2026 Volume: 01 Issue: 07 ISSN 1671-2838 Page No: 677-687

Pharmaceutical Care and Research

https://pcrjournal.com

Review Article

Volume: 01
Issue: 07

A COMPRESSIONSIVE REVIEW ON ENVIRONMENTAL IMPACT OF PHARMACEUTICAL INDUSTRIES.

Rakesh A. Mane[1], Dr. Prasad V. Patrekar[2], Shrirang V. Kharmate*[3], Satyajeet R. Jagdale[4], Pradeep C. Patil[5], Pratibha P. Shingade[6].

[1]Student, [2]Principal, [3]Assistant Professor, [4]Assistant Professor, [5]Assistant Professor, [6]Assistant Professor.

Eklavya College of Pharmacy, Tasgaon , Maharashtra, India

Article Received: 23 August 2026
Article Revised: 11 September 2026
Published on: 01 October 2026

***Corresponding Author: Shrirang V. Kharmate**
Student, Eklavya College of Pharmacy, Tasgaon, Maharashtra, India.

DOI: https://doi-doi.org/101555/ijpcr.2494

ABSTRACT

The pharmaceutical sector occupies a contradictory position with respect to environmental sustainability: it exists to protect human health, yet the manufacturing, use and disposal of its products generate ecological burdens that remain under-reported relative to sectors such as energy and transport. This review synthesises evidence from **open-access** peer-reviewed articles, systematic reviews and industry reports to examine four interrelated dimensions of pharmaceutical-industry sustainability: the carbon footprint of manufacturing and the wider healthcare sector; the discharge of active pharmaceutical ingredients (APIs) into surface water, groundwater, soil and sediment; the industry's contribution to antimicrobial resistance (AMR) through untreated antibiotic-manufacturing effluent; and lifecycle interventions aimed at reducing these impacts. The reviewed evidence indicates that pharmaceutical manufacturing is more emissions-intensive than the automotive industry, and that hundreds of pharmaceutical substances have been detected in the environment across more than seventy countries. Discharge from antibiotic manufacturers has been linked to resistant bacteria near production sites in India and China, compounding an AMR burden projected to cause ten million deaths annually by 2050. The review highlights promising interventions — green chemistry, enzymatic and continuous manufacturing, extended producer responsibility, eco-prescription and take-back schemes — while identifying regulatory fragmentation, inconsistent emissions reporting and limited life-cycle transparency as persistent obstacles. It concludes with policy and research recommendations.

KEYWORDS: *Pharmaceutical Industry; Environmental Sustainability; Carbon Footprint; Antimicrobial Resistance; Green Chemistry; Active Pharmaceutical Ingredients (Apis); Climate Change.*

1. INTRODUCTION

Medicines are among the most consequential inventions of modern civilisation, yet the industry that manufactures them has an environmental footprint studied far less than sectors such as energy, transport and heavy industry. Climate change is widely regarded as one of the greatest hazards to public health this century, which places the pharmaceutical industry in an unusual position: it must adapt to the health consequences of a warming climate while simultaneously reducing the emissions, chemical discharge and waste associated with its own operations [1].

The environmental impact of the sector is classified into two major categories of concern. The first is the carbon and resource footprint of pharmaceutical production, which includes greenhouse gas emissions as well as energy and water use throughout the synthesis, formulation, packing, and distribution of APIs. The second is the discharge of pharmaceuticals themselves into the environment through incorrect disposal of unneeded medications, excretion of drug metabolites following human and veterinary use, and manufacturing effluent [2]. The World Health Organization has identified antimicrobial resistance (AMR) as one of its top health problems, and a third, interrelated issue connects the two: antibiotic residues and untreated factory effluent contribute to the rise in AMR [3].

This review synthesises open-access scientific publications, systematic reviews and industry case studies around five questions: (i) how do pharmaceuticals enter the environment; (ii) what is the scale of the industry's carbon footprint; (iii) what are the ecotoxicological and AMR consequences of contamination; (iv) what mitigation strategies have industry, governments and the healthcare community introduced; and (v) what gaps remain in research, regulation and practice.

2. Sources and Pathways of Pharmaceutical Pollution

Pharmaceuticals reach the environment through several distinct but interconnected pathways, each requiring different mitigation measures — reducing manufacturing discharge, for instance, does nothing to reduce the quantity excreted after normal use.

