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REVIEW ARTICLE

A Review on Mitigating Antimicrobial Resistance by Combating Falsified Medicines in the Global Pharmaceutical Supply Chain

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Abstract: The proliferation of falsified and substandard medicines within global pharmaceutical supply chains presents a formidable threat to public health, directly exacerbating the crisis of antimicrobial resistance (AMR). The complicated and often opaque nature of these supply networks creates vulnerabilities that are exploited for the infiltration of fraudulent products. Falsified antimicrobials, which frequently contain sub-therapeutic concentrations of active pharmaceutical ingredients or incorrect components, fail to eliminate targeted pathogens. This inadequate treatment exerts selective pressure on microbial populations, fostering the survival and propagation of drug-resistant strains. Consequently, the efficacy of legitimate antimicrobial therapies is undermined, leading to prolonged illnesses, increased mortality, and escalating healthcare costs. Addressing this convergence of threats requires a multi-pronged strategy. Modern technologies such as blockchain, artificial intelligence (AI), and the Internet of Things (IoT) offer robust mechanisms for enhancing traceability, transparency, and authentication from manufacturer to patient. However, the successful implementation of these technologies is contingent upon surmounting significant financial, infrastructural, and regulatory hurdles, particularly in low- and middle-income countries (LMICs) where the burden is greatest. Strengthening international regulatory harmonization, bolstering national enforcement capacities, and fostering public-private partnerships are imperative. A collaborated global effort is essential to secure the integrity of the pharmaceutical supply chain, thereby preserving the utility of critical antimicrobial medicines and safeguarding global health security against the silent pandemic of AMR.

Keywords: Pharmaceutical Supply Chain; Falsified Medicines; Antimicrobial Resistance (AMR); Blockchain; Public Health; Health Policy

1. Introduction

The global pharmaceutical supply chain is a prominent part in modern healthcare, facilitating the distribution of essential medicines from manufacturers to patients across the world. The integrity and efficiency of this complex network, comprising manufacturers, distributors, wholesalers, and healthcare providers, are paramount for positive public health outcomes [1]. However, this system is increasingly compromised by the pervasive issue of falsified and substandard medicines. These fraudulent products are deliberately and fraudulently mislabeled with respect to identity and/or source. They may contain the wrong active ingredients, no active ingredients, or incorrect dosages, posing a direct danger to patient safety through treatment failure and potential toxicity [2]. The World Health Organization (WHO) has reported that a significant percentage of medicines circulating in low- and middle-income countries (LMICs) are either substandard or falsified, representing a multi-billion-dollar illicit market that preys on a vulnerable populace [3]. A particularly alarming consequence of this illicit trade is its direct contribution to the acceleration of antimicrobial resistance (AMR). AMR occurs when microorganisms such as bacteria, viruses, fungi, and parasites evolve to withstand the effects of medications previously used to treat them [4]. The misuse and overuse of antimicrobials are widely recognized as primary drivers of this phenomenon. Falsified antimicrobial drugs, by delivering sub-therapeutic doses, create an ideal environment for the selective survival of resistant pathogens. This process not only renders treatments ineffective for individual patients but also contributes to a pool of drug-resistant organisms that can spread globally, threatening to return medicine to a "pre-antibiotic" era where common infections could once again become lethal [5]. This review work discusses the critical intersection of pharmaceutical supply chain

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vulnerabilities, the proliferation of falsified medicines, and the escalating crisis of AMR. It investigates the mechanisms through which fraudulent drugs contribute to resistance and evaluates the potential of technological and policy interventions to fortify the supply chain against these interconnected threats.

2. Falsified Medicines and AMR

2.1. The Modern Pharmaceutical Supply Chain

The journey of a pharmaceutical product from its point of manufacture to the end-user is a multi-stage process involving numerous stakeholders and jurisdictions. The chain begins with manufacturers, who produce active pharmaceutical ingredients (APIs) and formulate them into finished dosage forms. These products are then transferred to distributors and wholesalers, who manage storage and transportation to pharmacies, hospitals, and clinics [6]. Each handover point in this intricate network represents a potential vulnerability. A lack of transparency and interoperability between the data systems of different stakeholders creates opportunities for falsified products to be introduced, often with counterfeit packaging and documentation that makes them nearly indistinguishable from legitimate medicines [7]. These vulnerabilities are most pronounced in LMICs, where regulatory oversight is often underfunded, enforcement is weak, and fragmented distribution systems create numerous entry points for illicit products [8].

