Ecological Resilience in The Face Of AMR: Strategies for A Sustainable Future

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***Abstract*—Background: Antimicrobial resistance (AMR) is a global health crisis with profound environmental consequences. Resistant microorganisms and antimicrobial residues enter ecosystems through pharmaceutical effluent, livestock runoff, hospital waste, and municipal sewage, thereby compromising ecological integrity and amplifying resistance pathways.**

Methodology: This descriptive review combines a structured literature survey (PubMed, Scopus, Web of Science, and Google Scholar, 2000–2025) with a qualitative analysis of environmental regulatory frameworks administered by the Ministry of Environment, Forest and Climate Change and the Pollution Control Boards, interpreted through a stakeholder-engagement framework. Key Findings: Pharmaceutical manufacturing effluent, hospital wastewater, livestock operations, and untreated sewage are the principal emission sources, delivering antibiotic residues, resistant bacteria, and mobile resistance genes to water, soil, and possibly air. Regulatory gaps persist in developing countries such as India, where pollution-control norms depend on conventional parameters (BOD, COD, TSS) and lack integration with AMR surveillance and One Health frameworks; antibiotic-specific effluent limits have not been finalized. Conclusion: Advancing ecological resilience requires adaptive regulatory models, risk-based monitoring, advanced effluent treatment at source, strengthened intersectoral collaboration, and formal recognition of AMR determinants as environmental pollutants. A phased implementation roadmap is proposed.

***Index Terms*—antimicrobial resistance; ecological resilience; One Health; Pollution Control Board; environmental governance; pharmaceutical effluent; antibiotic resistance genes**

I. INTRODUCTION

Antimicrobial resistance (AMR) is now considered one of the most serious threats to global health, food security, and sustainable development. A systematic analysis for 2019 estimated that bacterial AMR was the direct cause of approximately 1.27 million deaths that year and was associated with approximately 5 million deaths worldwide [1]. Long-term projections of mortality and economic burden remain debated, yet they have been used consistently to argue that the cost of inaction will be enormous [2]. The World Health Organization's Global Action Plan framed AMR as a problem that cannot be solved within clinical medicine alone [3]. Between 2000 and 2015, global antibiotic consumption rose by roughly two-thirds, with the steepest increases in low- and middle-income countries (LMICs) [4], while a large share of the antimicrobials produced worldwide is used in food-producing animals [5].

For many years, AMR research focused on hospitals and communities. It is now clear that the environment is not merely a bystander. Soil, surface water, sediments, and wastewater systems simultaneously serve as reservoirs of resistance genes, as conduits for the transmission of resistant bacteria and genes, and as ecological arenas in which new resistance combinations are formed and selected [6,7]. Unlike conventional chemical pollutants, antibiotic-resistant bacteria (ARB) can multiply, and antibiotic resistance genes (ARGs) can be transferred among unrelated bacteria through mobile genetic elements. The consequences of a single emission event may therefore amplify with distance and time rather than diminish [8,9].

Three emission streams are especially important: effluent from pharmaceutical manufacturing, wastewater from hospitals and other healthcare facilities, and runoff from livestock, poultry, and aquaculture operations. Each stream releases active pharmaceutical ingredients (APIs), resistant organisms, or both into the receiving environment [10–12]. India sits at the confluence of all three. It is one of the world's largest producers of generic

medicines and bulk drugs, a very large consumer of antibiotics, and a country where sanitation and effluent-treatment infrastructure have not kept pace with industrial and urban growth [13,14]. Studies near bulk-drug manufacturing clusters have recorded some of the highest antibiotic concentrations ever measured in environmental waters [15], and the identification of carbapenems genes in the environment of Indian cities has heightened concern over the international spread of resistance [16].

Despite this evidence, environmental regulation in many countries still relies on conventional parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS). These parameters were designed to detect organic load and particulates, not the biological and pharmacological properties that make AMR hazardous [17].

India's National Action Plan on AMR acknowledged the environmental dimension of the problem [18], yet the routine monitoring protocols of the Pollution Control Boards (PCBs) generally do not include antibiotic residues, ARB, or ARGs. This gap between the scale of the environmental hazard and the scope of governance instruments is the motivation for this review.

1.1 Rationale

This review situates AMR within an ecological and regulatory framework, moving the discussion beyond the conventional biomedical perspective. Earlier reviews have examined the occurrence and fate of antibiotics and ARGs in wastewater, soil, and water [19–22], the Indian situation, and the relevance of AMR to environmental regulators [23].