Manufacturing effluent. Process water, solvents, and unreacted API in inadequately treated form are released into adjacent water bodies by facilities that produce active pharmaceutical ingredients. The anti-inflammatory diclofenac was found in 50 nations at amounts that exceeded no-effect expectations in some places, according to a widely accepted literature analysis that found 631 distinct pharmaceutical chemicals in the environment across 71 countries (aus der Beek et al., 2016, as quoted in [1]). Pharmaceuticals were discovered in treatment plant effluent at milligram-per-liter amounts, several orders of magnitude more than what would be produced by human waste alone, according to field experiments conducted close to Indian production hubs [4].

Human and veterinary excretion. In actuality, this is the most common route: people only metabolise a portion of a dose and eliminate the remainder unmodified. Up to 95% of certain antibiotics are eliminated unaltered [4], and in the EU, 30–90% of a given dose is still present in urine

(as stated in [2]). A significant portion of pharmacologically active chemicals end up in receiving waters because conventional treatment, including activated sludge, cannot completely eliminate them [4].

Improper disposal. According to survey data from the UK, 63% of respondents disposed of their medications via household waste, 22% returned them to a pharmacy, and 11.5% flushed them down the sink or toilet. Less than half of respondents recognised that pharmaceuticals could be harmful to the environment (as described in [2]). Due to overprescription, treatment modifications, or dose-packaging inconsistencies, more than one-third of medications that are returned to pharmacies are categorised as avoidable waste [2].

Because these three pathways operate through different mechanisms, monitoring one does not substitute for monitoring the others: manufacturing effluent is concentrated near production clusters and can in principle be controlled at the point source, whereas excretion-based and disposal-based contamination are diffuse, arise from millions of individual decisions, and require behavioural and infrastructural responses rather than site-level engineering alone [2].

3. Carbon Footprint and Climate-Change Dimensions

Separate from the impacts of active substances, the industry carries a direct carbon footprint. Global pharmaceutical-sector emissions were estimated at roughly 52 megatonnes of CO2-equivalent in 2015 — larger than the 46 megatonnes produced that year by the automotive industry — and, on an intensity basis, pharmaceutical emissions were calculated to be 55% higher than automotive emissions (Belkhir & Elmeligi, 2019, as cited in [1]).

Table 1. Comparative global CO2-equivalent emissions of the pharmaceutical and automotive industries, 2015 (Belkhir & Elmeligi, 2019, as cited in [1]).

Metric (2015)	Pharmaceutical industry	Automotive industry
Global CO2-equivalent emissions	≈52 Mt CO2e	≈46 Mt CO2e
Emissions intensity (relative)	Reference level	≈35% lower than pharma

The industry would need to reduce emissions intensity by about 59% from present levels by 2025 in order to stay on pace with the 2016 Paris Agreement, a goal that is becoming more challenging to confirm due to inconsistent company-level reporting (as mentioned in [1]). Hospitals, anaesthetic gases, and medical equipment are all part of the broader healthcare industry footprint that includes pharmaceutical manufacture. The emissions from healthcare systems vary greatly by nation, reflecting variations in energy mix, care intensity, and reporting practices [1]. Decarbonising pharmaceutical supply chains helps reduce the industry's contribution to global warming, but a warmer climate is predicted to change the geographic distribution of vector-borne illnesses and worsen heat-related mortality; the 2003 European heatwave alone was linked to over 70,000 excess deaths (as cited in [1])

When combined, these pathways explain why pharmaceutical contamination is now regarded as a truly global phenomenon rather than a localised industrial issue: excretion and disposal produce chronic, low-concentration contamination nearly everywhere pharmaceuticals are consumed, whereas manufacturing hotspots produce acute, high-concentration contamination close to production sites (as cited in [1]).

4. Ecotoxicological Impacts on Aquatic and Terrestrial Systems

Advances in analytical chemistry, particularly mass spectrometry, now allow detection of pharmaceutical residues at trace concentrations — from nanograms to micrograms per litre — in surface water, groundwater, drinking water, soil and sediment worldwide. The most commonly detected classes are analgesics and NSAIDs (ibuprofen, naproxen, diclofenac), antibiotics, hormones and contraceptives, antihypertensives, anticonvulsants and psychotherapeutic agents such as antidepressants [4].

