotic resistance genes from livestock waste: occurrence, dissemination, and treatment. *npj Clean Water*, 3(4). https://doi.org/10.1038/s41545-020-0051-0.

Health Care Without Harm Europe (2023). *Procuring for Greener Pharma*. https://europe.noharm.org/sites/default/files/documents-files/7333/2023-02-08_HCWH-Europe_Procuring-greener-pharma.pdf.

Hiller, C.X., U. Hübner, S. Fajnorova, T. Schwartz and J.E. Drewes (2019). Antibiotic microbial resistance removal efficiencies by conventional and advanced wastewater treatment processes: a review. *Science of the Total Environment*, 685, 596–608. https://doi.org/10.1016/j.scitotenv.2019.05.315.

Hock, L., R. Luiken, E. Valério, M. Vargha, J. Vierheilig, S. Börjesson, T. Pitkänen and H. Schmitt (2026). Integrating AMR surveillance into wastewater monitoring systems in 2025: a position on the implementation of Article 17 of the Urban Wastewater Treatment Directive (UWWTD). *Eurosurveillance,* 31(3). https://doi.org/10.2807/1560-7917.ES.2026.31.3.2500289.

Huang, W., F. Wang, Y. Su, H. Huang and J. Luo (2025). Underestimated roles of phages in biological wastewater treatment systems: recent advances and challenges. *Journal of Hazardous Materials*, 495, 139007. https://doi.org/10.1016/j.jhazmat.2025.139007.

Jenner, A., N. Bhagwandin and S. Kowalski (2017). *Antimicrobial Resistance (AMR) and Multidrug Resistance (MDR): Overview of Current Approaches, Consortia and Intellectual Property Issues*. Geneva: WIPO. https://www.wipo.int/publications/en/details.jsp?id=4210.

Joakim Larsson, D.G. *et al.* (2018). Critical knowledge gaps and research needs related to the environmental dimensions of antibiotic resistance. *Environment International*, 117, 132–138. https://doi.org/10.1016/j.envint.2018.04.041.

Johar, A.A., M.A. Salih, H.A. Abdelrahman, H. Al Mana, H.A. Hadi and N.O. Eltai (2023). Wastewater-based epidemiology for tracking bacterial diversity and antibiotic resistance in COVID-19 isolation hospitals in Qatar. *Journal of Hospital Infection*, 141, 209–220. https://doi.org/10.1016/j.jhin.2023.08.011.

Kamarul Aryffin, H.A., M.A. Bin Sahbudin, S. Ali Pitchay, A.H. Abhalim and I. Sahbudin (2025). Technological trends in epidemic intelligence for infectious disease surveillance: a systematic literature review. *PeerJ Computer Science,* 11, e2874. https://doi.org/10.7717/peerj-cs.2874.

Karkman A., T.T. Do, F. Walsh and M.P.J. Virta (2017). Antibiotic-resistance genes in waste water. *Trends in* Microbiology, 26(3), 220–228. https://doi.org/10.1016/j.tim.2017.09.005.

Kaur, A., S. Arora, A. Kumar, A. Karnwal and R. Singh, (2026). Nature-based wastewater treatment technologies: a comprehensive review of constructed wetlands and vermifiltration. *Cleaner Water*, 5, 100204. https://doi.org/10.1016/j.clwat.2026.100204.

Khan, M.U., M.M. Rahman, N. Zahan, M.K. Masud, S. Sarker and M.H. Haque (2025). Electrochemical biosensing for antibiotic-resistant bacteria: advances, challenges, and future directions. *Micromachines*, 16(9), 986. https://doi.org/10.3390/mi16090986.

Kim, S., A. Zulli, E.M.G. Chan, D. Duong, R.Y. Linfield, C.E.M. McCormack, B.J. White, M.K. Wolfe, A.B. Boehm and A.J. Pickering (2026). Wastewater surveillance reveals patterns of antibiotic resistance across the United States. *Nature Communications*, 17, 4680. https://doi.org/10.1038/s41467-026-71195-4.