What has been lacking is a synthesis that links the emission sources documented in the scientific literature to the specific regulatory instruments of the Indian PCB system, tests them against emerging international practice, and converts the comparison into an actionable roadmap. By integrating microbiology, environmental science, and policy analysis, this paper aims to support a national roadmap for environmental AMR control and to strengthen India's contribution to the global One Health agenda [24,25].

1.2 Objectives

The primary objectives of this review are:

- To develop an integrated framework that formally recognizes AMR determinants as environmental pollutants within existing institutional mechanisms;
- To map the principal emission sources (pharmaceutical manufacturing effluent, hospital waste, and livestock runoff) and assess their impacts on water, soil, and air media;
- To assess regulatory alignment by critically examining PCB protocols against emerging global best practices;
- To formulate science-based policy recommendations to strengthen environmental governance; and
- To enhance long-term ecological resilience by advancing One Health principles and intersectoral collaboration.

II. METHODOLOGY

This study is a descriptive, narrative review that combines a structured literature survey with qualitative policy analysis. The analytical workflow proceeded in three interlinked stages: (i) analysis of legislation, guidelines, and scientific evidence; (ii) identification of regulatory gaps and overlaps; and (iii) translation of the gaps into actionable policy reforms based on a stakeholder-perspective framework. No primary human-subject data were collected.

2.1 Literature Search Strategy

Peer-reviewed literature was identified from PubMed, Scopus, Web of Science, and Google Scholar. Search terms, combined using Boolean operators, included “antimicrobial resistance”, “antibiotic resistance genes”, “environment”, “pharmaceutical effluent”, “hospital wastewater”, “livestock”, “wastewater treatment”, “regulation”, and “India”. Publications from 2000 to 2025 were prioritized, and older landmark papers were retained where they established a concept. Grey literature, including reports of the World Health Organization (WHO), the United Nations Environment Programme (UNEP), the Quadripartite organizations, and Indian ministries, was obtained from official websites. Articles were included if they concerned the environmental release, occurrence, selection, transmission, or regulation of

antimicrobial residues, ARB, or ARGs; purely clinical studies lacking an environmental component were excluded.

2.2 Regulatory Policy Review

A policy analysis was conducted of the environmental regulatory frameworks, legislation, guidelines, and operating protocols administered by the Ministry of Environment, Forest and Climate Change (MoEFCC) and the Central and State Pollution Control Boards, with attention to structural gaps, regulatory blind spots, and administrative overlaps in addressing antimicrobial discharge [26–28]. These were compared with international instruments and guidance documents [29–32].

2.3 Stakeholder Perspective Synthesis

To enrich the legal and technical analysis, a framework based on semi-structured interviews and focus-group discussions was evaluated as a model for capturing the perspectives of four groups: (i) regulatory authorities and policy-makers; (ii) environmental scientists and microbiologists; (iii) healthcare workers and hospital administrators; and (iv) pharmaceutical industry experts and waste-management engineers. In this review, the framework was applied as an analytical lens to published stakeholder analyses and policy documents rather than to new interview data.

2.4 Descriptive Synthesis

To organize the findings, descriptive methods were used, including a frequency-based classification of evidence by source type, environmental medium, and regulatory instrument. Because the included studies differ widely in design, analytical methods, and units, no quantitative meta-analysis was performed; the results are presented as a qualitative synthesis in the tables and figure below.

III. AMR AS AN ENVIRONMENTAL PROBLEM: CONCEPTUAL BACKGROUND

3.1 Global Burden and Driving Factors

The burden of AMR is unevenly distributed. The highest mortality rate attributable to bacterial AMR was estimated for western sub-Saharan Africa, while South Asia also bears a very heavy burden. A multivariable cross-country analysis suggested that variation in resistance levels was explained more by governance quality, sanitation, and infrastructure than by antibiotic consumption alone [33]. This is a notable finding for environmental policy, because it implies that preventing environmental transmission through better wastewater management and sanitation may be as important as prudent prescribing. The same reasoning underlies the One Health approach, in which the human, animal, and environmental sectors are interdependent in the emergence and spread of resistance [34].