Aquatic organisms are particularly vulnerable due to the high water solubility of many medicines. Fish populations are feminised by both synthetic and natural hormones; in one Swedish field experiment, rainbow trout subjected to undiluted treated sewage effluent shown decreased fertility, with plasma levels of the progestin levonorgestrel above human levels (as stated in [5]). While NSAIDs disrupt oocyte maturation and induce oxidative stress in fish and invertebrates, antidepressant chemicals have been detected in frog tissue and associated with delayed amphibian development [5]. The near-collapse of South Asia's vulture population due to exposure to diclofenac residues in the carcasses of treated cattle—ecotoxicity driven by a single compound—is arguably the most often reported instance of pharmaceutical ecotoxicity (as described in [5]).

According to EU testing protocols, beta-blockers like metoprolol and propranolol are water soluble, resistant to hydrolysis, and dangerous to aquatic life. Even at trace levels, anticancer medications exhibit mutagenic, carcinogenic, and teratogenic effects; cisplatin, one of the most toxic anticancer agents found in hospital and manufacturing wastewater, has been found in 58% of sampled hospital effluent [2]. Additionally, microbial populations in receiving waters are altered by antibiotic residues, a route to AMR that is covered below [4].

These findings illustrate a broader pattern in the ecotoxicology literature: effects are rarely visible from a single compound at typical environmental concentrations, but chronic, low-level exposure to complex pharmaceutical mixtures can produce measurable population-level consequences over time, particularly for species with long life cycles or slow reproduction [2].

5. Antimicrobial Resistance and Human Health Considerations

When bacteria are frequently exposed to low concentrations of antibiotic residues, AMR develops. More than 700,000 deaths worldwide are already attributed to drug-resistant infections; in the absence of effective intervention, this number is expected to rise to 10 million deaths annually by 2050, with

nearly a fifth of those deaths occurring in India alone. By the middle of the century, there will also likely be a 2–3.5% decline in global GDP, or about US$100 trillion [6].

The manufacturing-related AMR danger is concentrated in China and India, which together generate almost 80% of the antibiotics sold worldwide [1]. Antibiotic-resistant bacteria were discovered at 16 out of 34 examined locations in a 2016 field study of wastewater from three significant Indian manufacturing hubs: Hyderabad, New Delhi, and Chennai [7]. A 10 °C increase in regional temperature was linked to 4.2%, 2.2%, and 2.7% increases in resistance among E. coli, Klebsiella pneumoniae, and Staphylococcus aureus, respectively, according to research conducted in the United States. Similarly, a 30-country European study found a similar association with carbapenem- and multidrug-resistant pathogens, indicating that current AMR projections may underestimate the future burden (as cited in [1].

There is still little direct proof that trace pharmaceutical concentrations in drinking water, which are far lower than therapeutic doses, cause quantifiable harm to people, and no research has shown a direct impact at common exposure levels. This does not negate the risk, either, as the long-term cumulative consequences of exposure to pharmacological combinations and their interactions with other pollutants are still poorly understood [2]. The most obvious indirect threat to human health is antimicrobial resistance (AMR), which increases the danger of performing antibiotic-dependent treatments including surgery, chemotherapy, and transplantation as resistant bacteria become more common (as noted in [1]).

6. Industry Responses and Green Chemistry

Several industry-led efforts show how manufacturers have responded. The 2012 introduction of Centrient Pharmaceuticals' PureActives® enzymatic platform, which uses enzymes that couple side chains at room temperature without the use of harsh solvents or energy-intensive heating, almost halves the number of steps needed to produce beta-lactam antibiotics compared to the traditional 13-step process. When compared to traditional manufacturing, an internal life-cycle study showed a 63% decrease in carbon footprint [8]. In response to a 2016 UN plea for collective AMR action, manufacturers formed the AMR Industry Alliance. In 2018, the group released a Common Manufacturing Framework that established baseline environmental requirements and quantified effluent-discharge targets for antibiotic production across member facilities.

