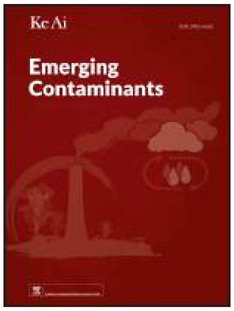

Ecological Consequences of Antibiotics Pollution in Sub-Saharan Africa: Understanding Sources, Pathways, and Potential Implications

Asha Ripanda, Dr. Mwemezi J. Rwiza, Elias Charles Nyanza, Miraji Hossein, Mateso Said Alfred, Alaa El Din Mahmoud, H.C. Ananda Murthy, Dr. Ramadhani Bakari, Said Ali Hamad Vuai, Revocatus L. Machunda

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Ecological Consequences of Antibiotics Pollution in Sub-Saharan Africa: Understanding Sources, Pathways, and Implications

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Ecological Consequences of Antibiotics Pollution in Sub-Saharan Africa: Understanding Sources, Pathways, and Potential Implications

Abstract

In Sub-Saharan Africa (SSA), the increasing use of antibiotics in human and veterinary medicine, combined with inadequate waste and water management systems, has intensified the problem of antibiotic pollution. Untreated or partially treated wastewater from industries, agricultural runoff, residential areas, and healthcare facilities is frequently discharged into the environment, often used for irrigation, contributing to antibiotic accumulation, the spread of resistance genes, and the rise of antibiotic resistance, posing serious threats to public health and environmental sustainability. The region's climatic conditions favour the survival and proliferation of microbial communities, including pathogens. Additionally, the high prevalence of infectious diseases such as HIV/AIDS, tuberculosis, and malaria, which often necessitate antibiotic use, further amplifies the issue. Systemic challenges, including poor waste management, inadequate or absent wastewater treatment infrastructure, weak regulatory enforcement, and the over-the-counter sale of antibiotics, exacerbate the crisis. Limited healthcare access often results in self-medication and improper antibiotic use, accelerating resistance spread. Evidence shows antibiotics in surface water, groundwater, effluents, food crops, environmental samples, and aquatic organisms, indicating their potential circulation through the food chain. However, a lack of comprehensive data on antibiotic pollution and its impacts on aquatic ecosystems in SSA hampers a thorough understanding of its scope and long-term effects. Addressing this crisis requires identifying contamination hotspots, evaluating ecological impacts, and establishing robust, region-specific regulatory frameworks to ensure environmental and public health safety

Keywords*:* *Antibiotics; Ecosystem health; Food chain; Contaminants of emerging concerns; Sub-Saharan Africa (SSA)*

Introduction

The use of antibiotics for medical treatments dates to ancient times. Initially, humans relied on extracts from medicinal plants. However, as populations grew, plant extracts alone became insufficient to meet the increasing demand. This led to the widespread use of synthetic and semi-synthetic drugs including antibiotics in treating humans, animals, and wildlife, as well as in agriculture. These substances, along with their metabolites and transformation products, often end up in sewage systems through various pathways. Urban growth is characterized by increased human activities, industrialization, and changes in lifestyle. Increased anthropogenic activities leading to the generation of toxic pollutants such as antibiotics, their metabolites, and transformational products. Antibiotics are frequently produced by soil microorganisms and are most likely a means for organisms in a complex environment, such as soil, to control the growth of competing microorganisms (Cycon et al., 2019; Waksman, 1947). Modern medicine has been transformed by antibiotics, which are essential for treating bacterial infections and enhancing both human and other animal health. However, the widespread and indiscriminate use has resulted in an emerging environmental concern of antibiotics pollution (Hossein et al., 2018; Hossein et al., 2022; Makaye et al., 2022; Makokola et al., 2019; H. Miraji et al., 2016; Miraji et al., 2021; Ripanda & Miraji, 2022; A. S. Ripanda et al., 2023). Figure 1, indicates that generally research on antimicrobial pollution are increasing both in SSA and globally, with few studies in Africa.

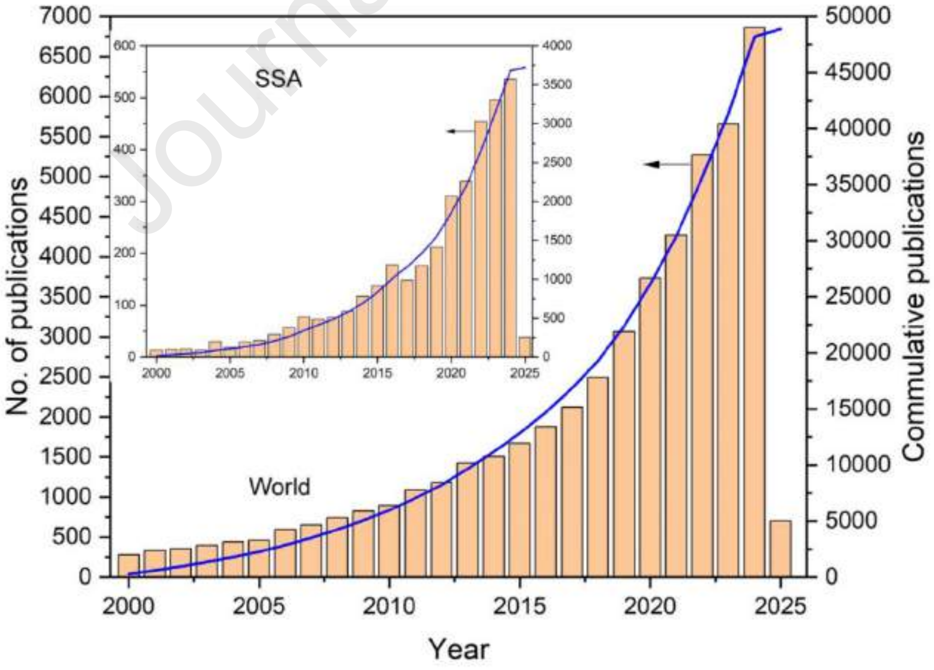

Figure 1: The number of absolute and cumulative publications on antibiotics pollution (Source: Scopus data base)

The data on co-authorship representation of African countries with the most publications between 2000 and 2025 provides valuable insights into the antimicrobial research landscape. This analysis was conducted by filtering affiliations to include only those from African countries, which means that while non-African countries like Australia and Canada appear in the data, they are represented solely through their collaborative contributions rather than as primary authors. Further results, indicates Nigeria stands out as the leading contributor, with total of 644 documents and 9,969 citations. This output not only reflects Nigeria's growing research capacity but also its impact on the global academic community. South Africa follows closely, producing 753 documents and garnering 20,037 citations, further solidifying its position as a significant player in scholarly research within Africa. Egypt also emerges as a prominent contributor, with 994 documents and 18,829 citations. This indicates a robust research environment that fosters research output and collaboration. Notably, both Ethiopia and Kenya are making strides in research, with Ethiopia contributing 270 documents and 4,611 citations, while Kenya has 179 documents with 4,798 citations. These figures highlight the increasing research capabilities in East Africa, suggesting that these nations are becoming vital contributors to the research discourse, Figure 2.

The concept of collaboration is illustrated through the metric of total link strength, which reflects the interconnectedness of research efforts. South Africa leads with a link strength of 672, closely followed by Nigeria at 482. This strong collaborative network not only enhances their research visibility but also facilitates greater academic partnerships. Meanwhile, countries like Kenya and Ethiopia, with link strengths of 250 and 258, respectively, indicate active participation in collaborative research initiatives, which are essential for addressing complex challenges through shared expertise. When comparing African countries to their non-African counterparts, the data reveals a noteworthy trend. Australia produced 68 documents with 2,344 citations, while Canada had 67 documents and 1,468 citations. Although these countries are not the primary authors, their presence in co-authorship arrangements with African researchers illustrates the global nature of academic collaboration and the importance of international partnerships in enhancing research impact. Despite the promising trends, the data also highlights disparities in research output among different African nations. Countries like Benin, with only 13 documents and 191 citations, and Namibia, with 12 documents and 349 citations, demonstrate lower levels of research activity on antimicrobial pollution. This underscores the potential for growth in these regions, where increased investment in research infrastructure and collaboration could significantly enhance their contributions to the scholarly community.

In Sub-Saharan Africa (SSA), wastewater is usually treated using waste-stabilization ponds (WSPs). Designs of the conventional WSPs do not incorporate removal or degradation of antibiotics which magnify the problem. Reports of occurrences of antibiotics and other emerging contaminants in the environment are globally available (Hossein et al., 2022; Hossein et al., 2023; Makokola et al., 2019; H. Miraji et al., 2016; Miraji et al., 2021; Ripanda & Miraji, 2022; Ripanda et al., 2022; Ripanda et al., 2021), and several measures have been proposed for their remediation (Asha Ripanda, 2022; Asha Ripanda, 2023; Hossein et al., 2023; H Miraji et al., 2023; A. Ripanda et al., 2023), for a healthier and more sustainable ecology. The occurrence of more than 15 antibiotics belonging to sulfonamides, β-lactams, macrolides and aminoglycosides classes, and trimethoprim in hospital effluents, wastewater treatment plants (WWTPs), and surface waters have been reported in SSA (Makaye et al., 2022; Makokola et al., 2019; Ngigi et al., 2020; Ripanda et al., 2024a; A. S. Ripanda et al., 2023). Antibiotics pollution poses significant risks to ecosystem health and functioning (Adelowo et al., 2012; Grenni et al., 2018; Ramírez-Malule et al., 2020; Wilkinson et al., 2022).

