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Socio-Ecological Drivers of Environmental Antibiotic Resistance and Public Health Vulnerability in Benin City, Nigeria: A Review

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ABSTRACT
Antimicrobial resistance (AMR) is a serious global public health problem, especially in urban areas of low- and middle-income countries, where environmental reservoirs can increase the spread of pathogens. The present review focuses on the socio-ecological determinants of environmental antibiotic resistance and its associated public health risks in the city of Benin in Nigeria. Using a socio-ecological model (SEM) and a One Health approach, peer-reviewed literature, academic dissertations and policy reports from 2000 to 2026 were systematically synthesized in the six core thematic domains of the One Health approach from PubMed, Scopus, Web of Science and Google Scholar. Informal distribution of antibiotics, non-prescription dispensing and partial course sales is possible because of the large number of patent medicine vendors (PMVs) operating without adequate regulatory oversight. Such practices and poor municipal waste management result in clear socio-ecological leakage points for pharmaceutical residues and multidrug-resistant organisms that enter drainage networks, soils and surface waters. For Benin City, spatial analytic techniques such as kernel density estimation and hotspot analysis are suggested to highlight any clustering of resistance profiles in high-density urban micro-environments, but this has not been done. The city of Benin needs integrated One Health strategies, integration of vendor stewardship, regulation of municipal waste, and local surveillance systems to mitigate environmental AMR.

Keywords: Antimicrobial Resistance, Benin City, Environmental Resistome, One Health, Patent Medicine Vendors, Public Health Vulnerability

INTRODUCTION

Antimicrobial resistance is a global public health emergency that significantly affects medical practices, patient outcomes and socio-economic development (Abdullahi *et al*., 2026; Alenzi *et al*., 2026). According to global estimates, bacterial AMR contributes to millions of deaths each year (Murray *et al*., 2022), and projection models predict that the number of deaths will increase in the coming years worldwide if effective measures for containment are not taken (Naghavi *et al*., 2024). In low- and middle-income countries (LMICs), where the distribution systems are poorly regulated (Klein *et al*., 2023), the consumption of antimicrobial agents has significantly increased. Structural vulnerabilities, such as poor health care facilities; a lack of diagnostic services; reduced water, sanitation and hygiene (WASH) services; and the widespread use of informal drug distribution systems, also contribute to the escalation of AMR in LMICs (Okeke *et al*., 2024; WHO, 2025). As a result, populations in areas such as Sub-Saharan Africa (SSA) are more severely affected by drug-resistant infections (Tadesse *et al*., 2017).

Extended-spectrum beta-lactamases (ESBL) and carbapenem-resistant gram-negative pathogens (CR-GNPs) are common in Sub-Saharan Africa and are part of the epidemiology of AMR (Sati *et al*., 2025; Ugbo *et al*., 2025). This ongoing healthcare treatment and trial-and-error use of antibiotics places high selection pressure on communicable diseases, which are highly endemic (Donkor *et al*., 2024; Sati *et al*., 2025; Ugbo *et al*., 2025). National-level surveillance in Nigeria has revealed high levels of resistance to primary therapeutic agents such as ampicillin, tetracycline and third-generation cephalosporins (Okeke *et al*., 2007; Ugbo *et al*., 2025), but there is no systematic documentation of the resistance profiles of these agents in Benin City (Donkor *et al*., 2024; Ugbo *et al*., 2025). In addition to clinical use, resistance determinants can also be introduced into local environments through community overuse, informal drug trade, and uncontrolled environmental discharge, all of which contribute to the development of resistance in the surrounding environment (Bengtsson-Palme *et al*., 2018; Larsson & Flach 2022).