Kümmerer, K. (2009). Antibiotics in the aquatic environment – a review – part I. *Chemosphere*, 75(4), 417–434. https://doi.org/10.1016/j.chemosphere.2008.11.086.

Lan, L., Y. Wang, Y. Chen, T. Wang, J. Zhang and B. Tan (2025). A review on the prevalence and treatment of antibiotic resistance genes in hospital wastewater. *Toxics*, 13(4), 263. https://doi.org/10.3390/toxics13040263.

Lin, K., N. Wu, S. Liu, J. Yao, H. You, S. Heng, X. Wang, J. Huang, P. Pullammanappallil and S. Yang (2026). Advanced treatment and disinfection of hospital wastewater: progress, monitoring gaps, and trends. *Water*, 18(5), 605. https://doi.org/10.3390/w18050605.

Liu, X., X. Guo, Y. Liu, S. Lu, B. Xi, J. Zhang, Z. Wang and B. Bi (2019). A review on removing antibiotics and antibiotic resistance genes from wastewater by constructed wetlands: performance and microbial response. *Environmental Pollution,* 254, Part A, 112996. https://doi.org/10.1016/j.envpol.2019.112996.

Londong, J., M. Barth and H. Söbke (2023). Reducing antimicrobial resistances by source separation of domestic wastewater. *Frontiers in Environmental Health*, 2, 1151898. https://doi.org/10.3389/fenvh.2023.1151898.

Lu, Z., G. Liu, H. Xie, Y. Zhai, Y. and X. Li (2024). Advances and solutions in biological treatment for antibiotic wastewater with resistance genes: a review. *Journal of Environmental Management*, 368, 122115. https://doi.org/10.1016/j.jenvman.2024.122115.

Lybecker, K.M. and S. Lohse (2015). *Innovation and Diffusion of Green Technologies: The Role of Intellectual Property and Other Enabling Factors (Global Challenges Report)*. Geneva: WIPO. https://www.wipo.int/edocs/pubdocs/en/wipo_rep_gc_2015_1.pdf.

Macedo, H.E., B. Lehner, J.A. Nicell, U. Khan and E.Y. Klein (2025). Antibiotics in the global river system arising from human consumption. *PNAS Nexus,* 4(4), pgaf096. https://doi.org/10.1093/pnasnexus/pgaf096.

Malcom, H.B. and D.A. Bowes (2025). Use of wastewater to monitor antimicrobial resistance trends in communities and implications for wastewater-based epidemiology: a review of the recent literature. *Microorganisms,* 13(9), 2073. https://doi.org/10.3390/microorganisms13092073.

Martinez, J.L. (2009). Environmental pollution by antibiotics and by antibiotic resistance determinants. *Environmental Pollution*, 157(11), 2893–2902. https://doi.org/10.1016/j.envpol.2009.05.051.

Mathai, T., T. Pal, N. Prakash and S. Mukherji (2023). Portable biosensor for the detection of enrofloxacin and ciprofloxacin antibiotic residues in food, body fluids, environmental and wastewater samples. *Biosensors & Bioelectronics*, 237, 115478. https://doi.org/10.1016/j.bios.2023.115478.

McCulligh, C. and D. Tetreault (2017). Water management in Mexico: from concrete-heavy persistence to community-based resistance. *Water Alternatives*, 10(2), 341–369. https://www.water-alternatives.org/index.php/alldoc/articles/vol10/v10issue2/359-a10-2-9/file.

Medina-Esparza, W.N. *et al.* (2025). Efficiency of a new biochar made from agave bagasse to remove conventional pollutants in samples from Laguna de Bustillos, Chihuahua, Mexico, and pharmaceutical derivatives in synthetic water. *Processes*, 13(6), 1861. https://doi.org/10.3390/pr13061861.

Meradji, S., N.S. Basher, A. Sassi, N.A. Ibrahim, T. Idres and A. Touati (2025). The role of water as a reservoir for antibiotic-resistant bacteria. *Antibiotics,* 14(8), 763. https://doi.org/10.3390/antibiotics14080763.