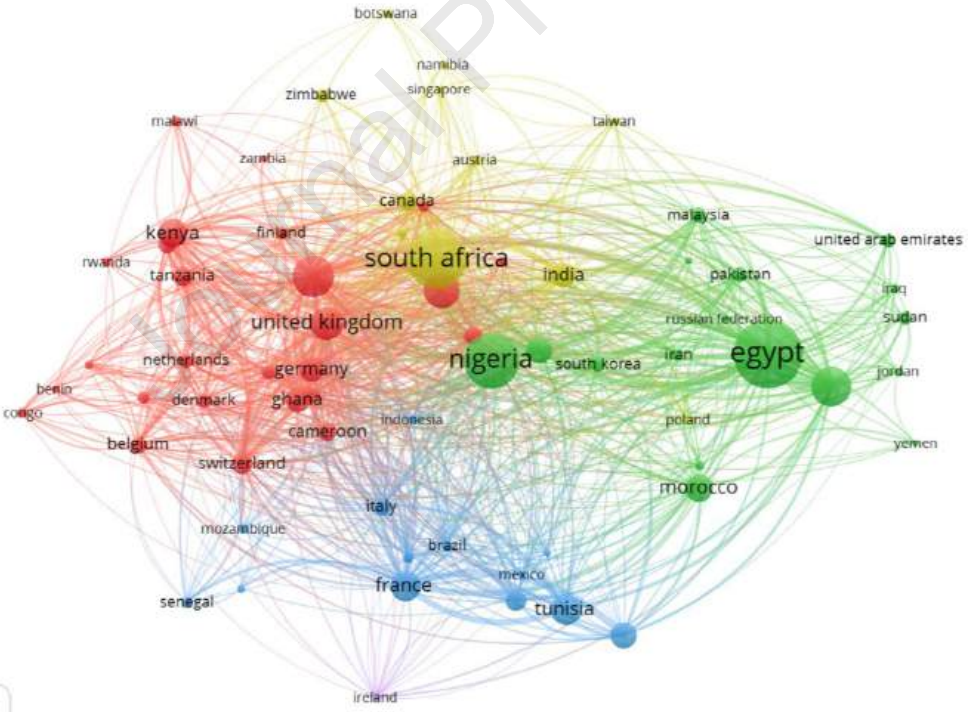

Figure 2: Co-authorship representation of African countries with the highest publication outputs from 2000 to 2025, highlighting both local contributions and international collaborations. (Source: Scopus data base)

The continuous exposure of bacteria to low levels of antibiotics in the environment creates selective pressure, favoring the survival and proliferation of antibiotic-resistant strains (Adelowo et al., 2020; Weiss et al., 2018; Yitayew et al., 2022). These resistant bacteria can transfer their resistance genes to other bacteria, including pathogenic microbes, leading to treatment complications (Adelowo et al., 2020; Gupta et al., 2019; Rong et al., 2021; Weiss et al., 2018; Yitayew et al., 2022) , and compromising human and ecological health. The disruption of microbial communities can have cascading effects on ecosystem stability, nutrient availability and recycling, and overall ecosystem functioning (Eapen et al., 2024; Huang et al., 2020; Kulik et al., 2023). Currently, in SSA, there is increased use of antibiotics to mitigate the increased diseases, which may go hand in hand with reports of their occurances in the environment. These antibiotics are also used in agronomic activities such as aquaculture, human therapeutic agents and veterinary drugs, including wildlife.

The potential ecological consequences of antibiotics contamination are significant and can have far-reaching impacts on ecosystems (Z. Li et al., 2023; Yarkwan, 2023). Disruption of microbial communities by antibiotics (da Silva-Brandao et al., 2023; Hossein et al., 2023; Karungamye, 2022; Karungamye et al., 2022; H Miraji et al., 2016; Msigala et al., 2017; Siachalinga et al., 2023; Virhia et al., 2023), can cascade through the food web, affecting primary producers, consumers, and decomposers (Miraji et al., 2021; Ripanda et al., 2022; A. S. Ripanda et al., 2023; Ripanda et al., 2021). Antibiotics pollution can promote the development and spread of antibiotic-resistant bacteria, compromising the effectiveness of antibiotics in clinical setting (Virhia et al., 2023). This may threaten wildlife health, as it can increase the incidence of antibiotic-resistant infections in vulnerable populations (da Silva-Brandao et al., 2023; Z. Li et al., 2023; Mishra et al., 2023; Siachalinga et al., 2023; Stocker et al., 2023), impacting ecological health and resilience. However, SSA faces unique challenges due to regional factors such as climatic conditions that favour growth and proliferations of pathogens leading to increased use of antibiotics hence pollution and related impacts, requiring intervention. To effectively combat antibiotic resistance, clinical facilities must strengthen laboratory capacity, adopt evidence-based prescribing practices, and engage in multidisciplinary collaborations. Investing in these areas will enhance the ability to address the region's unique challenges, such as high disease burdens, climatic factors, and reliance on herbal medicines, while minimizing the spread of resistant pathogens. Reports have been published detailing rampart use of non-prescription drugs by the communities including antibiotics (Kayode et al., 2020; Vickers-Smith et al., 2020), which may increase active chemical load in the environment. The non-prescribed dispensing of antibiotics is a widespread practice among community drug retail outlets (CDROs) in many Sub-Saharan African (SSA) countries (Belachew et al., 2021; Belachew et al., 2022; Ndaki et al., 2021; Nsengimana et al., 2023; Sono et al., 2023; Zewdie et al., 2024). This unchecked accessibility and misuse of antibiotics significantly heighten the risk of accelerating antibiotic resistance, undermining the effectiveness of the limited antibiotic in the region (Belachew et al., 2021). The growing concern over potential harm to ecosystems, including aquatic life and the increased risk to human health, domestic animals, and wildlife exposure, arises from the use of contaminated waters (Maranho et al., 2017; Molla, 2018; Ogunlaja et al., 2022; Tell et al., 2019), and food. This risk is exacerbated when partially or untreated wastewater is reused for irrigation, aquaculture, or urban water discharge, impacting the food chain. Therefore, the current work investigates ecological consequences of antibiotics pollution in Sub-Saharan Africa, focusing on the sources of antimicrobial pollutants, resistant genes, pathways, and potential implications.

Methodology

This literature review focuses on Sub-Saharan Africa, with countries selected based on the availability of data regarding antibiotics pollution, antibiotic resistance, and their genes, various environmental matrices including surface water, ground water, wastewater effluents, sediments, hospital waste, soils, and food chain. TITLE-ABS-KEY (("Antibiotic pollution" OR "antibiotics" OR "antibiotic resistance" OR "resistant genes" OR "resistant microbes" OR "resistant drug" OR "health impacts") AND ("Wastewater" OR "surface waters" OR "waters" OR "groundwater" OR "aquatics")), and 45,971 documents found. Some of keywords used are presented by Figure 3, together with these also included environmental matrices, and the names of individual Sub-Saharan African countries were used for the search.

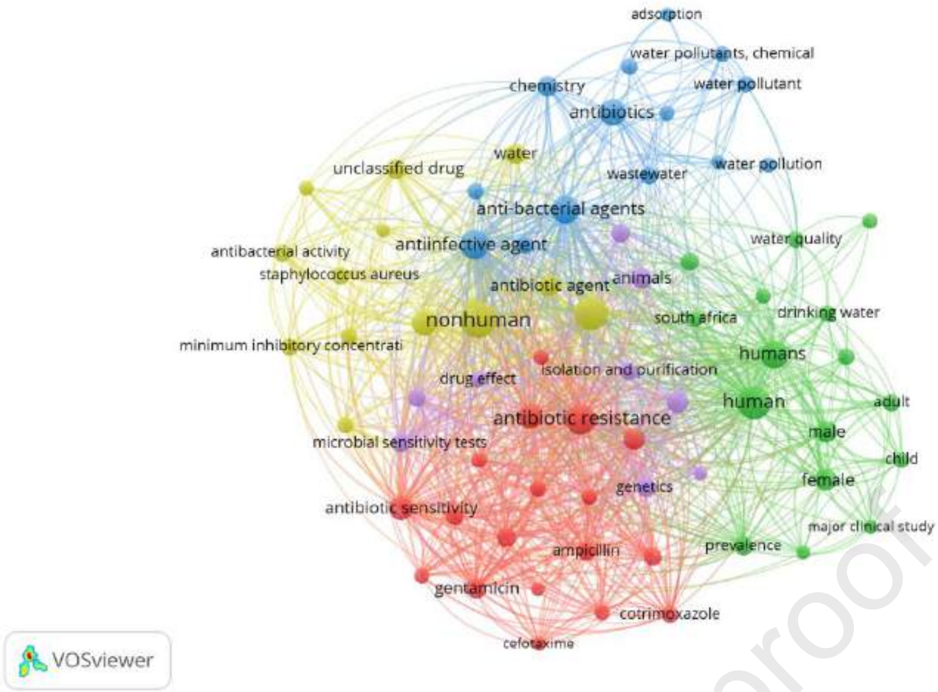

Figure 3: Keywords for 200 occurrences of antibiotics, antibiotic resistance and their genes for the recent 3720 papers affiliated in African countries (Source: Scopus data base)

The databases employed for sourcing journal articles included Web of Science, Scopus, Google Scholar, Wiley Online Library, ScienceDirect, Taylor & Francis Online, Sage Publishing, and PubMed. This comprehensive review primarily focused on the environmental presence, dissemination, and ecotoxicity, resulting in a dataset drawn from studies across Sub-Saharan Africa. (P. Gupta et al., 2023)