Packaging and API synthesis were the primary drivers of pharmaceutical environmental impact across multiple life-cycle assessments, according to a 2025 systematic review using PRISMA methodology that covered ten high-quality studies published between 2020 and 2025. Packaging-related energy use was the single largest cost driver in one product's life cycle, while green chemistry optimisation of a painkiller's synthesis route increased yield and reduced waste. In certain processes, switching to renewable energy sources like solar power reduced energy-related environmental expenses by 22%,

and switching from batch to continuous manufacturing decreased waste production and energy usage [10].

In the late 1990s, green chemistry—the reduction or elimination of hazardous materials in the design, production, and use of chemical compounds—was formalised through twelve guiding principles, which were later supplemented by twelve principles of green engineering. Together, these principles now serve as the foundation for the majority of industry initiatives to lessen the environmental impact of manufacturing (as cited in [1]). Since solvents make up between 80 and 90 percent of the mass used in pharmaceutical synthesis and are one of the biggest sources of pollution in the industry, a number of businesses now offer solvent-selection guidelines to assist chemists in selecting less hazardous substitutes. Complementary advancements include continuous production, which uses less energy, waste, and floor space than batch processing; biocatalysis, which uses enzymes under milder circumstances; and one-pot processes, which reduce purification stages and solvent consumption. Standardised green metrics

such as the E-factor (mass of waste per unit of product) and atom economy — are increasingly used to benchmark these interventions [10].

Table 2. Selected verified interventions and their reported environmental outcomes [8, 9, 10, 2].

Intervention	Lead actor(s)	Reported outcome
Enzymatic (PureActives®) antibiotic synthesis	Centrient Pharmaceuticals	63% lower carbon footprint vs. traditional route
Common Manufacturing Framework — effluent discharge targets	AMR Industry Alliance (13+ member companies)	Quantitative, science-based PNEC discharge limits adopted
Renewable energy in manufacturing	Multiple manufacturers (systematic review)	22% lower energy-related environmental cost
Batch → continuous manufacturing	Multiple manufacturers (systematic review)	Reduced energy use and waste generation
Eco-prescription (‘Wise List’ / Kloka Listan)	Stockholm County Council, Sweden	Environmental persistence/toxicity integrated into prescribing
Redispensing platform (PharmaSwap)	Certified pharmacies, Netherlands	~1/5 of returned medicines redispensed

7. Waste Management, Take-Back Schemes and Eco-Prescription

The most effective interventions act before pharmaceuticals become waste at all: disease prevention to reduce medicine demand, personalised and precision medicine that reduces trial-and-error prescribing, and packaging sized to match treatment duration and dispensed quantity — a particular challenge in individually dosed treatments such as oncology, where vial-size mismatches routinely generate preventable waste [2].

Where waste does arise, take-back programmes run through pharmacies, one-day collection events or mail-back schemes offer an alternative to household disposal, keeping medicines out of landfill

leachate and sewage systems. Extended Producer Responsibility (EPR) legislation shifts funding and administrative responsibility for collection and disposal from taxpayers to manufacturers under a 'producer pays' principle, and is increasingly recommended as a policy tool for pharmaceutical waste generally [2].

Eco-prescription incorporates a drug's environmental persistence and toxicity alongside its clinical suitability among therapeutically equivalent options; Sweden's Stockholm County Council maintains an environmental classification system as part of its 'Wise List' (Kloka Listan) to support this practice. In the Netherlands, the PharmaSwap platform lets certified pharmacies resell undamaged, near-expiry medicines to other pharmacies, with roughly a fifth of returned medicines considered suitable for redispensing. Community pharmacists can reduce expired-product waste through stock rotation and first-in-first-out inventory management while educating patients at the point of dispensing; distributors can cut transport emissions by consolidating regional deliveries; and patients themselves benefit from non-judgemental education campaigns discouraging hoarding and clarifying proper disposal routes, which are a cost-effective complement to formal collection infrastructure [2].

8. Policy, Regulatory and Reporting Gaps

Progress is hampered by lax regulations and a lack of openness, despite increased attention from the scientific community and business community. Only 25 of the more than 200 businesses that comprise the global pharmaceutical market disclosed direct and indirect greenhouse-gas emissions during the last five years, and only 15 had done so since 2012 (as noted in [1]). There is currently no international standard that establishes legally enforceable limitations on antibiotic-manufacturing discharge, and regulation of wastewater discharge is still variable across jurisdictions (as stated in [10]).