Table 1. Vulnerabilities at Various Stages of the Pharmaceutical Supply Chain

Supply Chain Stage	Stakeholders	Common Vulnerabilities for Infiltration of Falsified Medicines
1. Manufacturing	API Producers, Formulation Manufacturers	Use of substandard or incorrect Active Pharmaceutical Ingredients (APIs). Falsification of manufacturing records and batch numbers. Production in unregulated or illicit facilities.
2. Distribution	Wholesalers, Distributors, Repackagers, Transporters	Introduction of falsified products into legitimate shipments. Diversion of legitimate products to unregulated markets. Lack of secure, climate-controlled storage and transport, leading to degradation.
3. Dispensing	Pharmacies (Retail & Hospital), Clinics, e-Pharmacies	Infiltration of falsified stock through corrupt procurement. Dispensing medicines from unauthorized suppliers. Sale of products with falsified packaging that mimics authentic goods.
4. Post-Market	Patients, Healthcare Providers, Regulatory Bodies	Lack of robust systems for reporting adverse events or suspected poor-quality drugs. Difficulty in executing effective product recalls due to poor traceability. Self-medication by patients from unregulated street markets or online sources.

2.2. Falsified and Substandard Medicines

The WHO defines falsified medical products as those that "deliberately/fraudulently misrepresent their identity, composition or source." This definition is distinct from substandard medicines, which are authorized products that fail to meet quality standards [3]. However, both categories pose significant risks. The impact of these medicines is multifaceted. For patients, the consequences range from treatment failure for life-threatening conditions like malaria, HIV/AIDS, and bacterial infections, to adverse reactions from toxic ingredients [9]. For healthcare systems, they erode public trust in medical institutions and professionals, impose significant economic burdens due to prolonged hospitalizations and the need for more expensive second-line treatments, and waste limited healthcare resources [10]. The global scale of this issue is vast, with organized criminal networks leveraging sophisticated methods to manufacture and distribute these products across porous borders, making detection and interception exceedingly difficult [11].

2.3. Antimicrobial Resistance: The Silent Pandemic

AMR is a natural evolutionary process, but its acceleration is an anthropogenic crisis driven by the selective pressure exerted by the widespread use of antimicrobial agents in human and veterinary medicine, as well as in agriculture [4, 5]. When a microbial population is exposed to an antimicrobial, the most susceptible organisms are eliminated, while those with innate resistance survive and multiply. This dynamic is dangerously amplified by improper use, such as patients failing to complete a full course of antibiotics or the use of antimicrobials for non-susceptible infections (e.g., viral illnesses) [12]. The clinical and economic implications of AMR are staggering. Infections caused by resistant pathogens are associated with higher rates of mortality, longer hospital stays, and substantially

increased healthcare expenditures. The WHO has declared AMR to be one of the top 10 global public health threats facing humanity, with projections suggesting that by 2050, AMR-related deaths could surpass those from cancer if no effective action is taken [13].

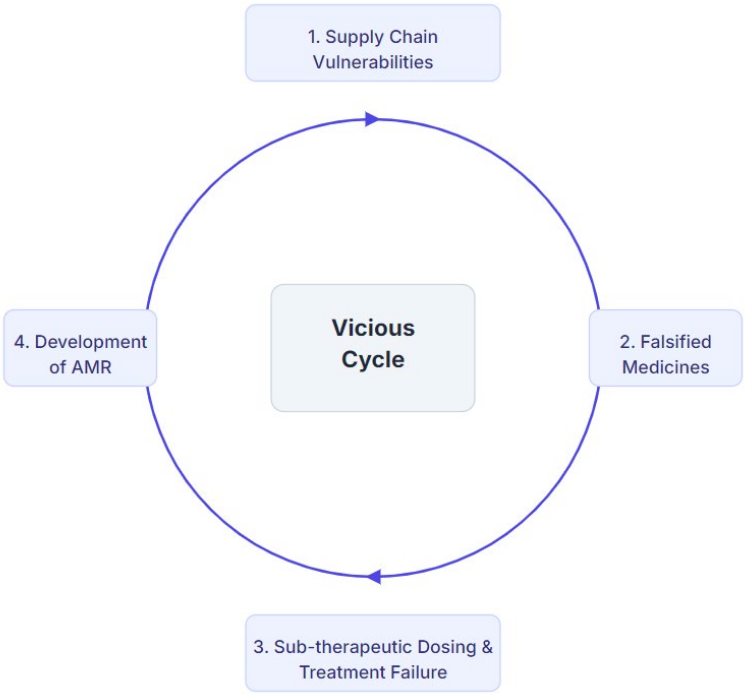

Figure 1. The Vicious Cycle of Falsified Medicines and Antimicrobial Resistance (AMR)

3. How Falsified Medicines Drive Antimicrobial Resistance?

3.1. The Mechanism of Resistance Development

The link between falsified antimicrobial agents and the rise of AMR is direct and causal. The primary mechanism is the administration of sub-therapeutic doses of an active pharmaceutical ingredient [14]. When an infection is treated with an antimicrobial that is under-dosed, the concentration of the drug in the body is insufficient to eradicate the entire pathogenic population. While a portion of the weaker, more susceptible pathogens may be killed, the stronger, partially resistant variants survive. These survivors are then free to replicate without competition, passing on their resistance traits and leading to the emergence of a fully resistant strain [9, 15]. This process not only fails the individual patient but also introduces a more formidable pathogen into the community. Furthermore, some falsified products contain the wrong active ingredient entirely, which can lead to inappropriate treatment that needlessly exposes a patient's microbiome to an antibiotic, fostering resistance without any therapeutic benefit for the primary infection [11].