Source and circulation of antibiotic pollutants

Antibiotics, their metabolites, and transformational products can enter the environment through hospital effluents, pharmaceutical waste, agricultural effluents, and improper disposal of unused or expired medications (Hossein et al., 2018; Hossein et al., 2022; Makaye et al., 2022; Makokola et al., 2019; H. Miraji et al., 2016; Miraji et al., 2021; Moto et al., 2023b; Ripanda & Miraji, 2022; A. S. Ripanda et al., 2023), the largest contribution is from the use of medicines, where they can pass through our bodies into the environment. Once in the environment, antibiotics can persist, accumulate (Hossein et al., 2018; Hossein et al., 2022; Makaye et al., 2022; Makokola et al., 2019; H. Miraji et al., 2016; Hossein Miraji et al., 2023; Miraji et al., 2021; Moto et al., 2023a; Ripanda & Miraji, 2022; A. S. Ripanda et al., 2023) , and interact with ecosystems in ways that have far-reaching consequences. Figure 4, indicates that antibiotics originates from therapeutic use in both human and veterinary, other agronomic activities, direct disposal, effluent release untreated or after partial treatment from pharmaceutical industry, or hospitals (Hossein et al., 2023; Novick & Ness, 1984; Ripanda et al., 2024b; A. S. Ripanda, 2024; A. S. Ripanda et al., 2023), and contaminated agricultural field (Manyi-Loh et al., 2018). This leads to their persistent occurances in the environment and circulation through food chain creating harm to entire ecology. Nantaba and Coallegues reported occurances of quantifiable levels of antibiotics in Lake Victoria, and their ecotoxic risk assessed (Nantaba et al., 2024). Report of levofloxacin (2–120 ng g−1 dm; dry mass), ciprofloxacin (3–130 ng g−1 dm) enoxacin (9–75 ng g−1 dm), ibuprofen (6–50 ng g−1 dm), metoprolol (1–92 ng g−1 dm) and propranolol (1–52 ng g−1 dm) being predominant (Nantaba et al., 2024). Murchison Bay, being the chief recipient of sewage effluents, municipal and industrial waste from Kampala city and its suburbs, had the highest levels (Nantaba et al., 2024), this indicates potential impacts to this ecosystem, including bioconcentration, bioaccumulation, in fish and other lower aquatic species and biomagnification in higher animals, leading to their circulation in food chain. Report of prevalence of antimicrobial determinants in fish from Lake Victoria are available (Khatiebi et al., 2024; Mumbo et al., 2023; Onjong et al., 2021). Marijani (2022) reported that *E. coli* isolates were resistant to penicillin, erythromycin, gentamicin, azithromycin, and tetracycline, while *Salmonella spp.* isolates exhibited resistance to gentamicin, tetracycline, penicillin, and erythromycin (Marijani, 2022), a similar study in nile pech reported similar results (Ally, 2022). . These isolates were from marine and freshwater fishes consume in the region. Similar report from Nigeria indicated that isolates from shellfish were 100% susceptible to ciprofloxacin, azithromycin and erythromycin and resistant to cefotaxime, cefuroxime, imipenem/clastatin, augmentin and nitrofurantoin (Oramadike et al., 2024), and from fish ponds (Ayedun et al., 2022). The introduction of antimicrobial pollutants to the environment, their sources and circulation in the environment and through food chain is detailed in Figure 4.

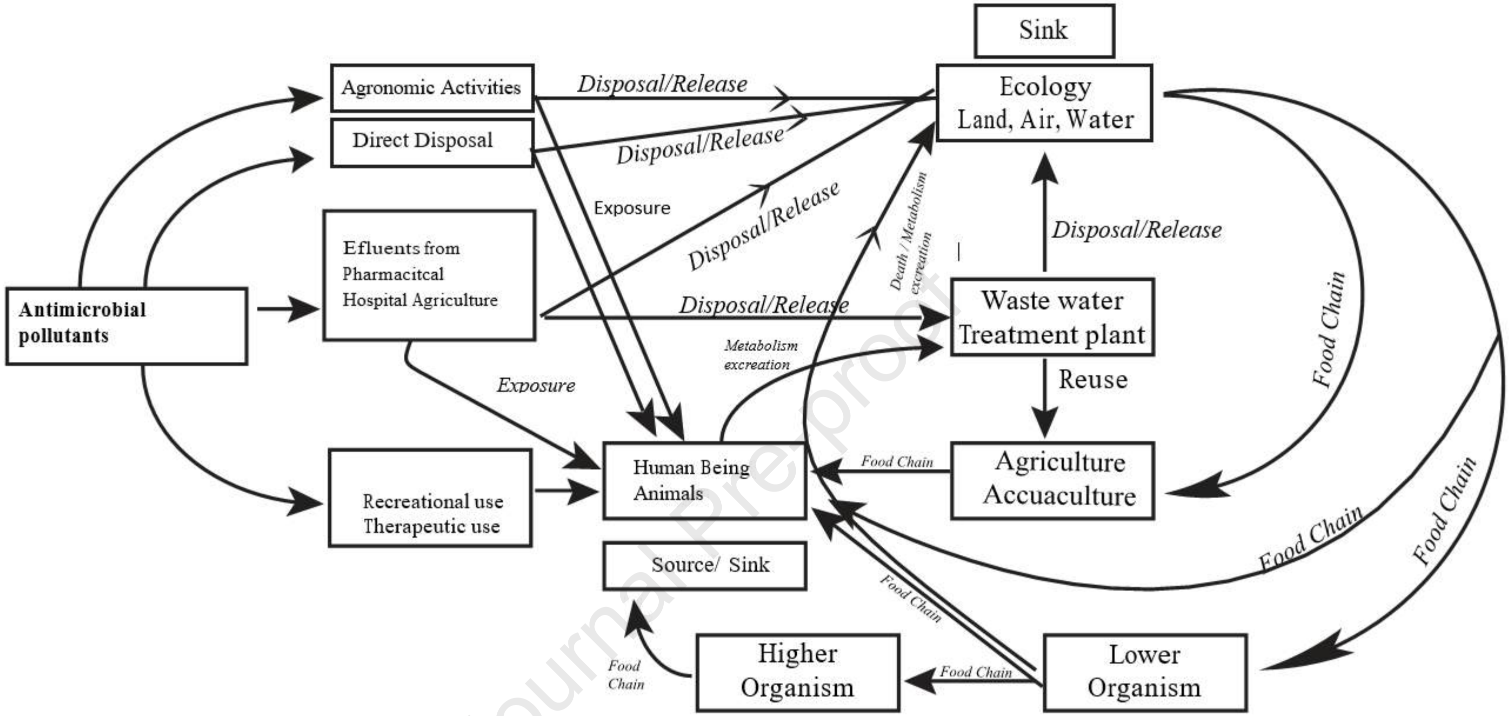

Figure 4: **Sources, and flow of antimicrobial pollutants such as antibiotics in different environmental compartments, and through food chain as summarized (A. Ripanda, 2024).**

Studies indicate that up to 70% of antibiotics used in aquaculture and livestock are excreted without being metabolized, subsequently contaminating surrounding water bodies (Kumar et al., 2020; Van et al., 2020). Additionally, the inadequate treatment of wastewater from healthcare facilities and industrial processes further exacerbates the problem (Hossein et al., 2023; Makaye et al., 2022; Makokola et al., 2019; Miraji et al., 2021; Ripanda & Miraji, 2022; Ripanda et al., 2022; A. S. Ripanda et al., 2023; Ripanda et al., 2021), which threaten the ecosystem safety and sustainability. Furthermore, the improper disposal of expired or unused medications contributes to this pollution, as many communities lack proper waste management systems. These practices not only threaten water quality but also pose significant risks to human health and the environment, highlighting the urgent need for improved regulatory frameworks and sustainable management practices across the continent.

Environmental Consequences of Antibiotic pollution

Antibiotic pollution may pose potential ecological consequences across Africa, significantly impacting ecosystem health, biodiversity, and agricultural sustainability. Report of occurances of 47 pharmaceuticals, 31 of which were detected in African waters. Seven of detected pharmaceuticals (propyphenazole, sulfamerazine, levamisole, tryptophan, dibucaine, albuterol, and fenpropimorph) are not approved medications in South Africa (Madikizela, Nuapia, et al., 2022). These results suggest a need for further research into the fate of pharmaceuticals in surface waters, and a quantification of the risks associated with the identified drugs because they are likely to accumulate in the tissues of fish/aquatic organisms, thus affecting humans (Madikizela, Nuapia, et al., 2022), as similarly, reported in Kenya (Kandie et al., 2020), and other SSA countries (Khatiebi et al., 2023; Nantaba et al., 2020). This contamination was associated with a marked decrease in microbial diversity and an increase in antibiotic-resistant bacteria, raising concerns about the potential for resistant strains to enter the food chain and compromise public health. Similarly, research indicates that the use of effluents from wastewater treatment for irrigation not only elevated antibiotic levels in agricultural soils but also resulted in reduced soil microbial activity, which is crucial for nutrient cycling and plant health (Bougnom et al., 2020; Slobodiuk et al., 2021). The presence of these pollutants has far-reaching implications, as they can disrupt essential ecosystem functions, threaten food security by diminishing crop yields, and exacerbate the public health crisis of antibiotic resistance. These findings highlight the urgent need for comprehensive strategies to address antibiotic pollution, safeguard environmental health, and protect the livelihoods of communities dependent on agriculture in Africa.