Five policy directions emerge consistently from the reviewed literature:

- **Science-based emissions targets** — corporate targets aligned with the Paris Agreement (e.g., via the Science Based Targets initiative) alongside mandatory, standardised emissions reporting.
- **Value-chain accountability** — governmental and institutional purchasers using procurement power to reward manufacturers that meet sustainability and AMR-reduction criteria.
- **Compliance monitoring** — oversight of manufacturing, distribution and marketing practice, paired with incentives for compliant manufacturers and removal of incentives for non-compliant ones.
- **Investment in One Health** — funding for antimicrobial research, diagnostics, vaccines and alternatives that reduce dependence on antibiotics facing resistance.
- **Cross-sector collaboration** — closer cooperation between manufacturers, regulators, healthcare professional bodies, NGOs and research institutes to build enforceable, consistent standards [1, 10].

The World Health Organization's guidance on environmental aspects of good manufacturing practice — adopted as an annex to its GMP technical report series — represents one step toward such

harmonisation, giving manufacturers and inspectors a shared framework for managing antimicrobial and chemical contamination during production [11].

9. DISCUSSION: RESEARCH GAPS AND FUTURE DIRECTIONS

The research compiled here share a number of common shortcomings. Geographic bias is prevalent: reviews based on English-language, indexed databases typically over-represent findings from North America and Europe, while South and East Asian manufacturing clusters, which make up a significant portion of the world's API production, are still relatively understudied in peer-reviewed literature [10]. Company-to-company comparability is limited by the lack of industry standardisation in life-cycle assessment methodology, despite its growing use [10]. Because regulatory limits are usually defined for single chemicals rather than realistic mixtures, there is still scientific doubt regarding the long-term consequences of low-dose, multi-compound exposure on human health [2].

Promising directions for future work include standardised, mandatory sustainability and emissions reporting for producers of all sizes; expanded environmental monitoring around manufacturing clusters in developing countries; artificial-intelligence-assisted process optimisation combined with green chemistry to reduce the resource intensity of synthesis and packaging; and circular-economy strategies such as API recovery from effluent and pharmaceutical-packaging recycling [10].

This study itself has a methodological limitation: the reference list was limited to publicly available studies, reports, and reviews in order to ensure that all listed sources could be freely and permanently verified by readers. A number of regularly cited primary research on this subject are located behind subscription paywalls; in cases where their conclusions were still pertinent, they are only indirectly cited here through the open-access reviews that address them (marked "as cited in" throughout). For readers without institutional journal access, this enhances accessibility and repeatability; but, compared to a review with unlimited database access, the review relies more largely on a narrower range of open-access synthesis sources.

10. CONCLUSION

The environmental impact of pharmaceutical manufacturing spans carbon emissions comparable to, or exceeding, those of heavy industry; the dispersal of hundreds of active pharmaceutical substances through water, soil and sediment worldwide; and a meaningful contribution to the growing threat of antimicrobial resistance. These are best understood as three facets of a single underlying problem — reconciling the industry's purpose of protecting human health with the environmental cost of achieving that goal at global scale.

The evidence reviewed here shows that solutions exist and, in places, are already delivering results: enzyme-based manufacturing cutting carbon footprint by 63%, renewable-energy adoption reducing process-level environmental cost by up to 22%, and industry-wide effluent-discharge targets for antibiotic manufacturers. These gains remain far from universal, however: only a small fraction of

pharmaceutical companies report emissions, discharge standards vary widely between jurisdictions, and the underlying research base remains geographically concentrated. Standardised reporting, stronger international regulation, sustained investment in green chemistry, and closer collaboration across the health, environmental and regulatory sectors will be essential to bring the industry's operations into line with the planetary and public-health needs it exists to serve.