The city of Benin, the capital of Edo State, represents intricate urban dimensions that are common to quickly expanding West African cities (Omoregie *et al*., 2024; Diala *et al*., 2025). The population in the city of Benin City has also been expanding at a rate that far exceeds its infrastructure development, resulting in significant gaps in the treatment of sewage, solid waste management and maintenance of the drainage network (Ndukwe & Ibrahim, 2024; Isokpehi *et al*., 2025). Typical tropical hydrological conditions characterized by seasonal floods and shallow groundwater tables provide an environment for the transport and persistence of environmental pollutants in cities (Diala *et al*., 2025). Furthermore, informal health outlets are the main source of health services for a large segment of the population (Adamu *et al*., 2020). A comprehensive synthesis is needed to understand the interactions among informal health-care practices, urban infrastructure deficits, the dissemination of molecular resistance, and spatial vulnerability in Benin City. This review highlights the socioecological drivers of environmental AMR and public health vulnerability in Benin to provide a basis for policy interventions for One Health and future empirical studies and to inform cities in West Africa facing similar challenges. It is the first synthesis specifically for Benin City, which combines the socio-ecological model with One Health principles to map the informal pharmaceutical distribution network, the dynamics of the environment's resistome, and spatial vulnerabilities. This synthesis goes beyond national-level reviews to highlight local vulnerabilities and identify city-specific action points to address them in the local context of Benin City's specific infrastructure and regulations.

MATERIALS AND METHODS

This review included peer-reviewed publications, academic dissertations and policy documents from institutions concerning antimicrobial resistance, environmental resistomes, informal pharmacies, and spatial health mapping in Sub-Saharan Africa, specifically in Nigeria and Benin City.

Search Strategy and Information Sources

The electronic databases, namely, PubMed, Web of Science, Google Scholar and Scopus, were systematically searched for articles using combination terms with Boolean operators: ("Antimicrobial Resistance" OR "AMR" OR "Resistome") and ("Socio-Ecological Model" OR "One Health") and ("Patent Medicine Vendors" OR "Informal Healthcare") and ("Benin City" OR "Nigeria"). The search focused on studies specific to Benin City; however, where no such data were available, broader Nigerian or West African studies were included.

Inclusion and Exclusion Criteria

To maximize the relevance of the literature to the urban LMIC environment, studies published from 2000 to 2026 that offered empirical data, theoretical frameworks, or methodological evaluations were selected (Chen *et al*., 2026). Studies were included if they contained primary or secondary data on antibiotic distribution, the prevalence of resistance genes, the effects of municipal wastes, or environmental contamination in West Africa. There were no non-English publications or articles that were not available in full-text or non-peer-reviewed commentaries without empirical support.

Data Extraction and Synthesis

The collected data were thematically synthesized in six thematic areas that included theoretical socio-ecological frameworks, informal healthcare delivery dynamics, environmental resistome molecular mechanisms, spatial vulnerability mapping methodology, methodological approaches and policy interventions. Data on prevalence, gene frequencies and consumption patterns were synthesized narratively, while qualitative information on regulatory and behavioural practices was included.

Socio-Ecological and One Health Frameworks in Environmental AMR

The socio-economic model (SEM) offers an analytical framework for understanding public health phenomena because of the dynamic interactions between systems at the individual, interpersonal, institutional, community, and public policy levels (Kilanowski, 2017). Traditional biomedical perspectives view AMR mostly as a clinical problem in which individuals are prescribed it by providers and adhering to it by patients, whereas SEM highlights AMR as a multilevel process influenced by wider socio-economic factors, cultural norms, healthcare systems and ecological environments (Kilanowski, 2017; Vors *et al*., 2026). Interpersonal relationships, economic barriers and local unstructured access to health care influence individual behaviour such as self-medication or treatment non-adherence (Auta *et al*., 2019). At the institutional and policy levels, antibiotic stewardship laws and regulations, definitions, and pharmaceutical waste management control the movement of antimicrobial agents between society and the environment (Yu *et al*., 2026).

In addition, the One Health conceptual approach explicitly links the operational dependency between human and animal health and surrounding terrestrial and aquatic ecosystems (Ramirez-Plascencia *et al*., 2025), complementing the SEM. Resistant microbial species and resistance-conferring genes are easily transferred between these domains via various mechanisms, such as agricultural runoff, wastewater effluent, direct human-to-animal contact and contaminated water distribution systems (Bengtsson-Palme *et al*., 2018). Environmental matrices are more than just passive receptors for chemical contaminants; they are dynamic reservoirs and mixing points of selection pressure and horizontal gene exchange. One health principle can be applied to the integration of SEM, leading to a comprehensive framework for the analysis of environmental AMR (Figure 1).