Impacts of environmental parameters on fate of antibiotics

Environmental parameters such as pH, organic matter, and the presence of other substances play a crucial role in the behavior and fate of antibiotics in soil and water, as well as in the transfer of antibiotic resistance genes (ARGs) (Deng et al., 2024). The pH influences the solubility and degradation rate of antibiotics; in more acidic or alkaline conditions, certain antibiotics degrade faster, reducing their persistence in the environment (Feng et al., 2021). Organic matter can either bind antibiotics, reducing their bioavailability, or facilitate their mobility through complexation, depending on the antibiotic's properties (Conde-Cid et al., 2020; Feng et al., 2021). Studies show that high organic matter content in soil can act as a reservoir, slowing antibiotic degradation and prolonging their environmental presence (Guo et al., 2024; Nkoh et al., 2024). Additionally, the presence of metals like copper or zinc, which are common in agricultural and industrial runoff, can co-select for ARGs (Maurya et al., 2020; Mazhar et al., 2021). In such environments, bacteria exposed to both antibiotics and metals are more likely to develop and transfer resistance due to shared stress responses impacting ecological health. Further, the soils with high organic carbon and metal concentrations were hotspots for ARGs, and similar findings have been reported in wastewater-impacted environments in Africa (Agramont et al., 2020; Bosch et al., 2023). These interactions highlight the importance of environmental conditions in both the persistence of antibiotics and the dissemination of resistance genes.

In the environment, antibiotics can be absorbed by plants through their roots, especially when present in soil or irrigation water (El Gemayel & Bashour, 2020; Marques et al., 2021). The uptake and interaction of antibiotics with plants depend on the type of antibiotic, plant species, and environmental conditions (El Gemayel & Bashour, 2020). Research has shown that antibiotics like tetracycline and sulfonamides are readily absorbed by plants such as lettuce, radish, and wheat (Camacho-Arévalo et al., 2021; Tasho et al., 2020), with antibiotics accumulating in edible plant tissues which may impact human and other animal health through food chain. Plants may develop tolerance to these compounds by modifying their metabolic pathways, such as producing detoxifying enzymes or altering cell membrane permeability to reduce antibiotic accumulation (El Gemayel & Bashour, 2020). Studies revealed that antibiotic uptake is higher in crops grown in soils irrigated with wastewater, posing risks to food safety and human health through the consumption of contaminated crops.

Development of tolerance mechanisms

Plants have developed several tolerance mechanisms to cope with antibiotic toxicity, allowing them to survive in contaminated environments. One key mechanism is the activation of detoxification pathways, where plants produce enzymes such as peroxidases, cytochrome P450 monooxygenases, and glutathione S-transferases (GSTs) to break down and detoxify antibiotics (P. Chakraborty et al., 2023; Jaiswal et al., 2021; Kurade et al., 2021). These enzymes modify the chemical structure of antibiotics, rendering them less harmful. Another tolerance mechanism is the sequestration of antibiotics in vacuoles or cell walls, isolating the toxic compounds from critical cellular functions (Martín, 2020; Wei et al., 2023). Additionally, plants can alter their membrane permeability to restrict antibiotic uptake or actively pump antibiotics out of cells through transport proteins, such as ATP-binding cassette (ABC) transporters (Seukep et al., 2022).

Research has shown that plants like lettuce accumulates enrofloxacin and ciprofloxacin from intensive animal husbandry (McCormick et al., 2024). Enrofloxacin levels was 7.3 µg/kg in fresh poultry litter, while its metabolite ciprofloxacin was 39.22 µg/kg after storage. Although no fluoroquinolones were detected in soils, lettuce from manured plots contained 14.97 µg/kg of enrofloxacin and 9.77 µg/kg of ciprofloxacin at 14.97, providing evidence of fluoroquinolone bioaccumulation in plants. Similarly the abundance of sul1 and intI1 in poultry litter was not affected by storage (McCormick et al., 2024). Plants like wheat and lettuce (Choe et al., 2024), and rice, produce higher levels of antioxidant enzymes, such as superoxide dismutase and catalase in response to antibiotic exposure, reducing oxidative stress caused by stressors such as antibiotics. In some cases, plants may also use bioaccumulation as a defence strategy, storing antibiotics in less metabolically active tissues. Studies in Africa, particularly in wastewater-irrigated agricultural regions, have demonstrated that plants exposed to antibiotic-laden environments develop such tolerance mechanisms (Bougnom et al., 2020; Gudda et al., 2020; Onalenna & Rahube, 2022), allowing them to survive but potentially introducing these contaminants into the food chain.

Antibiotics, soil health, fertility, and agriculture productivity

Antibiotics can significantly impact soil health and fertility, which are critical for sustainable agriculture. When antibiotics enter the soil through agricultural runoff, wastewater irrigation, or manure application (Zalewska et al., 2021), they can disrupt the microbial communities essential for nutrient cycling and organic matter decomposition. Studies have shown that the presence of antibiotics such as tetracyclines and sulfonamides can reduce the diversity and abundance of beneficial soil microbes (Conde-Cid et al., 2020; Li et al., 2024), including bacteria involved in nitrogen fixation and organic matter breakdown. This disruption can lead to decreased soil fertility, as key nutrients become less available to plants. Additionally, antibiotics can inhibit important soil processes such as the decomposition of organic materials (Li et al., 2024), which is vital for maintaining soil structure and nutrient availability. A study by Xie et al (2020) (Wang et al., 2020), reported that soils contaminated with antibiotics exhibited lower enzyme activity associated with nutrient cycling, indicating impaired soil function. Moreover, the persistence of antibiotics in the soil can lead to the selection of antibiotic-resistant bacteria, which can further complicate agricultural practices by compromising plant health and food safety. The accumulation of resistant strains in the soil can also pose risks to human health, particularly through the consumption of crops grown in contaminated soils. In Sub-Saharan Africa, where agricultural practices often involve the use of wastewater and manure, the effects of antibiotic pollution on soil health are increasingly recognized as a significant concern for food security and environmental sustainability. This indicates potential impact on livelihood for Africa as antibiotic pollution may lead to decreased agricultural production, which is a major economic activity. Additionally, antibiotic residues can accumulate in crops, raising food safety concerns and limiting market access (Arsène et al., 2022). vegetables grown in antibiotic-contaminated soils contained residues exceeding permissible limits (Akhter et al., 2024; Akhter et al., 2023) , which could jeopardize public health and consumer confidence. Furthermore, the proliferation of antibiotic-resistant bacteria in agricultural settings increases the risk of resistant strains entering the food chain (Akhter et al., 2024), complicating treatment options for infections and threatening human health. As agriculture in Africa faces these interconnected challenges, addressing antibiotic pollution is crucial for promoting sustainable farming practices, ensuring food security, and safeguarding public health across the continent.

Antibiotics use and prescription practices in SSA

Antibiotic prescription rates are notably elevated in hospitals across sub-Saharan Africa (Siachalinga et al., 2023). This is largely attributed to the prevalent practice of empirical prescribing, primarily driven by the absence of microbiology testing (Siachalinga et al., 2023). Furthermore, guidelines for antibiotic use are either absent or inadequately adhered to when they are available (Siachalinga et al., 2023). Further results revealed a widespread occurrence of antibiotic utilization in hospitals, with rates frequently exceeding 50% (Siachalinga et al., 2023). The prevalence varied, ranging from 37.7% in South Africa to a substantial 80.1% in Nigeria. Notably, there was a significant trend towards the prescription of broad-spectrum antibiotics, possibly influenced by the limited availability of facilities within hospitals (Siachalinga et al., 2023). Concerns related to co-payments for microbiological tests might be contributing to the reliance on empirical prescribing. This situation is compounded by the lack of guidelines or poor adherence to existing guidelines, with adherence rates dropping as low as 4% (Siachalinga et al., 2023). The double-edged sword of antibiotic prescription and pollution is intricately linked to the lifecycle of antibiotics, from their production to their use and eventually disposal (Anuar et al., 2023). In Africa, the acquisition of antibiotics without a prescription remains prevalent, and in certain African countries, all community pharmacies engage in dispensing antibiotics without the requirement for a prescription (Sono et al., 2023).

Similarly, the manufacturing process can contribute to environmental pollution as residual antibiotics, as well as by-products and impurities from manufacturing, may enter waterways if not effectively managed, creating harm. Similarly, the use of antibiotics in clinical settings results in pollution. After consumption, antibiotics are partially metabolized and excreted by humans and other animals. Untreated effluents from households, industries, and healthcare facilities may contain trace amounts of antibiotics, releasing effluents may contaminate surface water, groundwater, and entire ecology. Equally important, antibiotic use in agriculture for disease prevention and growth promotion in livestock, may lead to their release into the environment through animal waste and runoff. Antibiotics, once in the environment, can persist for long periods. This persistence increases the likelihood of them interacting with ecosystems and contributing to antibiotic resistance. The presence of antibiotics in the environment exerts selective pressure on bacteria. This can lead to the development and spread of antibiotic-resistant strains, contributing to the global issue of antibiotic resistance. Practices such as overprescription, misuse, and improper disposal of unused antibiotics can contribute to the presence of varying concentrations of these drugs in the environment.