REFERENCES

1. Sharma, S., & Tiley, A. (2021). Environmental sustainability in the pharmaceutical industry. In *Climate Change and the Health Sector* (pp. 195–203). Routledge India. https://doi.org/10.4324/9781003190516-24
2. Paut Kusturica, M., Jevtic, M., & Trifunovic Ristovski, J. (2022). Minimizing the environmental impact of unused pharmaceuticals: Review focused on prevention. *Frontiers in Environmental Science, 10*, Article 1077974. https://doi.org/10.3389/fenvs.2022.1077974
3. WHO. (n.d.). *Antimicrobial resistance* [Fact sheet]. World Health Organization. Retrieved 2026, from https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance
4. Patneedi, C. B., & Prasadu, K. D. (2015). Impact of pharmaceutical wastes on human life and environment. *Rasayan Journal of Chemistry, 8*(1), 67–70. https://rasayanjournal.co.in
5. Yasir, A. A. (2017). Environmental impact of pharmaceuticals and personal care products. *Journal of Global Pharma Technology, 9*(9), 58–64.
6. Jonas, O. B., Irwin, A., Berthe, F. C. J., Le Gall, F. G., & Marquez, P. V. (2017). *Drug-resistant infections: A threat to our economic future* (Vol. 2, Final report). World Bank Group. https://documents1.worldbank.org/curated/en/323311493396993758/pdf/final-report.pdf
7. Changing Markets Foundation & Ecostorm. (2016). *Superbugs in the supply chain: How pollution from antibiotics factories in India and China is fuelling the global rise of drug-resistant infections*. Changing Markets Foundation. https://changingmarkets.org/report/superbugs-in-the-supply-chain/
8. Centrient Pharmaceuticals. (2017). *Centrient Pharmaceuticals sustainability report 2017*. Centrient Pharmaceuticals Global Communications. https://www.centrient.com/sites/default/files/files/Sustainability/Centrient_SustainabilityReport_2017_web.pdf
9. AMR Industry Alliance. (2018). *Responsible use of antibiotics: Common antibiotic manufacturing framework for tackling AMR*. AMR Industry Alliance Secretariat. https://www.amrindustryalliance.org/wp-content/uploads/2018/02/AMR_Industry_Alliance_Manufacturing_Framework.pdf
10. Eshun, J., & Odamtten, M. (2025). Environmental sustainable performance in the pharmaceutical industry: A systematic review of literature. In *Proceedings of the International Conference on*

Engineering, Science, and Urban Sustainability (ICESUS 2025) (Advances in Engineering Research, pp. 347–362). Atlantis Press. https://doi.org/10.2991/978-94-6463-970-4_22

11. WHO. (2020). Points to consider for manufacturers and inspectors: Environmental aspects of manufacturing for the prevention of antimicrobial resistance (Annex 6). In *WHO Expert Committee on Specifications for Pharmaceutical Preparations: Fifty-fourth report* (WHO Technical Report Series, No. 1025). World Health Organization. https://cdn.who.int/media/docs/default-source/medicines/norms-and-standards/guidelines/trs1025/trs1025-annex6.pdf
12. Aus der Beek, T., Weber, F.-A., Bergmann, A., Hickmann, S., Ebert, I., Hein, A., & Küster, A. (2016). Pharmaceuticals in the environment: Global occurrence and potential cooperative action under SAICM (UBA Texte 67/2016). *Umweltbundesamt (German Environment Agency).* https://www.umweltbundesamt.de/sites/default/files/medien/1968/publikationen/iww_abschlussbericht_saicm_arzneimittel_final.pdf
13. Lenzen, M., Malik, A., Li, M., Fry, J., Weisz, H., Pichler, P.-P., Chaves, L. S. M., Capon, A., & Pencheon, D. (2020). The environmental footprint of health care: A global assessment. *The Lancet Planetary Health, 4*(7), e271–e279. https://doi.org/10.1016/S2542-5196(20)30121-2
14. Klein, E. Y., Van Boeckel, T. P., Martinez, E. M., Pant, S., Gandra, S., Levin, S. A., Goossens, H., & Laxminarayan, R. (2018). Global increase and geographic convergence in antibiotic consumption between 2000 and 2015. *Proceedings of the National Academy of Sciences, 115*(15), E3463–E3470. https://doi.org/10.1073/pnas.1717295115
15. Wilkinson, J. L., Boxall, A. B. A., Kolpin, D. W., et al. (2022). Pharmaceutical pollution of the world's rivers. *Proceedings of the National Academy of Sciences, 119*(8), e2113947119. https://doi.org/10.1073/pnas.2113947119
16. Oaks, J. L., Gilbert, M., Virani, M. Z., Watson, R. T., Meteyer, C. U., Rideout, B. A., Shivaprasad, H. L., Ahmed, S., Chaudhry, M. J. I., Arshad, M., Mahmood, S., Ali, A., & Khan, A. A. (2004). Diclofenac residues as the cause of vulture population decline in Pakistan. *Nature, 427*, 630–633. Free full text: https://pubs.usgs.gov/publication/1003726
17. World Health Organization. (2015). *Global action plan on antimicrobial resistance.* WHO. https://www.who.int/publications/i/item/9789241509763
18. O'Neill, J. (2016). *Tackling drug-resistant infections globally: Final report and recommendations.* Review on Antimicrobial Resistance, HM Government and Wellcome Trust. https://amr-review.org/sites/default/files/160518_Final%20paper_with%20cover.pdf
19. Kanakaraju, D., Glass, B. D., & Goh, P. S. (2025). Advanced oxidation process-mediated removal of pharmaceuticals from water: A review of recent advances. *Environmental Science and Pollution Research, 32*(24), 14316–14350. https://doi.org/10.1007/s11356-025-36547-5