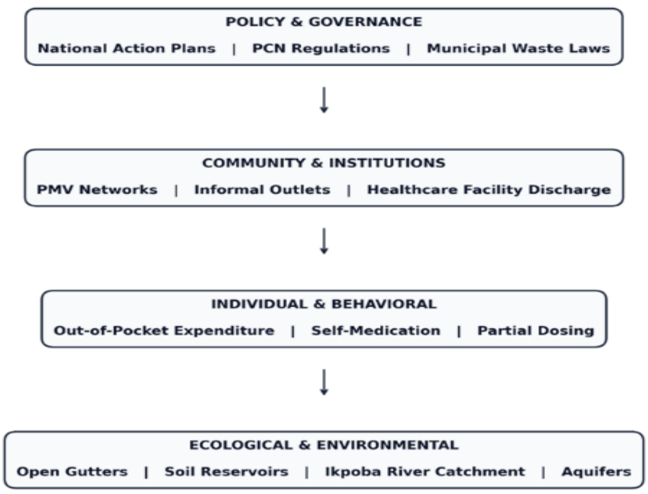

Figure 1: Socio-ecological and One Health Framework Illustrating Multilevel Drivers of Environmental Antimicrobial Resistance in Urban Settings

RESULTS AND DISCUSSION

Informal Healthcare Outlets and Socio-Ecological Conduits

The Nigerian healthcare delivery system is largely decentralized, with an important central element: the Patent Medicine Vendors (PMVs), who serve as the first point of contact for most Nigerian urban households (Adamu *et al*., 2020). PMVs, which are mostly designed to increase the availability of drugs in less-served areas, have since spread throughout urban areas with the ability to offer prompt drug sales at low prices without the need for formal clinical consultation or diagnostic testing (Auta *et al*., 2019; Adamu *et al*., 2020). The Pharmacists Council of Nigeria (PCN) regulates the statutory operations of PMVs and prescribes that they can only sell over the counter (OTC) patent medicines and are not allowed to dispense prescription-only medicines, including systemic antibiotics (PCN, 2022). However, empirical research shows that many individuals are not complying, partly because of a lack of financial resources for regulatory action, partly because of financial gain, and partly because of the high demand of consumers. (Auta *et al*., 2019; Adamu *et al*., 2020)

Consumer dependence on PMVs is determined by economic constraints, namely, out-of-pocket healthcare financing (Molobe & Odukoya 2021). Patients with financial difficulties often ask for 'broken blisters' (partial doses of antibiotics). To keep the business going and customers coming, vendors regularly meet these demands, and consumers end up being exposed to what amounts to subtherapeutic doses of antibiotics, which favour the growth of resistant strains of bacteria (Berendonk *et al*., 2015). Moreover, pharmaceutical waste disposal systems are not well established, and PMVs and households dispose of used, deteriorated or expired antibiotic stocks directly into municipal solid waste dumps or open earthen drainage channels (Molobe & Odukoya 2021). There is no documentation of the presence of active pharmaceutical ingredients, antibiotic residues, and enteric pathogens in the open gutters in Benin City drainage systems or in the reviewed literature, but these open gutters are hypothesized to be physical socio-ecological conduits that transport these compounds to the wider urban ecosystem (Rizzo *et al*., 2013; Larsson & Flach 2022). The key systemic drivers, vendor behaviours and environmental impacts of informal markets are summarized in Table 1.

Table 1: Socio-Ecological Drivers, Operational Practices, and Corresponding Environmental Health Impacts in informal Healthcare Markets

Systemic Driver	Operational Practice	Environmental/Health Outcome
Out-of-pocket financing	Partial dosing/"Broken blisters" sales	Sublethal selection pressure, bacterial resistance
PCN regulatory enforcement gaps	Non-prescription antibiotic sales	Community-wide antibiotic misuse
Absence of diagnostic testing	Empirical broad-spectrum dispensing	Accelerated intestinal resistome amplification
Suboptimal medical waste management	Uncontrolled pharmaceutical disposal in gutters	Direct soil and surface water chemical contamination