Strategies to address antibiotic pollution include improved prescription practices in healthcare, better management of pharmaceutical waste, enhanced wastewater treatment, and sustainable agricultural practices that minimize the use of antibiotics. Efforts to combat antibiotic pollution require a holistic approach, involving healthcare professionals, regulatory bodies, pharmaceutical companies, and the agricultural sector. Implementing proper disposal methods, promoting responsible antibiotic use, and investing in advanced wastewater treatment technologies are essential steps to mitigate the environmental impact of antibiotics. Additionally, raising awareness among the public and healthcare providers about the importance of antibiotic stewardship can contribute to reducing unnecessary prescriptions and, consequently, antibiotic pollution.

Status of antibiotics pollution in SSA

Currently, there is increased report of antibiotic pollution in the region including Tanzania (Baniga et al., 2020; Hossein et al., 2018; Kihampa, 2014; Makokola et al., 2019; A. S. Ripanda et al., 2023), Kenya (Kairigo et al., 2020; Kimosop et al., 2016; Muriuki et al., 2020; Ngigi et al., 2020; Ngumba et al., 2016; Yang et al., 2016), Uganda (Onohuean & Igere, 2022; Wamala et al., 2018; Weiss et al., 2018), and (Doutoum et al., 2019; Koumaré et al., 2022; Mansaray et al., 2022; TALAKI et al., 2020; Woksepp et al., 2023) in other SSA countries. Concerns about antibiotic pollution are due to practices such as release of contaminated effluents, reuse of effluents for irrigation, and improper waste management, misuse, and overuse of antibiotics resulting into development and dissemination of antibiotic-resistant pathogens. Recent views by Madikizela et al. and Faleye et al., indicates higher levels of environmental antibiotic concentrations in Africa than anywhere in the world (A.C. Faleye et al., 2018; Madikizela, 2023; Madikizela, Nuapia, et al., 2022; Madikizela, Rimayi, et al., 2022; Thu et al., 2022), report on how this status can reflect SSA is lacking .The aquatic food and their products, on the other hand, have been identified as potential transmission root and aquatic habitats as potential reservoirs of extended-spectrum-lactamase (ESBL)-producing bacteria (Moto et al., 2023a; Nnadozie & Odume, 2019; Tzouvelekis et al., 2012) , raising the risk of ecological degradation and increasing wildlife disease. The presence of antibiotic residue such as metronidazole may have effects to the ecosystem as there are reports of the ability of metronidazole to affect soybean plants and soil microbiota (Jjemba, 2002), cause toxicity effect in intestinal tissue of fish (*Onchorhynchus mykiss*) (Gürcü et al., 2016) and aquatic ecosystem as a whole (Lanzky & Halting-Sørensen, 1997), which indicates a possibility of increased disease burden in wildlife populations and the deterioration of the ecological health. Figure 4 presents map of SSA, showing report of antibiotic pollution in selected matrices in environmental compartments, and reported non prescriptional use of antibiotics.

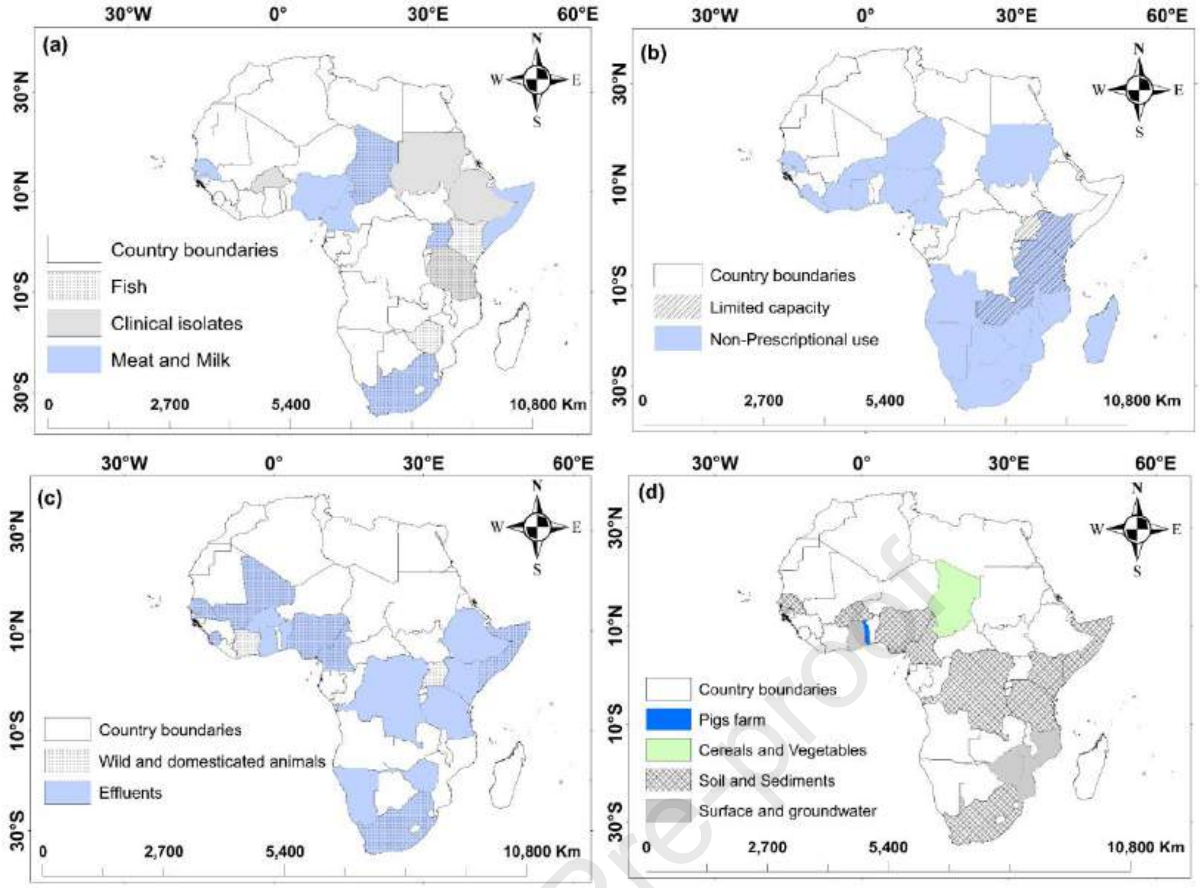

Figure 5: Selected SSA countries showing report of antibiotic pollution, presence of antibiotic resistant microbial populations, including pathogens, and resistant genes in selected matrices in environmental compartments, and reported non prescriptional use of antibiotics (Base map data source: OCHA, https://data.humdata.org/dataset/cod-ab-tza. Map created by authors.)

Presented studies (Figure 4) indicate the potential ecosystem exposure to antibiotics, their metabolic and transformational products (Abdallah et al., 2022; Agyarkwa et al., 2022; Gyesi et al., 2022; Odonkor et al., 2022; Otoo et al., 2022; Quarcoo et al., 2022), antibiotic resistant microbes (Abasse et al., 2021; Al Salah et al., 2020; Coulidiaty et al., 2021; Devarajan et al., 2017; Gufe et al., 2019; Kagambèga et al., 2022; Limya et al., 2020; Markkanen et al., 2023), and resistant genes (Assoumy et al., 2021; Fall-Niang et al., 2019; Mugadza et al., 2021; Salamandane et al., 2022; Salamandane et al., 2021; Taviani et al., 2022), which may harm ecosystems. Further, the presented studies indicate the presence of antibiotics (Cige et al., 2023; Deguenon et al., 2022; Mohamed et al.; Mohamed et al., 2020), in surface waters including organism living in (Kairigo et al., 2020; Matee et al., 2023; Ngigi et al., 2020; Ngumba et al., 2016; Yang et al., 2016), effluents (Mbanga et al., 2023), (Baniga et al., 2020; Kihampa, 2014; Musa et al., 2019; A. S. Ripanda et al., 2023), soil, poultry farm (Doutoum et al., 2019; TALAKI et al., 2020; Woksepp et al., 2023), agricultural areas (Ajibola et al., 2021; Lateefat et al., 2022; Ngogang et al., 2020; Takemegni et al., 2021; Tsafack et al., 2021), sediments (Denku et al., 2022; Ergie et al., 2019; Esemu et al., 2022; Mohammed et al., 2022; Teshome et al., 2020), feeds, milk (Enurah et al., 2019; Founou et al., 2018), wild animal (Baron et al., 2021), and other matrices (Agrawal et al., 2020; Jesumirhewe et al., 2022; Kimosop et al., 2016; Koumaré et al., 2022; Manishimwe et al., 2021; Mansaray et al., 2022; Muriuki et al., 2020; Onohuean & Igere, 2022; Wamala et al., 2018; Weiss et al., 2018). These results indicate potential for exposure to human through food chain. Exposure to antibiotics can select for resistant strains of pathogenic bacteria, which can then transfer their resistance genes to other microbial community in the environment (Z. Li et al., 2023; Mishra et al., 2023; Salam et al., 2023a) posing a significant concern for human and animal health as it reduces the effectiveness of antibiotics in treating infections (Kulik et al., 2023; Moyo et al., 2023).