3.2 The Environmental Resistome: Natural and Anthropogenic Components

Resistance is an ancient phenomenon. Resistance determinants have been recovered from 30,000-year-old permafrost sediments [35], and soil bacteria carry diverse resistomes that overlap with those of human pathogens [36,37]. The environment therefore holds a large natural reservoir of genes that can be activated. What has changed over the past century is the intensity of human-driven selection and dissemination. Archived soils from the Netherlands show an increase in ARG abundance since the 1940s, coinciding with antibiotic use [38], and a recent review emphasized that human activities, including faecal and industrial pollution, are major drivers of ARG abundance in many settings. In many human-impacted environments, a large share of the ARG signal can be explained by faecal pollution alone [39], underscoring the importance of sanitation as an AMR intervention.

3.3 Selection, Co-selection, and Gene Transfer

Three processes link environmental pollution to the evolution of resistance. First, antibiotic residues can select for resistant bacteria at concentrations far below those needed to inhibit susceptible strains. Experiments have shown selection at a fraction of the minimum inhibitory concentration (MIC) [40,41], and this evidence was used to derive predicted no-effect concentrations for resistance selection (PNEC-MIC) for 111 antibiotics [42]. Second, co-selection by non-antibiotic agents such as heavy metals can maintain multidrug-resistance plasmids even in the absence of antibiotics [43]. Third, horizontal gene transfer mediated by integrons, plasmids, and transposons allows ARGs to move between environmental and clinical bacteria. The class 1 integron-integrase gene (*intI1*) has been proposed as an indicator of

anthropogenic pollution because it is abundant in impacted environments and easily measured. Together, these processes explain why even low-level, long-term contamination is relevant to regulators [44].

IV. EMISSION SOURCES AND PATHWAYS: KEY FINDINGS

Resistant microorganisms and sub-lethal concentrations of antimicrobial agents enter environmental media through several principal vectors. Figure 1 summarizes the main emission sources, transport pathways, and receiving media discussed in this section, and Table 1 summarizes representative evidence for each source.

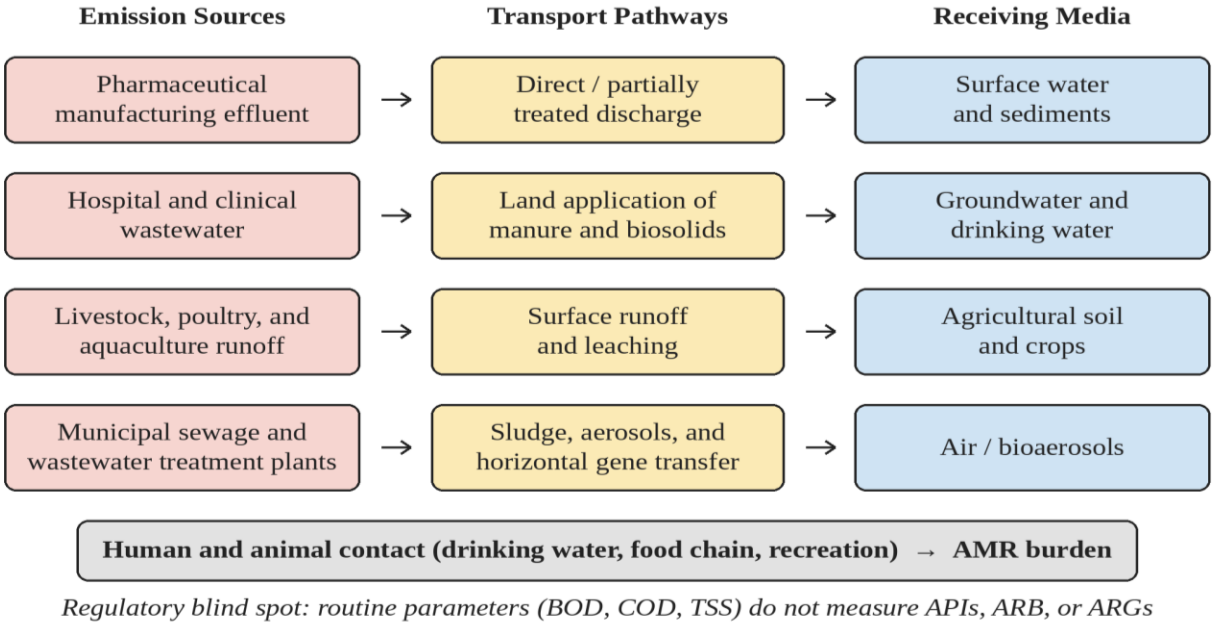

Figure 1. Conceptual framework of AMR emission sources, transport pathways, receiving environmental media, and the resulting exposure of humans and animals. The regulatory blind spot arises because routine effluent parameters do not measure APIs, ARB, or ARGs (original schematic prepared by the authors) [45,46]