Ministério da Saúde (2019). *Plano de Ação Nacional de Prevenção e Controle da Resistência aos Antimicrobianos no Âmbito da Saúde Única 2018–2022 (PAN-BR)*. Brasília: Ministério da Saúde. https://www.gov.br/saude/pt-br/centrais-de-conteudo/publicacoes/svsa/antimicrobianos/plano-nacional-antimicrobianos-pan-br-14fev19-isbn.pdf/view.

Ministry of Public Health – Qatar (2024). *Qatar: National Antimicrobial Resistance Action Plan 2024–2030*. Geneva: WHO. https://www.who.int/publications/m/item/qatar--national-antimicrobial-resistance-action-plan-2024-2030.

Mulchandani, R., Y. Wang, M. Gilbert and T.P. Van Boeckel (2023). Global trends and projections of antimicrobial use in food animals: 2020 to 2030. *PLOS Global Public Health*, 3(3), e0001305. https://doi.org/10.1371/journal.pgph.0001305.

Muñoz, R. and B. Guieysse (2006). Algal–bacterial processes for the treatment of hazardous contaminants: a review. *Water Research*, 40(15), 2799–2815. https://doi.org/10.1016/j.watres.2006.06.011.

Novoa-Luna, K.A., A. Mendoza-Zepeda, R. Natividad, R. Romero, M. Galar-Martínez and L.M. Gómez-Oliván (2016). Biological hazard evaluation of a pharmaceutical effluent before and after a photo-Fenton treatment. *Science of the Total Environment,* 569–570, 830–840. https://doi.org/10.1016/j.scitotenv.2016.06.086.

Nuevo J.J.M., J.A.G. Fortaleza, K.S.P. Cabuhat, C.J.N. Ong, A.C. Jalova, F.A. Mortel and G.D. Bacalzo (2026) CRISPR-driven strategies to disrupt methicillin-resistant Staphylococcus aureus biofilms: a review. *Frontiers in Cellular and Infection Microbiology*, 16, 1784529. https://doi.org/10.3389/fcimb.2026.1784529.

Oon Y.-L., Y.-S. Oon, M. Ayaz, M. Deng, L. Li and K. Song (2023) Waterborne pathogens detection technologies: advances, challenges, and future perspectives. *Frontiers in Microbiology.*, 14:1286923. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2023.1286923/full.

Parry, L., T. Leslie, S. Onasanya and S. Fenwick (2026). *Multi-Country Technical Assistance Approach for Strengthening AMR Surveillance in LMICs: Lessons from the Fleming Fund*. London: Fleming Fund. https://www.flemingfund.org/wp-content/uploads/293def9c0f0cef643a0503b65dd8738b.pdf.

Pham, M.N., F. Nishimura, J.C.W. Lan and K.S. Khoo (2024). Recent advancement of eliminating antibiotic-resistant bacteria and antibiotic resistance genes in livestock waste: a review. *Environmental Technology & Innovation,* 36, 103751. https://doi.org/10.1016/j.eti.2024.103751.

Pourrostami Niavol, K., A, Bordoloi and R. Suri (2024). An overview of the occurrence, impact of process parameters and the fate of antibiotic resistance genes during anaerobic digestion processes. *Environmental Science and Pollution Research*, 31, 41745–41774. https://doi.org/10.1007/s11356-024-33844-3.

Pursey, E., D. Sünderhauf, W.H. Gaze, E.R. Westra and G. van Houte (2018). CRISPR-Cas antimicrobials: challenges and future prospects. *PLoS Pathogens*, 14(6), e1006990. https://doi.org/10.1371/journal.ppat.1006990.

Rahman, A., M.M. Rahman, M.A. Haque, P. Shinu, M.M. Rahman, A.A. Khan and S. Rushd (2026). Biochar-based catalysts for sustainable wastewater treatment: advances, mechanisms, and future perspectives. *Catalysts*, 16(6), 538. https://doi.org/10.3390/catal16060538.

Rathinavelu, S. *et al.* (2024). Mapping the scarcity of data on antibiotics in natural and engineered water environments across India. *Frontiers in Antibiotics*, 3, 1337261. https://doi.org/10.3389/frabi.2024.1337261.