Additionally, the presence of antibiotics in the environment can disrupt natural microbial communities and ecological processes. Antibiotics can have unintended effects on non-target organisms, including beneficial bacteria and other microorganisms that play vital roles in ecosystem functioning (Costanzo & Roviello, 2023; Kulik et al., 2023; Nakakande et al., 2023; Yarkwan, 2023). Furthermore, the disruption of the natural balance in ecosystems due to the presence of antibiotics and other chemical loads can have cascading effects on wildlife health. Changes in microbial communities and the emergence of antibiotic-resistant bacteria can lead to an increased prevalence of diseases in wildlife populations (Kulik et al., 2023; Yarkwan, 2023), this can have implications for the overall health and stability of ecosystems. Antibiotic contamination and resistance are known to impose ecosystem injury and their effects are transboundary, and interdisplinary measures and collaborative efforts are required for ecological safety. Ripanda et al. [7] suggested wastewater effluents treatment and reduced discharge, while Onohuean et al. [112] highlighted food safety and market surveillance. Similarly, in a recent work it was observed that in some SSA countries limited data on active chemical pollution such as antibiotics is due to absence of state of art equipment [6], and further Siachalinga and colleagues [35], reported a trend of considerable prescribing broad-spectrum antibiotics which could be due to lack of facilities within hospitals, along with concerns of co-payments to perform microbiological tests, resulting in empiric prescribing hence potential antimicrobial pollution [35], as similarly reported by other scholars [123, 124]. Similarly, report of lack of guidelines or low adherence to guidelines of antibiotics prescription [35], was raised. There is the need for microbiological facilities and testing, within hospitals to be made available and the cost subsidized to eradicate empirical prescription. Similarly, environmental surveillance and monitoring is needed, to ensure public health safety. Key components may include monitoring water sources, foods and feeds, and aquatic foods for the presence of antibiotic residues, assessing soil quality to understand the impact of agricultural practices and antibiotic use in livestock, and tracking air quality to gauge the dispersion of antimicrobial agents.

Challenges unique to Sub-Saharan Africa

SSA faces unique challenges that may potentially amplify antibiotic pollution, and therefore the ecological consequences. Climatic conditions, such as high temperatures, humidity, and seasonal rainfall (Chowdhury et al., 2018; Nguru & Mwongera, 2023; Situma et al., 2024), create environments conducive to bacterial survival and proliferation. This, combined with inadequate sanitation, release of contaminated effluents, and inadequate waste management, contribute to the persistence and spread of antibiotic-resistant bacteria (Asif et al., 2024; Gomes, 2024). This results into increased burden of infectious diseases. Data indicates the region faces a significant disease burden, including infectious diseases like malaria, tuberculosis, and HIV, which often require prolonged antibiotic treatments (Baral et al., 2024; Duffey et al., 2024; Makam & Matsa, 2021). According to WHO reginal office, as of 2022, approximately 25.6 million people in the African region are living with HIV, with 20.8 million in East and Southern Africa and 4.8 million in West and Central Africa (Kareem et al., 2023; Tadesse et al., 2024). Similarly, about 760,000 individuals contracted HIV in 2022, with report of approximately 380,000 deaths from AIDS-related illnesses, while women and girls accounted for 62% of all new HIV infections in sub-Saharan Africa in 2023 (Eaton et al., 2021).

Several SSA countries are among the 30 high TB burden countries globally. For instance, Sierra Leone had an estimated TB burden of 289 cases per 100,000 population in 2021 (Asare et al., 2021; Jemiluyi & Bank-Ola, 2021; Nunes et al., 2025). TB remains a leading cause of death among people living with HIV in SSA, exacerbating the public health challenge in the region 2021 (Asare et al., 2021; Jemiluyi & Bank-Ola, 2021; Nunes et al., 2025). SSA bears a disproportionately high share of the global malaria burden. In 2021, the region accounted for approximately 95% of malaria cases and 96% of malaria deaths (Oshagbemi et al., 2023; Sempungu et al., 2023). Children under five are particularly vulnerable, representing about 80% of all malaria deaths in the region (Aheto, 2022; Mbishi et al., 2024; Oguoma et al., 2021). (Doohan et al., 2024; Duvignaud et al., 2021; P. Li et al., 2023; Malik et al., 2023; McLean et al., 2023; Sharif et al., 2023; Woolsey & Geisbert, 2021). This high disease prevalence further accelerates the emergence and transmission of resistant infections, presenting a complex challenge for public health and ecological stability.

This further threatens public health as many healthcare facilities in the region are under-resourced, with limited access to advanced diagnostic tools for identifying resistant infections and monitoring antimicrobial resistance trends (Loosli et al., 2021; Pokharel et al., 2019). A study by Umutesi and Coallegues recommended strengthening of antimicrobial resistance diagnostic capacity in rural Rwanda (Umutesi et al., 2021). Similarly, Okoliegbe and Coallegues reported that many African laboratories confront substantial difficulties in implementing efficient quality assurance programs (Musa et al., 2023). This hampered AMR surveillance due to lack of laboratory capacity, insufficient data collection and analysis, and poor stakeholder collaboration (Musa et al., 2023). Yet, several initiatives and programs, including the World Health Organization’s Global Antimicrobial Resistance and Use Surveillance System (GLASS), the Africa Centres for Disease Control and Prevention (Africa CDC) Antimicrobial Resistance Surveillance Network (AMRSNET), and the Fleming Fund, a UK government initiative aimed at tackling AMR in low- and middle-income countries, have been established to strengthen AMR surveillance.

However, some positive steps are being taken. Facilities that implement infection prevention and control (IPC) measures, such as proper hygiene protocols, handwashing, and isolation of infected patients, have shown a reduction in resistant infection rates. While there have been significant strides in reducing the incidence of some infectious diseases, the region continues to grapple with high prevalence rates, particularly in countries like Eswatini, Lesotho, and South Africa, which have some of the highest HIV rates globally. Efforts to combat these diseases are further complicated by socioeconomic factors, limited healthcare infrastructure, and emerging health threats. Sustained investment in healthcare systems, education, and access to treatment is crucial to mitigate the burden of infectious diseases in SSA. Collaborative efforts between international organizations and governmental agencies have led to training healthcare workers in antimicrobial stewardship, improving awareness of resistance mechanisms, and encouraging the prudent use of antibiotics. To effectively combat antibiotic resistance, clinical facilities must strengthen laboratory capacity, adopt evidence-based prescribing practices, and engage in multidisciplinary collaborations. Investing in these areas will enhance the ability to address the region's unique challenges, such as high disease burdens, climatic factors, and reliance on herbal medicines, while minimizing the spread of resistant pathogens.

Potential implications of antibiotic resistance

Antibiotic resistance is a pressing global health concern with profound implications for both human, animal populations and the entire ecology (Zinsstag et al., 2023). The overuse, misuse and improper disposal of antibiotics have fueled the emergence and spread of antibiotic-resistant bacteria (da Silva-Brandao et al., 2023; Siachalinga et al., 2023; Tadesse et al., 2023; Virhia et al., 2023; Yismaw et al., 2023; Zinsstag et al., 2023), rendering previously effective treatments ineffective, resulting into treatment hospitalizations, complications, and increased mortality rates. Antibiotic residues induce and accelerate antibiotic resistance development, promote the transfer of antibiotic-resistant bacteria to humans and other organisms, cause allergies (penicillin) (Macy & Adkinson Jr, 2023), and may induce other severe pathologies, like cancers (furazolidone, sulfamethazine, and oxytetracycline) (Arsène et al., 2022), bone marrow toxicity (Arsène et al., 2022), anaphylactic shock, nephropathy (gentamicin), mutagenic effects, and reproductive disorders (chloramphenicol) (Elisabeth, 2023). This resistance arises through various mechanisms, such as genetic mutations and horizontal gene transfer (Abdallah et al., 2022; Mugadza et al., 2021; Yitayew et al., 2022), allowing bacteria to withstand the effects of antibiotics. This is particularly concerning (Moyo et al., 2023), in SSA, where infectious diseases like malaria, tuberculosis, and bacterial infections are prevalent. As of 2019, SSA had the highest mortality rate of about 24 deaths per 100,000 attributable to AMR compared to other regions (Kariuki et al., 2022), this may impair ability to manage common infections, which results in prolonged illness (Holloway & Everard, 2023; Moyo et al., 2023; Nakakande et al., 2023; Stocker et al., 2023) , greater mortality rates, and more expensive healthcare. Antibiotic resistance also can make interventions such as surgeries, chemotherapy, and organ transplants (Costanzo & Roviello, 2023; Salam et al., 2023a), more difficult and additional burden on healthcare systems. Similarly important, the use of antibiotics such as glycopeptide and avoparcin as feeds additives for the growth promotion of animals may result to the occurrence of vancomycin-resistant enterococci in food animals. In this case, vancomycin-resistant enterococci and vancomycin resistance determinants can therefore spread from animals to humans complicating treatments (Oliveira et al., 2020; Wegener, 2003). Therefore, surveillance, infection prevention and control measures, responsible antibiotic use in both human and other organisms, and the development of new antibiotics and alternative treatments is needed for ecological safety and sustainability.

Ecosystem health

Ecosystem health is a holistic measure of the well-being and resilience of an ecological system, reflecting its capacity to sustain biodiversity, support vital ecological processes (Asha Ripanda, 2022; S. K. Chakraborty et al., 2023; Davis et al., 2023) , and resist or recover from disturbances. A healthy ecosystem is characterized by a dynamic balance where various species coexist, interact, and contribute to the overall stability and functionality of the environment. It encompasses the intricate web of relationships between living organisms, their physical surroundings, and the countless interactions that define the ecosystem's structure (S. K. Chakraborty et al., 2023). Ecosystem health is not only vital for the persistence of diverse flora and fauna but also crucial for the well-being of human societies that depend on these systems for resources, climate regulation, and other essential ecosystem services (Nozarpour et al., 2023). Human activities, such as pollution (Shi et al., 2023; Wilkinson et al., 2022), habitat destruction (Shaikh et al.; Sun et al., 2023), and climate change (Campbell et al., 2018; S. R. Gupta et al., 2023; Noureen et al., 2022), can pose significant threats to ecosystem health, underscoring the importance of sustainable practices and conservation efforts to ensure sustainability.