20. Kurul, F., Doruk, B., & Topkaya, S. N. (2025). Principles of green chemistry: Building a sustainable future. *Discover Chemistry, 2*, Article 68. https://doi.org/10.1007/s44371-025-00152-9
21. 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
22. MacFadden, D. R., McGough, S. F., Fisman, D., Santillana, M., & Brownstein, J. S. (2018). Antibiotic resistance increases with local temperature. *Nature Climate Change, 8*, 510–514. https://doi.org/10.1038/s41558-018-0161-6
23. McGough, S. F., MacFadden, D. R., Hattab, M. W., Mølbak, K., & Santillana, M. (2020). Rates of increase of antibiotic resistance and ambient temperature in Europe: A cross-national analysis of 28 countries between 2000 and 2016. *Eurosurveillance, 25*(45), 1900414. https://doi.org/10.2807/1560-7917.ES.2020.25.45.1900414
24. Welton, T. (2015). Solvents and sustainable chemistry. *Proceedings of the Royal Society A, 471*(2183), 20150502. https://doi.org/10.1098/rspa.2015.0502
25. Dzidzornu, E. D., Cherian, J. J., D'souza, J., Pandit, J. M., Bernal, M., Radovan, D., & von Bruchhausen, T. (2023). Ecopharmacovigilance: A review of cause, impact, and remedies. *Medical Writing, 32*(1). https://journal.emwa.org/clinical-trials/pharmacovigilance/
26. Kenyon, C. (2022). Concentrations of ciprofloxacin in the world's rivers are associated with the prevalence of fluoroquinolone resistance in Escherichia coli: A global ecological analysis. *Antibiotics, 11*(3), 417. https://doi.org/10.3390/antibiotics11030417
27. Heeley, J., Boobier, S., & Hirst, J. D. (2024). Solvent flashcards: A visualisation tool for sustainable chemistry. *Journal of Cheminformatics, 16*, Article 61. https://doi.org/10.1186/s13321-024-00854-9
28. Harrison, S., Barnett, C., Short, S., Uluseker, C., Silva, P. V., Pavlaki, M. D., Roberts, S., Vieira, M., Lofts, S., Loureiro, S., & Spurgeon, D. J. (2025). Continuous improvement towards environmental protection for pharmaceuticals: Advancing a strategy for Europe. *Environmental Sciences Europe, 37*, Article 128. https://doi.org/10.1186/s12302-025-01180-z
29. Davey, C. J. E., Dubey, A., Keutmann, P., ter Laak, T. L., de Senerpont Domis, L., & van Wezel, A. P. (2025). Wastewater remediation of pharmaceuticals with ozone and granular active carbon: A risk-driven approach. *Environmental Science: Water Research & Technology, 11*, 2986–3000. https://doi.org/10.1039/D5EW00600G
30. United Nations Environment Programme. (2022). *Environmental dimensions of antimicrobial resistance: Summary for policymakers.* UNEP. https://wedocs.unep.org/bitstream/handle/20.500.11822/38373/antimicrobial_R.pdf