4.1 Pharmaceutical Manufacturing Effluent

Direct discharge of untreated or partially treated wastewater from antibiotic manufacturing is the most concentrated source of APIs in the environment. In a historical study of a treatment plant serving approximately 90 bulk-drug manufacturers near Hyderabad, fluoroquinolone concentrations in the effluent were in the milligram-per-litre range, exceedingly even the levels found in the blood of patients undergoing treatment. Subsequent work documented contamination of surface water, groundwater, and drinking water in the same region. Metagenomic analysis of downstream river sediments revealed a marked enrichment of ARGs, as well as of integrases and transposases that mediate gene transfer, and fluoroquinolone resistance (*qnr*) genes were found in water, soil, and the faecal flora of residents. Functional metagenomics later identified a novel mobile carbapenem-hydrolysing beta-lactamase in sediments contaminated by antibiotic-production waste, and a study from the Hyderabad region linked effluent pollution to extended-spectrum beta-lactamase- and carbapenemase-producing pathogens in the local environment [47].

Table 1. Principal environmental sources of AMR determinants and representative evidence [48-52].

Source	Principal contaminants	Representative evidence
Pharmaceutical manufacturing effluent	High concentrations of APIs (e.g., fluoroquinolones); ARB; ARGs and mobile genetic elements	Milligram-per-litre fluoroquinolone levels in treated effluent near Hyderabad; enrichment of ARGs and gene-transfer elements in river sediments; novel mobile carbapenemase from contaminated sediments.

Hospital and healthcare-facility wastewater	Antibiotic residues and metabolites; disinfectants; MDR pathogens	Persistence and gene exchange of resistant bacteria in hospital sewage networks; antibiotics and resistant bacteria in water near a hospital in Ujjain, India
Livestock, poultry, and aquaculture	Veterinary antibiotics; resistant gut bacteria; ARGs; metals (co-selection)	Diverse and abundant ARGs on pig farms; spread to soil through manure application; global trends in animal antimicrobial use
Municipal sewage and WWTPs	Mixed residues from households, hospitals, and industries; ARB and ARGs	WWTPs as hotspots of emission; European effluent ARG profiles mirror clinical resistance resistance genes to last-resort antibiotics in Indian river sediments
Agricultural soil (receiving medium)	Residues from manure and biosolids; resistant soil bacteria; ARGs	Increasing ARG abundance in soils archived since the 1940s

4.2 Hospital and Healthcare-Facility Wastewater

Hospital effluents are concentrated streams containing excreted antibiotics and their metabolites, disinfectants, and multidrug-resistant (MDR) pathogens. Resistant bacteria and ARGs can persist in hospital sewage networks and exchange genes, and conventional treatment does not eliminate them [53]. Early work showed that antibiotic excretion from hospitals and households can promote resistance in wastewater bacteria [54]. In India, antibiotics and resistant bacteria were found in water associated with a hospital in Ujjain, and environmental sampling in New Delhi detected the *bla*NDM-1 gene in public tap-water and seepage samples, highlighting that inadequate sanitation allows clinically important genes to circulate in the urban environment. Regulatory attention to this source has so far focused on the segregation and pre-treatment of infectious waste rather than on routine monitoring of AMR indicators in liquid effluent [55].

4.3 Livestock, Poultry, and Aquaculture Runoff

Globally, antimicrobial use in food animals was estimated at more than 60,000 tonnes in 2010, with a projected increase of about two-thirds by 2030. Because many veterinary antibiotics are poorly absorbed, a large fraction is excreted unchanged and enters manure and slurry. Diverse and abundant ARGs were found on Chinese pig farms, markedly enriched compared with control sites. When manure is applied to agricultural land, antibiotic residues, resistant bacteria, and ARGs reach the soil and can then reach surface water and groundwater through runoff and leaching. Policy analyses suggest that limiting antimicrobial use in animals can reduce consumption without necessarily harming productivity, but the environmental dimension, including manure-management standards, remains largely absent from the regulatory frameworks of LMICs [56].