ReViRAE. *About Us*. ReViRae. https://revirae.com.br/sobre-nos.

Rizzo, L., C. Manaia, C. Merlin, T. Schwartz, C. Dagot, M.C. Ploy, I. Michael and D. Fatta-Kassinos (2013). Urban wastewater treatment plants as hotspots for antibiotic resistant bacteria and genes spread into the environment: a review. *Science of the Total Environment*, 447, 345–360. https://doi.org/10.1016/j.scitotenv.2013.01.032.

Saeed, U., R.A. Insaf, Z.Z. Piracha *et al.* (2023). Crisis averted: a world united against the menace of multiple drug-resistant superbugs – pioneering anti-AMR vaccines, RNA interference, nanomedicine, CRISPR-based antimicrobials, bacteriophage therapies, and clinical artificial intelligence strategies to safeguard the global antimicrobial arsenal. *Frontiers in Microbiology*, 14, 1270018. https://doi.org/10.3389/fmicb.2023.1270018.

Sambaza, S.S. and N. Naicker (2023). Contribution of wastewater to antimicrobial resistance: a review article. *Journal of Global Antimicrobial Resistance*, 34, 23–29. https://doi.org/10.1016/j.jgar.2023.05.010.

Sampeney, E.T., I.M. Bryant, R.K. Sam, G.S. Botchway, P.K. Yeboah-Danso, P. Dotsey, I. Yaala and D.O. Agyei (2025). Revolutionizing industrial wastewater management in Ghana: sustainable innovations for a cleaner future. *Desalination and Water Treatment*, 324, 101589. https://doi.org/10.1016/j.dwt.2025.101589.

Sridevi, H., V. Gosu and R. Juturu (2026) Recent advances in biochar from lignocellulosic and non-lignocellulosic feedstocks for heavy metal remediation. *Discover Applied Sciences*, 8, 819. https://doi.org/10.1007/s42452-026-08853-1.

Sykehusinnkjøp H.F. (2023). *Experience Report: Environmental Requirements for Pharmaceutical Procurements 2022–2023*. Vadsø: The Norwegian Hospital Procurement Trust (NHPT). https://www.sykehusinnkjop.no/4937c6/siteassets/bilder/nyheter/2024/miljokrav-legemidler-rapport/erfaringsrapport-miljo-2023_engelsk-versjon.pdf.

Taneja, N. and M. Sharma (2019). Antimicrobial resistance in the environment: the Indian scenario. *Indian Journal of Medical Research,* 149(2), 119–128. https://doi.org/10.4103/ijmr.IJMR_331_18.

United Nations Environment Programme (UNEP) (2023). *Bracing for Superbugs: Strengthening Environmental Action in the One Health Response to Antimicrobial Resistance*. Nairobi: UNEP. https://www.unep.org/resources/superbugs/environmental-action.

United Nations (UN) General Assembly (2024*). Political Declaration of the High-level Meeting on Antimicrobial Resistance*. New York: UN. https://documents.un.org/doc/undoc/ltd/n24/278/35/pdf/n2427835.pdf?_gl=1*1l7uzui*_ga*MzY3NzE5MTYxLjE3MjA5OTAzNzA.*_ga_TK9BQL5X7Z*MTczNTM0NzIzMy4yMC4wLjE3MzUzNDcyMzMuMC4wLjA.

Urzua-Abad, M.M. *et al.* (2024). Detection of carbapenemases in *Enterobacterales* and other Gram-negative bacilli recovered from hospital and municipal wastewater in Mexico City. *Scientific Reports*, 14(1), 26576. https://doi.org/10.1038/s41598-024-76824-w.

Wang, T., Z. Ni, B. Kuang, L. Zhou, X. Chen, Z. Lin, B. Guo, G. Zhu and J. Jia (2022). Two-stage hybrid microalgal electroactive wetland-coupled anaerobic digestion for swine wastewater treatment in South China: full-scale verification. *Science of the Total Environment*, 820, 153312. https://doi.org/10.1016/j.scitotenv.2022.153312.