Environmental Resistome, Horizontal Gene Transfer, and Biomarkers

Aquatic and soil matrices represent active environmental resistome resulting from the presence of antibiotic residues (Eghomwanre *et al*., 2016; Larsson & Flach 2022). All the antibiotic resistance genes found in pathogenic, commensal and environmental microorganisms make up the environmental resistome. The "mobilome" is the sum of all the conjugative plasmids, transposons, insertion sequences, and integrons that disseminate these genes (Partridge *et al*., 2018; Eghomwanre & Amadasun, 2022). As explained in Figure 2, horizontal gene transfer (HGT) occurs very quickly in polluted urban environments through transformation, transduction, and conjugation. Furthermore, the high density of microbes in open drainage systems, high nutrient levels and subinhibitory concentrations of antimicrobials in these systems provide ideal conditions for plasmid transfer by conjugation in Benin City (Rizzo *et al*., 2013). These aquatic microenvironments are important for the transfer of clinically relevant ARGs, including ESBLs, which are either environmental saprophytes or human enteric pathogens (Gillings *et al*., 2015; Von Wintersdorff *et al*., 2016).

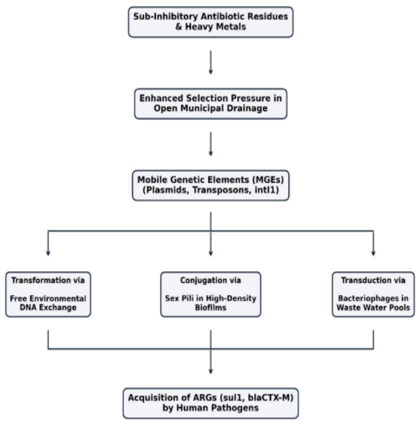

Figure 2: Pathways of Horizontal Gene Transfer and ARG Amplification within Urban Drainage Ecosystems

Spatial Epidemiology and Public Health Vulnerability Hotspots

Environmental AMR is not evenly distributed in the urban landscape but rather is concentrated in specific public health vulnerability hotspots (WHO, 2023). Structural factors such as population density, commercial trading areas, increased flood frequencies, and inconsistent sanitation facilities in Benin City are responsible for the spatial variability in resistance risk (Isokpelu *et al*., 2025). Rapid urbanisation has created very high-density informal settlements without the provision of latrines connected to sewerage networks, and the pit latrines are connected to shallow aquifers where they leak, while unchanneled municipal drains overflow during the rainy season (Oluwafemi *et al*., 2022; WHO, 2023).

Geographic information systems (GIS) and spatial statistics can be used to map and identify AMR hotspots in the environment. Geographic data, including the locations of PMV outlets and informal pharmacies as GPS coordinates, can be transformed into continuous density surfaces through kernel density estimation (KDE) to generate a density map of infrastructure for the commercial distribution of informal drugs (Oteri *et al*., 2021; Oluwafemi *et al*., 2022). Moreover, a hot spot analysis (Gi*) was performed to test spatial autocorrelation and to determine the resistance value clusters of bacterial isolates with significantly high resistance values, such as high multiple antibiotic resistance (MAR) indices. Spatial analysis methods such as KDE and Getis-Ord Gi may have been able to detect overlap between dense clusters of PMV businesses, open drainage intersections and flood-prone residential areas in Benin City, providing key exposures; however, these methods are not currently conducted or published in Benin City (Rizzo *et al*., 20213; Diala *et al*., 2025).

Discussion

Based on the primary literature and empirical findings reviewed thus far, it can be inferred that environmental antibiotic resistance in Benin is essentially a socioecological phenomenon; however, empirical findings from primary studies within the city are necessary (Kilanowski, 2017; Abdullahi, *et al*., 2026). Structural socioeconomic settings, informal health care relationships and a lack of municipal infrastructure are direct drivers of the biological mechanisms of resistance, including the acquisition of horizontal gene transfer via intI1 integrons and the amplification of the sul1 and blaCTX-M genes (Gillings, *et al*., 2015; Molobe and Odukoya, 2021; Ugbo *et al*., 2025). To address this health challenge, methodological paradigms need to be examined in addition to scalable policy interventions (Abdullahi *et al*., 2026). Traditionally, the research field of AMR has been methodologically divided. Microbiological isolation, antimicrobial susceptibility testing (AST), quantitative polymerase chain reaction (qPCR), and metagenomic sequencing are quantitative methods. Accurate measurements of resistance gene abundance and phenotypic patterns from these laboratory methods fail to capture social, economic or behavioral factors that can withstand selection pressure (Isokpehi *et al*., 2025’ Vors, *et al*., 2026). Qualitative research methods such as key informant interviews and focus group discussions, on the other hand, can evaluate the processes, decision-making, patient purchasing behaviour, and practices of vendors but cannot establish biological causality (Adamu *et al*., 2020; Molobe and Odukoya, 2021).