Antibiotic pollution, can disrupt natural microbial communities, affecting the balance of microorganisms essential for nutrient cycling, soil fertility, and other ecological processes (Lencastre et al., 2023; Traore et al., 2023). Similarly, antibiotics may accumulate in organisms, magnify within the food chain. This bioaccumulation can lead to higher concentrations of antibiotics in predators at the top of the food chain, potentially posing risks to higher organisms, including humans. The presence of antibiotics in the environment exerts selective pressure on bacteria, favoring the survival and proliferation of antibiotic-resistant strains (S. K. Chakraborty et al., 2023; da Silva-Brandao et al., 2023; Holzinger et al., 2023; Hossein et al., 2023; Rapport et al., 1998), leading to the transfer of resistance genes among bacteria, further contributing to the global antibiotic resistance crisis. Efforts to combat antibiotic pollution are needed including focus on implementing improved waste management, including wastewater treatment, promoting responsible antibiotic use, and raising awareness about the environmental impact of contamination. Revisiting regulation to include other contaminants and international collaboration are essential to mitigate the long-term effects on ecosystems.

Status of ecosystem health and its connection to wildlife diseases

The presence and frequency of wildlife diseases in SSA are closely related to the state of the ecological health (Berkhout et al., 2023; Islam et al., 2023). SSA is home to a diverse array of ecosystems, ranging from expansive savannas and rainforests to freshwater and marine environments. A variety of wildlife species, many of which are endemic and of great conservation significance, rely on these ecosystems for vital habitats (Akani, 2023). However, numerous factors, including human activities, climate change, and habitat degradation, have significantly impacted ecosystem health in the region. Deforestation, land conversion for agriculture, and unsustainable resource extraction have led to habitat loss and fragmentation, disrupting natural ecological processes (S. R. Gupta et al., 2023). Contamination from industrial activities, mining, and improper waste disposal further contribute to environmental degradation (Ulucak & Baloch, 2023). Figure 5 presents conceptualization of the relationships between human, animal, wildlife, ecosystem, and circulation of diseases. The consequences of these ecosystem disturbances are manifold and have profound implications for wildlife health (Ulucak & Baloch, 2023). Disrupted ecosystems can lead to changes in species interactions, alter population dynamics, and increase the risk of disease transmission (Ulucak & Baloch, 2023). When ecosystems become imbalanced, there can be an increase in the prevalence and emergence of infectious diseases in wildlife populations, which may be transferred to human and domestic animals and the entire ecosystems. SSA has experienced several notable wildlife disease outbreaks, such as Ebola in great apes and bats, anthrax in herbivores, and various zoonotic diseases like rabies and trypanosomiasis (Gilbert et al., 2023). These outbreaks not only pose threats to wildlife but can also have spillover effects on human populations, leading to public health crises (Manes et al., 2023; Vora et al., 2023).

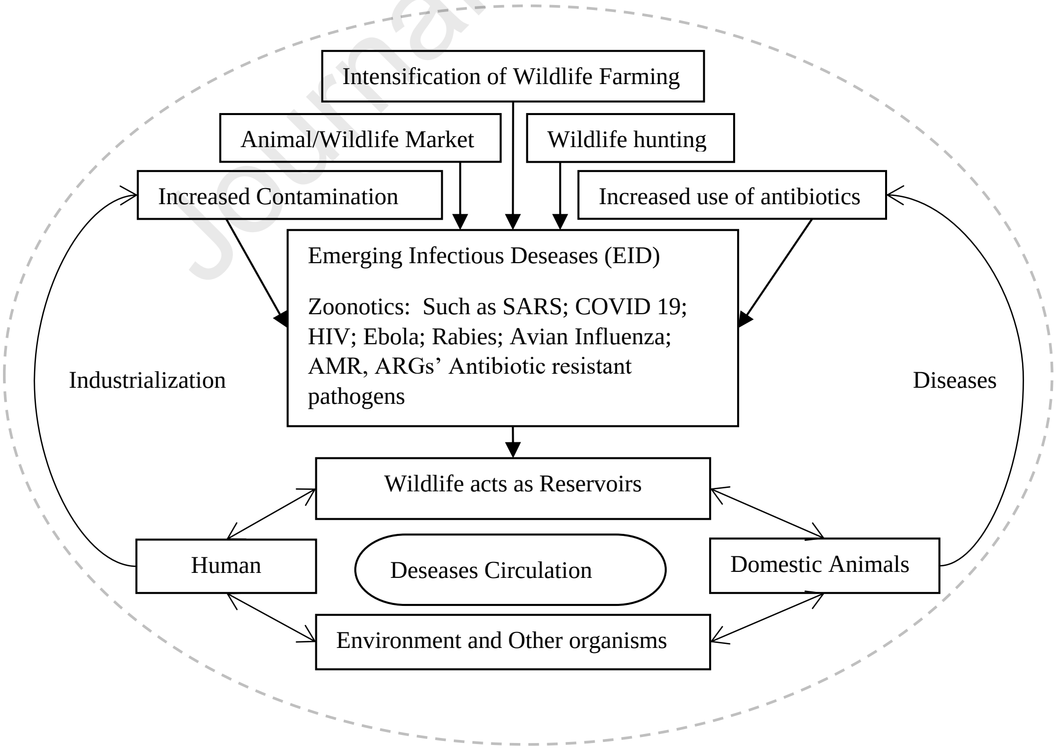

Figure 6: Conceptualization of the circulation of wildlife diseases and factors that magnify their occurrences.

Furthermore, the interconnectedness of ecosystems in SSA means that changes in one ecosystem can have ripple effects across the region (Lakshmisha & Thiel, 2023; Lencastre et al., 2023; Schaeffer et al., 1988; Vora et al., 2023). For example, alterations in freshwater ecosystems due to contamination or water scarcity can impact aquatic wildlife populations, disrupt food chains, and affect the livelihoods of communities that rely on these resources (Berkhout et al., 2023; Ogwu et al., 2023; Rapport et al., 1998; Schaeffer et al., 1988). To address the status of ecosystem health and its connection to wildlife diseases in SSA, there is a need for integrated and holistic approaches. Conservation efforts should focus on preserving and restoring habitats, promoting sustainable land and resource management practices, and enhancing environmental monitoring and surveillance systems as reported by previous researchers (Berkhout et al., 2023; Ogwu et al., 2023; Rapport et al., 1998; Ray, 2023; Schaeffer et al., 1988; Traore et al., 2023). Collaboration between governments, local communities, researchers, and conservation organizations is crucial to develop effective strategies that consider the complex interplay between ecosystem health, wildlife diseases, and human well-being. By safeguarding ecosystem health, we can protect wildlife populations, mitigate disease risks, and ensure the long-term sustainability of SSA biodiversity.

Impact of Human activities on ecosystem health and wildlife diseases

Anthropogenic activities (Berkhout et al., 2023; Rapport et al., 1998; Schaeffer et al., 1988), have significant contribution to the deterioration of ecological health and the increased occurrence of wildlife diseases. As human populations grow and expand, the demand for resources and the alteration of natural landscapes intensified, leading to a range of negative impacts on ecosystems and wildlife (Gabyshev et al., 2023; Lakshmisha & Thiel, 2023; Schaeffer et al., 1988). A study by Namusisi and colleagues (Namusisi et al., 2021), reported twenty-nine percent (29.0%, CI: 24.4–33.9) of respondents were engaged in hunting of wildlife such as chimpanzee (Pan troglodytes) and 45.8% (CI: 40.6–51.0), cane rats *(Thryonomyidae spp*), indicating presence of anthropogenic activities. Among the named reasons as why communities hunt, includes acquisition of animal protein (55.3%, CI: 50.1–60.4), medicinal and cultural uses of wildlife and or its parts (22.7%, CI:

18.6–27.4) (Namusisi et al., 2021). Similarly, hunting and bushmeat consumption is persistent for other perceived reasons; including bushmeat strengthens the body, helps mothers recover faster after delivery, boosts one’s immunity and hunting is exercise for the body (Namusisi et al., 2021). However, it was reported that respondents fall sick after consumption of bushmeat at least once (7.9%, CI: 5.3–11.1), with 5.3% (CI: 2.60–9.60) reporting similar symptoms among some family members (Namusisi et al., 2021). The participants have awareness of diseases transmissible from wildlife to humans (37.0%, CI: 32.1–42.2), although 88.7% (CI: 85.0–92.0) (Namusisi et al., 2021), had heard of Ebola or Marburg without context. Similarly, hunting non-human primate poses a health risk (cOR = 0.4, 95% CI = 0.1–0.9), compared to edible rats (cane rats) and wild ruminants (cOR = 0.7, 95% CI = 0.2–2.1). These results suggests that pathways for zoonotic disease spillover to humans exist at interface areas driven by livelihoods, nutrition, and cultural needs. The negative impacts of anthropogenic activities on ecosystem health and wildlife diseases need concerted efforts for their mitigation. It is crucial to prioritize habitat protection, restoration (Gilbert et al., 2023; Mwakapuja et al., 2013; van Heezik & Brymer, 2018), and sustainable land management in conservation programs.