4.4 Municipal Sewage and Wastewater Treatment Plants

Municipal wastewater treatment plants (WWTPs) receive mixed inputs from households, hospitals, and industries and are widely regarded as hotspots for the release of antibiotics, ARB, and ARGs into the environment. A study of 62 European WWTPs found that ARG profiles in effluents mirror regional clinical resistance patterns, and metagenomic analysis of sewage from cities worldwide showed that ARG abundance varies systematically with region and sanitation. These findings underpin the proposal to use sewage as a medium for AMR surveillance. Where treatment is absent or inadequate, as is common in many Indian towns, raw sewage is a significant route by which resistance determinants reach rivers, as Indian studies of river sediments and sewage treatment plants indicate [57].

4.5 Impacts on Water, Soil, and Air Media

In aquatic systems, antibiotic and ARG contamination has been documented from small streams to continental-scale estuaries. Sediments are particularly important because they accumulate residues and gene-carrying bacteria and can release them again. Indian rivers affected by untreated urban waste carry resistance genes against last-resort antibiotics, seasonal variation in antibiotic residues and resistant *Escherichia coli* has been described for the Kshipra River, and in the upper Ganges the abundance of *bla*NDM-1 was found to increase with seasonal mass pilgrimages. In terrestrial systems, irrigation with

manure, biosolids, and wastewater delivers residues and ARGs to soil, from where they can enter crops and the food chain. Evidence for the air medium (bioaerosols from wastewater aeration, animal housing, and waste burning) is comparatively limited, which is itself a research and regulatory gap. Quantitative risk frameworks must also acknowledge that abundance does not translate directly into human health risk; what matters is the combination of gene mobility, host pathogenicity, and likelihood of exposure [58].

V. THE INDIAN SCENARIO: REGULATORY INERTIA IN A DEVELOPING NATION

5.1 Evidence of the Environmental AMR Burden in India

India has been described as a country where high antibiotic consumption, uncontrolled availability, inadequate sanitation, intensive animal production, and a vast pharmaceutical sector coexist. A review of the Indian environmental literature concluded that data on antibiotics and ARGs in water, soil, and food are scarce, fragmented, and obtained with non-standardized methods. National surveillance of AMR in LMICs, including India, remains primarily clinical and of limited coverage [59].

5.2 Regulatory Frameworks and Gaps

The analysis shows that monitoring of industrial and healthcare waste is structurally limited in developing countries such as India. Pollution-control norms lack formal integration with biological AMR surveillance. The standard parameters monitored by regulatory bodies (BOD, COD, TSS, and the like) fail to capture the spread of ARB and ARGs in the receiving environment. As a result, One Health principles remain conceptually isolated rather than embedded in environmental governance. India's NAP-AMR 2017–2021 acknowledged environmental contamination and called for action, and the Bio-Medical Waste Management Rules, 2016 require the pre-treatment of laboratory and microbiological waste and prescribe standards for the treatment and disposal of healthcare waste. Nevertheless, neither instrument sets enforceable limits for antibiotic residues or resistance indicators in effluent [60].

An important regulatory step was the MoEFCC draft notification of January 2020, which proposed effluent standards for antibiotic residues from bulk-drug and formulation units. Revised effluent standards for the pharmaceutical industry were subsequently notified in August 2021; however, according to submissions made by pollution-control authorities during proceedings before the National Green Tribunal, the antibiotic-specific residue limits proposed in the draft could not be finalized. The policy trajectory therefore reflects both the political acceptance of the problem and the difficulty of translating it into enforceable, measurable standards. Challenges include the absence of validated analytical methods for routine laboratory use, uncertainty about science-based limit values, and concerns about compliance costs for small manufacturers [61].

5.3 Comparison with Global Practices

International practice is moving toward explicit recognition of antimicrobial pollution. In 2024, the WHO issued guidance on wastewater and solid waste management for antibiotic manufacturing, including science-based targets for discharge. These build on the PNEC-MIC approach to resistance selection and complement industry initiatives such as the AMR Industry Alliance's manufacturing framework [62]. In the European Union, the recast Urban Wastewater Treatment Directive introduces a requirement for quaternary treatment at large plants, extended producer responsibility for pharmaceutical and cosmetics producers, and monitoring that includes AMR. The EU environmental risk assessment guideline for medicinal products requires environmental data at the marketing-authorization stage. The UNEP and the Quadripartite One Health Joint Plan of Action explicitly call for environmental action on AMR. Table 2 compares selected instruments by their relevance to the Indian context.

Table 2. Comparison of selected international and Indian instruments relevant to environmental AMR governance [63].