Werkneh, A. A., & Islam, M. A. (2023). Post-treatment disinfection technologies for sustainable removal of antibiotic residues and antimicrobial resistance bacteria from hospital wastewater. *Heliyon, 9*(4), e15360. https://doi.org/10.1016/j.heliyon.2023.e15360

Wisconsin Economic Development Corporation (WEDC) (2022). *Mexico's Pharmaceutical Industry Grows*. Madison: WEDC. https://wedc.org/market-intelligence/posts/mexicos-pharmaceutical-industry-grows.

World Bank (2024). *Stopping the Grand Pandemic: A Framework for Action: Addressing Antimicrobial Resistance Through World Bank Operations.* Washington, D.C.: World Bank. https://www.worldbank.org/en/topic/health/brief/antimicrobial-resistance-amr.

World Health Organization (WHO) (2024) *Guidance on Wastewater and Solid Waste Management for Manufacturing of Antibiotics*. Geneva: WHO. https://www.who.int/publications/i/item/9789240097254.

World Health Organization (WHO) (2024). *Wastewater and Environmental Surveillance for One or More Pathogens: Guidance on Prioritization, Implementation and Integration: Pilot Version*. Geneva: WHO. https://www.who.int/publications/m/item/wastewater-and-environmental-surveillance-for-one-or-more-pathogens--guidance-on-prioritization--implementation-and-integration.

World Health Organization (WHO) (2024). *World Leaders Commit to Decisive Action on Antimicrobial Resistance*. Geneva: WHO. https://www.who.int/news/item/26-09-2024-world-leaders-commit-to-decisive-action-on-antimicrobial-resistance.

World Health Organization (WHO) (2025). *Wastewater and Environmental Surveillance: Summary for Antimicrobial Resistance*. Geneva: WHO. https://www.who.int/publications/m/item/wastewater-and-environmental-surveillance--summary-for-antimicrobial-resistance.

World Health Organization (WHO) (2026). *Antimicrobial Resistance*. Geneva: WHO. https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance.

World Health Organization (WHO) Regional Office for Europe (2025). *Bacteriophages and Their Use in Combating Antimicrobial Resistance*. Geneva: WHO. https://www.who.int/europe/news-room/fact-sheets/item/bacteriophages-and-their-use-in-combating-antimicrobial-resistance.

World Health Organization (WHO), Food and Agriculture Organization of the United Nations (FAO) and World Organisation for Animal Health (WOAH) (2020). *Technical Brief on Water, Sanitation, Hygiene and Wastewater Management (WASH) to Prevent Infections and Reduce the Spread of Antimicrobial Resistance (AMR)*. Geneva: WHO. https://www.who.int/publications/i/item/9789240006416 .

World Intellectual Property Organization (WIPO) (2010). *University–Industry Link: The Case of UNAM–IB Tech*. Geneva: WIPO. https://www.wipo.int/en/web/ip-advantage/w/stories/university-industry-link-the-case-of-unam-ib-tech.

World Intellectual Property Organization (WIPO) (2017). *Innovation and Intellectual Property*. Geneva: WIPO. https://www.wipo.int/en/web/ipday/2017/innovation_and_intellectual_property.

World Intellectual Property Organization (WIPO) (2023). *News – Global Health: Intellectual Property and Global Health News*. Geneva: WIPO. https://www.wipo.int/en/web/global-health/w/news/2023/news_0016.

World Intellectual Property Organization (WIPO) (2024). *WIPO GREEN: Facilitating Dissemination of Green Technology*. Geneva: WIPO. https://www.wipo.int/en/web/wipo-magazine/articles/wipo-green-facilitating-dissemination-of-green-technology-38134.

World Intellectual Property Organization (WIPO) (2024). *WIPO Guide to Trade Secrets and Innovation*. Geneva: WIPO. https://doi.org/10.34667/TIND.49735.

World Intellectual Property Organization (WIPO) (n.d.). *Copyright*. Geneva: WIPO. https://www.wipo.int/en/web/copyright.

World Intellectual Property Organization (WIPO) (n.d.). *Copyright Registration Systems*. Geneva: WIPO. https://www.wipo.int/en/web/copyright/activities/copyright-registration/index.