The changes in land use associated with urbanization to cater for growing population (Das & Das, 2019; Komugabe-Dixson et al., 2019; Mwabumba et al., 2022; Peng et al., 2018), are causing destruction of ecosystems and natural services. Land use changes, for example, are largely represented in the transformation of different land types in the riparian area of Lake Tanganyika, where there are more settlements, with the conversion of forestland to arable land being the most prominent. Nonetheless, the rate of land use change in the region was not very high, substantial changes happened in the towns, particularly in the north. As a result, wildlife habitat and other ecosystem services are being lost, potentially leading deterioration of ecosystem health and increased diseases (Sintayehu, 2018). Similarly, pathogenic organisms are spreading more broadly geographically, within and across populations, and between other animals and humans. Most of studies utilize freshwater macroinvertebrate species, to address overall freshwater ecosystem health (O’Brien et al., 2016). As a result of the diminishing health of the freshwater environment, there is a need for more indicators that can capture both short and long-term changes, as well as the overall trend in freshwater ecosystem health (Elias, 2021). The absence of any sensitive taxa or the presence of few if any; increased dominance of only a few taxa that are tolerant to pollution, indicating that pollution has a significant influence on ecosystem health (Elias, 2021; Hossein et al., 2023; Hossein Miraji et al., 2023), requiring intervention.

The majority of factors that influence ecological health are anthropogenic in nature, climate change, globalization, population growth, and other new social habits will accelerate the trend (Ford et al., 2020; Pozio, 2020). As global 'traffic' grows, infectious pathogens have increased opportunities to mingle, transfer between species, and exchange genetic materials, potentially resulting in novel fatal pathogens. Bush meat and other wet market products are becoming widely available. These problems are exacerbated by emerging social activities in industrialized countries, such as a love for exotic pets, wild animal products, and unmanaged ecotourism. These factors have a significant impact on pathogen dynamics and cross-species pathogen crossover. Domestic animal grazing zones overlap or are adjacent to wildlife areas, resulting in increased contact and competition for natural resources. Similarly, farmed wildlife including deer and elk and, wildlife relocation countrywide and worldwide. Endangered wildlife species can become infected with a variety of infections including resistant infections. Finally, as people encroach on previously inaccessible habitats and settings, they come into contact with new infections (Mwakapuja et al., 2013), and could spread them beyond their historical limits.

Potential contribution of antibiotics pollution to deterioration of ecosystem health

Nature is increasingly being considered as a manageable resource for enhancing human well-being in cities (H.-Y. Liu et al., 2021). By treating nature as a product that gives health benefits and determining minimal amounts required to attain benefits, we risk trivializing a profound subjective response to nature (Jimenez et al., 2021). In this case, the world may end up with a diluted, biodiversity-depleted form of nature with harmed ecological functions (Armstrong, 2024; Mahecha et al., 2022). We could worsen ongoing movements toward more impoverished settings by establishing a new baseline of what is deemed normal. Among concerns of these substances in the environment, are hormonal disruption in fish (Gairin et al., 2022; Islam et al., 2024), decline sperm count, intersexuality, muscularization of female fish and the antimicrobial resistance (AMR) (Huang et al., 2020), as a result of discharge of antibiotics and other antimicrobial pollutants into the environment, which lead to extinction of some species. Antibiotic, ciprofloxacin caused cardiac dysfunction in zebrafish, such as decreased heart rate and cardiac output (Shen et al., 2019). Short-term exposure to ciprofloxacin doses of 1, 10, and 100 g.L1 had sublethal effects on Neotropical catfish (*Rhamdia quelen*) (Kitamura et al., 2022). In addition, Ciprofloxacin increased antioxidant system activity (Catalase in liver and posterior kidney) (Kitamura et al., 2022). These results indicates that under short-term exposure, Ciprofloxacin causes toxic effects in R. quelen that requires intervention, for ecosystems sustainability. Antibiotics are essential in the treatment of diseases; however, AMR has been deemed a threat to public health by the WHO and is expected to cost around 10 million lives per year by 2050. Antibiotics and other emerging contaminants in the environment (Ahmad et al., 2021; Salam et al., 2023b; Tang et al., 2023), are globally available which also may contribute to increased active chemical load and may pose unknown effects in the ecosystem, hence requiring intervention.

Antibiotic pollution mitigation strategies and policy implications

Mitigating antibiotic pollution requires a comprehensive strategy engaging multiple stakeholders, including governments, healthcare providers, the pharmaceutical industry, the agricultural sector, and the public. Addressing antibiotic pollution in already contaminated ecosystems requires a multifaceted approach that combines regulatory, technological, and community-based strategies. Primarily, implementing stricter regulations on antibiotic usage in agriculture and wastewater management is essential to limit further contamination. Additionally, adopting bioremediation techniques, such as using specific microbial strains that can degrade antibiotics or absorb residues, can help restore soil and water quality. Studies indicate that certain bacteria, like *Pseudomonas putida*, can effectively degrade tetracycline in contaminated soils (Chen et al., 2023; H. Liu et al., 2021). Phytoremediation, which utilizes plants to absorb and detoxify pollutants, can also be employed; plants like sunflower and willow have demonstrated effectiveness in extracting antibiotics from contaminated soils (Kafle et al., 2022). Furthermore, enhancing community awareness and engagement in monitoring and managing local water sources can lead to more sustainable practices. Integrating these strategies into a comprehensive management plan, alongside regular monitoring of antibiotic levels and microbial communities, will be crucial for mitigating the impacts of antibiotic pollution and promoting the recovery of affected ecosystems.

Similarly, mitigation strategies focusing on at the source are required to ensure safety and limit further pollution. Several crucial policy implications and mitigating tactics for antibiotic contamination (Muhaj & Tyring, 2023), are need. The need to promote appropriate and responsible use of antibiotics in both human and veterinary medicine, including the need to promote adherence to treatment guidelines (Muhaj & Tyring, 2023), educating healthcare professionals and the public on the risks of antibiotic overuse, improper disposal, misuse, and discouraging the use of antibiotics for non-bacterial infections (H. & Ripanda, 2019; Patel et al., 2023; Zhang et al., 2023). Mitigating antibiotic resistance is a complex challenge that requires a multifaceted approach involving various stakeholders, including healthcare professionals, policymakers, researchers, and the public. Establishment of collection programs for unused or expired medications and promoting safe disposal practices (Costanzo & Roviello, 2023). The government, industries and other stake holders need to upgrade and optimize wastewater treatment plants to effectively remove antibiotics from effluents before discharge into water bodies, and if possible, abolish direct disposal to water bodies (Ventola, 2015). Promote and encourage adoption of sustainable farming practices that minimize the use of antibiotics in livestock and aquaculture (Aslam et al., 2018). The need to enforce and strengthen water quality regulations to limit the discharge of antibiotics from industrial sources, agricultural runoff, and sewage treatment plants (Aslam et al., 2018). This includes revising guidelines for quality monitoring and assessment to include strict limits on antibiotic concentrations in effluents and implementing monitoring programs to ensure compliance. Funders need to invest in research and development of innovative technologies for the removal or reduction of antibiotics from water, wastewater, and agricultural runoff. This may potentially be realized through fostering international collaboration and knowledge sharing to address antibiotics contamination on a global scale. The overall combination of regulatory measures, technological advancements, educational campaigns, and collaborative efforts is essential to mitigate antibiotics contamination. The negative effects of antibiotics on the environment can be lessened, protect ecosystem health, and address the worldwide problem of antibiotic resistance by putting these tactics and policy implications into practice.

Conclusions

Anthropogenic activities are a major driver of ecological degradation, contributing to pollution, declining ecosystem health, and amplified disease prevalence. Antibiotic pollution, in particular, has raised significant concerns about the health and sustainability of ecosystems in Sub-Saharan Africa. Although data on antibiotic contamination in the region is limited, evidence from studies conducted in surface water and near industries such as pharmaceutical plants has revealed alarming levels of antibiotic residues in aquatic ecosystems. These pollutants, along with their metabolites and transformation products, can independently or synergistically degrade ecosystem health and intensify wildlife diseases. Reports also have shown antibiotic-resistant bacteria in aquatic wildlife, highlighting the potential for disease transmission between wildlife, livestock, and humans. This interaction exacerbates health risks and creates a ripple effect of harm across interconnected ecosystems. Effective management of aquatic ecosystems, particularly in protected areas and reserves, is critical to maintaining ecological balance and resilience. To address antibiotic pollution in Sub-Saharan Africa, a comprehensive and coordinated policy approach is vital. This may include identifying pollution hotspots. and balancing economic development with environmental protection by conducting risk assessment before approval of any developmental project. The need for raising public awareness on pathogenic microbes and environment that promote their production growth and survival, this will aid to decrease the burden of infectious diseases and hence antibiotic use. Initiate awareness program on proper use and disposal of antibiotics and other antimicrobials to the family level. Similarly, educate farmers on the responsible use of antibiotics in agriculture, emphasizing practices that prevent overuse and misuse, such as adhering to prescribed dosages, understanding withdrawal periods, and using antibiotics only, when necessary, under veterinary supervision. This will promote sustainable farming practices in the region. There is a need for improving waste management systems, and implementing robust monitoring frameworks for antibiotic residues and resistance this may include to make available equipments for analysis of these pollutants available. Similarly, the need for all clinical facilities to have equipped microbiological laboratory for microbiological testing, this will aid to eradicate the practice of empirical prescription of antibiotics. Similarly, improving waste management systems by ecofriendly techniques, but this requires research to tailor these methods to regional challenges. Fostering regional and international collaboration, and investing in research on antibiotic alternatives will further strengthen efforts. These actions will aid to mitigate the impacts of antibiotic pollution, support ecosystem health, and combat the growing threat of antimicrobial resistance, ensuring a sustainable future for both human and ecological well-being.

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Competing interest

None