Instrument / Guidance	Scope	AMR-related provisions	Relevance or gap for India
WHO guidance on wastewater and solid waste management for antibiotic manufacturing (2024)	Global	Science-based targets for antibiotic discharge; waste-management practices	Technical basis for Indian standards; adaptation and laboratory capacity required

PNEC-MIC resistance-selection limits	Scientific	Predicted no-effect concentrations for 111 antibiotics	Risk-based threshold values; sensitive analytical methods required
AMR Industry Alliance manufacturing framework (2018)	Voluntary, industry	Principles for responsible antibiotic manufacturing and emission assessment	Voluntary; limited to participating companies
Directive (EU) 2024/3019 [30]	European Union	Quaternary treatment; extended producer responsibility; monitoring including AMR	Model for municipal treatment and producer responsibility; infrastructure and financing differ
EMA environmental risk assessment guideline	European Union	Environmental risk data for medicinal products at the time of authorization	To the authors' knowledge, no equivalent routine requirement exists in India
MoEFCC draft (2020) and pharmaceutical effluent notification (2021)	India	Proposed limits for antibiotic residues; revised conventional effluent standards	Antibiotic-specific limits not final, according to submissions before the National Green Tribunal
Bio-Medical Waste Management Rules, 2016	India	Pre-treatment of microbiological waste; treatment and disposal standards	No AMR indicators for liquid effluent
NAP-AMR 2017–2021	India	Recognition of the environmental dimension of AMR	No enforceable environmental targets or indicators
UNEP report and One Health Joint Plan of Action	Global	Call for environmental action on AMR under One Health	Non-binding; translation into domestic law and monitoring required

VI. MONITORING, SURVEILLANCE, AND RISK ASSESSMENT

Measurable indicators are essential for a credible regulatory response. At the level of manufacturing and healthcare effluents, direct chemical measurement of priority antibiotics against risk-based thresholds such as PNEC-MIC values is feasible by liquid chromatography–mass spectrometry and provides a clear compliance endpoint. For biological indicators, *intI1* has been proposed as a low-cost proxy for anthropogenic pollution, and culture-based quantification of selected resistant indicator organisms such as extended-spectrum beta-lactamase-producing *E. coli* can be incorporated into existing microbiology laboratories. At the population level, wastewater-based surveillance and metagenomic sequencing provide an integrated view of resistance patterns in communities [64].

Monitoring should be embedded in a structured risk-assessment logic. A human-health risk-assessment framework for environmental resistance has been proposed that considers sources, the fate of genes and organisms in the environment, and the likelihood of human exposure and transmission. Because the relationship between abundance and risk is non-linear, risk-based prioritization, such as a focus on mobile genes against critically important antibiotics in settings with human exposure, is more appropriate than attempting to regulate every gene. Environmental regulators have also been urged to harmonize sampling and analytical protocols, define a minimum set of indicators, and build data repositories that can be linked to clinical surveillance [65].

VII. PROPOSED STRATEGIES FOR ECOLOGICAL RESILIENCE

A multi-level regulatory roadmap is needed to bridge the gap between environmental risk and governance. The following strategies are consistent with the evidence discussed above and with international recommendations [66].

7.1 Integrated Pollution Frameworks

Active antimicrobial discharges and resistance determinants should be formally classified as environmental pollutants under the Environment (Protection) Act and associated rules, so that PCBs have a clear legal mandate for monitoring and enforcement. Priority antibiotics should be listed with discharge limits derived from ecological and resistance-selection thresholds. Finalizing the antibiotic-residue standards proposed in 2020 would be a concrete first step. Manufacturers could additionally be required to disclose API emissions across the supply chain, consistent with voluntary industry frameworks [67].

7.2 Adaptive Regulatory Models

Because resistance patterns continue to evolve, regulation must be adaptive. Monitoring protocols should be reviewed periodically and revised in line with new epidemiological evidence, with provisions for emerging indicators and new analytical techniques. A phased approach could begin with chemical monitoring of the highest-risk facilities (bulk-drug clusters, large hospitals, intensive livestock units) and expand progressively to indicator organisms and ARG panels as laboratory capacity grows. Regulatory sandboxes and pilot programmes in high-risk catchments would generate local evidence before national-level scale-up [68].