World Intellectual Property Organization (WIPO) (n.d.). *Industrial Designs*. Geneva: WIPO. https://www.wipo.int/en/web/designs.

World Intellectual Property Organization (WIPO) (n.d.). *IP Assignment and Licensing*. Geneva: WIPO. https://www.wipo.int/en/web/business/assignment-licensing.

World Intellectual Property Organization (WIPO) (n.d.). *IP Audit – Description and Toolkit*. Geneva: WIPO. https://www.wipo.int/documents/d/tisc/docs-en-tisc-toolkit-ip-audit-description.pdf.

World Intellectual Property Organization (WIPO) (n.d.). *Patents*. Geneva: WIPO. https://www.wipo.int/en/web/patents.

World Intellectual Property Organization (WIPO) (n.d.). *Trade Secrets*. Geneva: WIPO. https://www.wipo.int/en/web/trade-secrets.

World Intellectual Property Organization (WIPO) (n.d.). *Uncovering IP Risks and Potential: IP Audit*. Geneva: WIPO. https://www.wipo.int/en/web/business/ip-audit.

Wroński, M., J. Trawiński and R. Skibiński (2024). Antifungal drugs in the aquatic environment: A review on sources, occurrence, toxicity, health effects, removal strategies and future challenges. *Journal of Hazardous Materials*, 465, 133167. https://doi.org/10.1016/j.jhazmat.2023.133167

Wu, F., Q. Zhu, L. Zhang, W. Shen, J. Gong, H.K. Lee and S. Tang (2025). Recent progress of biosensing techniques for environmental antibiotic resistance genes. *TrAC Trends in Analytical Chemistry*. 191, 118380. https://doi.org/10.1016/j.trac.2025.118380.

Xu, Z., D. Zhao, J. Lu, J. Liu, G. Dao, B. Chen, B. Huang and X. Pan (2023). Multiple roles of nanomaterials along with their based nanotechnologies in the elimination and dissemination of antibiotic resistance. *Chemical Engineering Journal*, 455 (Part 2), 140927. https://doi.org/10.1016/j.cej.2022.140927.

Yamin, D., V. Uskoković, A.M. Wakil *et al.* (2023). Current and future technologies for the detection of antibiotic-resistant bacteria. *Diagnostics*, 13(20), 3246. https://doi.org/10.3390/diagnostics13203246.

Ye, M., L. Lv, W. Chen, W. Gao, Y. Chen and K. Liu (2026). Fate and removal of antibiotic resistance bacteria and genes in medical wastewater: potential of membrane bioreactors. *Chemical Engineering Journal*, 535, 175598. https://doi.org/10.1016/j.cej.2026.175598.

Zhang, S., T. Xu, C. Zhang, H. Zhou, T. Liu and H.-L. Song (2025). A review of antibiotic resistance generation and control in wastewater and solid waste system. *Journal of Environmental Chemical Engineering,* 13(5), 118014. https://doi.org/10.1016/j.jece.2025.118014.

Zhou, Z., I.-H. Cho and U.S. Kadam (2025). CRISPR-Cas-based diagnostics in biomedicine: principles, applications, and future trajectories. *Biosensors*, 15(10), 660. https://doi.org/10.3390/bios15100660.

Antimicrobial resistance (AMR) is a growing global health challenge that extends beyond healthcare settings into the environment. Wastewater plays an important role in the spread of antimicrobial residues, resistant microorganisms and resistance genes, while also offering opportunities for surveillance, treatment and risk reduction.

This report explores how innovation, intellectual property (IP) and technology transfer can support efforts to address AMR in wastewater within a One Health framework. It examines global patenting trends, IP management strategies, licensing and technology transfer approaches that can facilitate the development and uptake of relevant technologies.

A complementary technology section presents practical approaches to detecting, monitoring and managing AMR in wastewater, drawing on technologies and case studies from different countries and settings.

Together, the two parts provide insights for policymakers, researchers, innovators and other stakeholders seeking to strengthen AMR responses through technological innovation, collaboration and the effective use of IP to support technology development, adaptation and implementation.