These stand-alone limitations are addressed in recent frameworks that emphasize molecular–behavioural triangulation. An integrated approach involves the direct connection between molecular information about ARG prevalence and mobilome dynamics and spatial patterns of behavior, vendor dispensing patterns and waste disposal practices (Zhang *et al*. 2021). If the abundance of specific markers (such as sul1) is correlated with an environment-specific sales profile of informal drug vendors, clear attribution pathways between human activity and environmental resistance can be established (Gillings *et al*., 2015).

However, some analytical challenges are associated with the use of molecular-behavioural research in tropical, low-resource settings (Larsson and Flach, 2022; Bengtsson-Palme *et al*., 2018). When the cold chain is broken, the ambient temperature increases, causing the nucleic acids in the samples to degrade faster (Omoregie & Okoro, 2024). High organic content in tropical urban soils and contaminated drainage water also contains some enzymes, which may impede the efficiency of DNA extraction and the ability to amplify by PCR (Larsson and Flach, 2022; Bengtsson-Palme *et al*., 2018). Additionally, strong seasonality-induced precipitation can lead to major hydrological dilution effects affecting ambient bacterial concentrations such that seasonally stratified and standardized sampling protocols are necessary (Bengtsson-Palme *et al*., 2018; Isokpehi *et al*., 2025).

One Health Policy Implications and Strategic Interventions

Mitigating environmental AMR and public health vulnerability in Benin City requires moving beyond traditional clinical stewardship toward an integrated One Health policy framework (Arnold *et al*., 2024). Strategic interventions must target key socio-ecological conduits across public policy, municipal infrastructure, and informal healthcare markets (Abdullahi *et al*., 2026).

PMVs continue to be a major source of community healthcare, and rigid prohibition models may not be effective. Structured training programs are needed to certify that PMVs, as responsible medicine dispensers, are established by regulatory bodies such as the PCN. The interventions should include basic stewardship modules, ban the selling of part of an antibiotic treatment course, and implement incentive systems for patients to be referred to formal diagnostic centers.

The establishment of accessible medical waste collection infrastructure that eliminates environmental leakage points is necessary. Environmental protection agencies should have special receptacles for pharmaceuticals at recognized PMV clusters and community health centers to prevent direct disposal of expired or unused drugs into municipal drains.

Improving municipal sanitation is of paramount importance for limiting the expansion of the resistome in the environment. Interventions in civil engineering in Benin City should focus on repurposing and providing cover to all open earthen drains to allow the flow of rainwater, especially in areas identified as vulnerability hotspots. Advanced filtration technologies that can remove mobile genetic elements and active pharmaceutical residues need to be integrated into municipal wastewater treatment plants before the release of effluents to natural water bodies such as the Ikpoba River.

Localized environmental surveillance systems that are established on a routine basis based on key indicators (intI1, sul1, blaCTX-M) will enable public health officials to monitor AMR resistome shifts and assess the effectiveness of stewardship interventions over time.

CONCLUSION

Antimicrobial resistance-related environmental issues in Benin City are linked to the socio-ecological issues. Together, economic constraints, informal pharmaceutical distribution by patent medicine vendors, and deficient municipal waste management and sanitation infrastructure lead to the release of antimicrobial residues and resistant microorganisms into the urban environment. A paradigm shift of molecular-behavioural triangulation and the application of One Health intervention packages (combining regulatory enforcement, municipal infrastructure and community stewardship) are needed to address this public health risk.

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CONFLICT OF INTEREST
The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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ETHICAL APPROVAL
This article is a systematic review of published literature and secondary data; no direct human or animal experiments were conducted. Ethical approval was not needed for this study.

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