7.3 Intersectoral Alliances

Formal data-sharing and steering networks linking environmental regulators, research institutions, healthcare networks, and industry should be established. Linking environmental monitoring with clinical surveillance would enable regulators to identify when environmental signals precede clinical outbreaks, and health authorities to understand environmental factors. Joint programmes of PCBs, state health departments, animal husbandry agencies, and agricultural universities could harmonize sampling, laboratory methods, and reporting, and the extended producer responsibility mechanisms applied in the EU could be evaluated for pharmaceutical producers in India [69].

7.4 Advanced Effluent Treatment Technologies

Deploying advanced treatment at the point of origin is one of the most effective ways of reducing emissions. Conventional activated-sludge processes remove antibiotics and ARGs incompletely, and a substantial load of both may remain in the effluent. Advanced oxidation processes (AOPs), including ozonation and UV-based processes, can degrade antibiotic residues and reduce ARGs, although performance depends on the water matrix, dose, and target gene, and energy and by-product aspects must be evaluated. Disinfection processes can inactivate ARB, but their effect on extracellular ARGs and the potential for regrowth must be managed [70]. Membrane bioreactors and optimized microbial filtration can add further barriers. For antibiotic manufacturers, source segregation, pre-treatment of high-concentration waste, and zero-liquid-discharge systems are especially relevant. Treatment upgrades should be prioritized according to risk rather than applied uniformly, beginning with manufacturing clusters and hospital effluents.

7.5 Implementation Roadmap

A phased roadmap is proposed to operationalize these strategies:

1. Short term (1–2 years): finalize antibiotic-residue effluent standards for bulk-drug and formulation units; validate and publish standardized analytical methods; and establish baseline monitoring programmes in known hotspots.
2. Medium term (3–5 years): extend monitoring to hospitals, large livestock operations, and major municipal WWTPs; include indicator organisms and *intI1* or equivalent markers; and establish a national environmental AMR data repository linked to clinical surveillance.
3. Long term (5–10 years): implement risk-based treatment upgrades, evaluate extended producer responsibility for pharmaceutical residues, and embed environmental AMR targets in successive national action plans and One Health forums.

VIII. CHALLENGES, LIMITATIONS, AND FUTURE PERSPECTIVES

Several obstacles lie in the way of implementation. First, analytical standardization is incomplete: methods for ARG quantification and for measuring antibiotics at ecologically relevant concentrations differ among laboratories, hindering comparability [6,17]. Second, for India, the evidence base is geographically concentrated in a few well-studied hotspots, and long-term time-series data are sparse [14,65]. Third, regulatory enforcement depends on laboratory capacity, trained personnel, and the financial resources of State PCBs, which vary widely. Fourth, there is legitimate concern about the cost burden on small and medium manufacturers and the potential effect on the availability of affordable medicines, which argues for phased implementation and technical assistance. Fifth, the translation of environmental abundance into human-health risk remains uncertain [62].

This review has its own limitations. As a narrative review, it is subject to selection bias, no formal quality assessment was applied to the included studies, and stakeholder perspectives were drawn from published

sources rather than from new primary data. The policy situation is changing rapidly, and the regulatory details discussed here should be verified against the latest official notifications. Future research should prioritize harmonized national surveys of antibiotics and ARGs in rivers, soil, and wastewater; evaluation of the cost-effectiveness of treatment upgrades under Indian conditions; quantitative exposure and risk models; and the use of metagenomic and wastewater-based surveillance as routine regulatory tools [7,56,57].

IX. CONCLUSION

Antimicrobial resistance is an urgent environmental challenge that demands integrated governance. This review highlights how industrial, agricultural, and clinical waste streams, combined with weak regulatory protocols, accelerate resistance pathways in environmental media.

Evidence from India and elsewhere shows that pharmaceutical effluent, hospital wastewater, livestock runoff, and untreated sewage carry antibiotic residues, resistant bacteria, and mobile resistance genes to rivers, soil, and ultimately people. Through a synthesis of policy analysis and stakeholder perspectives, this paper identifies critical gaps in current PCB frameworks, chiefly the absence of enforceable limits for antibiotic residues and of AMR indicators in routine monitoring.

Advancing ecological resilience requires a fundamental shift from purely biomedical interventions toward adaptive, One Health-aligned environmental governance. Formal recognition of AMR determinants as pollutants, risk-based monitoring, advanced treatment at source, and strengthened intersectoral collaboration are essential steps. Prioritizing ecological AMR management is a cornerstone of global public-health security and sustainable environmental stewardship.

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