3.2. Evidence from High-Burden Regions

The devastating impact of this intersection is most evident in LMICs, particularly in regions of sub-Saharan Africa and Southeast Asia, which face a dual burden of high infectious disease prevalence and weak pharmaceutical regulation. Extensive studies on antimalarial drugs, for example, have revealed a high prevalence of falsified and substandard products containing insufficient amounts of artemisinin-based compounds [16]. This has been directly linked to the emergence and spread of artemisinin-resistant strains of *Plasmodium falciparum*, threatening to reverse decades of progress in malaria control [17]. Similarly, the circulation of falsified antibiotics for treating common infections like pneumonia and sepsis contributes to the rising rates of multidrug-resistant bacteria, leaving clinicians with fewer effective treatment options and forcing reliance on last-resort antibiotics that are often more toxic and expensive [18]. These regions are caught in a vicious cycle where the high cost of legitimate medicines drives patients towards cheaper, unregulated sources, which in turn fuels the AMR crisis that their healthcare systems are least equipped to handle [8].

4. Technological Interventions for Supply Chain Integrity

The opacity and fragmentation of the conventional pharmaceutical supply chain necessitate the adoption of advanced technologies to ensure product integrity. Innovations in digital tracking and authentication offer promising pathways to secure the chain from end to end, thereby preventing the entry of falsified medicines.

4.1. Blockchain for End-to-End Traceability

Blockchain technology, a distributed and immutable digital ledger, has emerged as a powerful tool for enhancing transparency in complex supply chains [19]. Blockchain can establish a verifiable product pedigree by creating a shared, unalterable record of every transaction a drug package undergoes—from the manufacturer to the pharmacy shelf—. Each stakeholder in the supply chain can record its "touchpoint" with the product as a time-stamped block of data, which is cryptographically linked to the previous one. This creates a chain of custody that is resistant to tampering, allowing regulators, distributors, and even consumers to authenticate a drug's provenance with a high degree of confidence [20]. Pilot projects, such as the MediLedger Project, have demonstrated the feasibility of using a permissioned blockchain network among pharmaceutical manufacturers and distributors to track and verify prescription medicines, thereby complying with regulations like the U.S. Drug Supply Chain Security Act (DSCSA) [21].

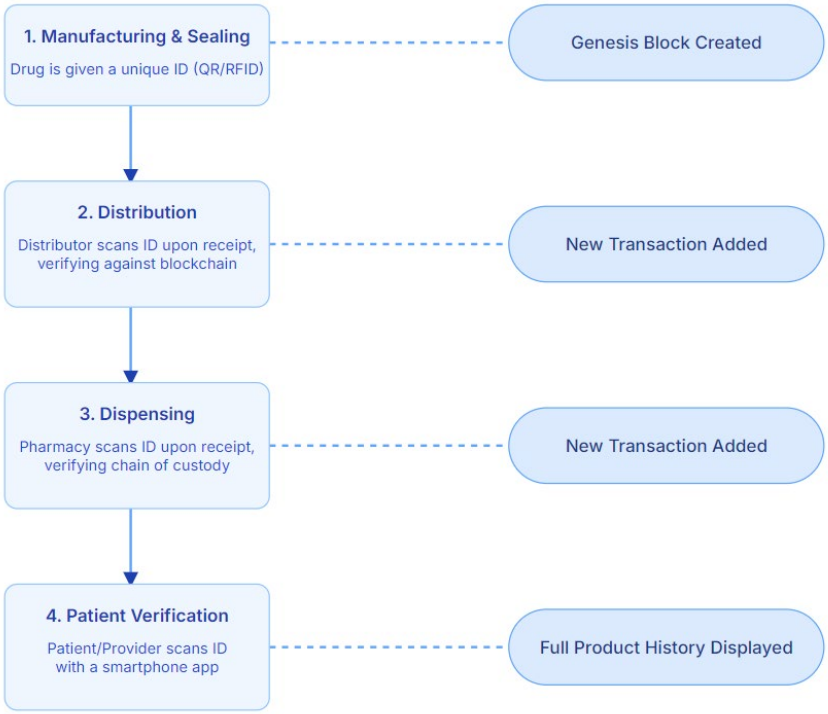

Figure 2. Blockchain-Based Pharmaceutical Traceability System

4.2. Artificial Intelligence and Machine Learning for Anomaly Detection

Artificial intelligence (AI) and machine learning (ML) offer the capability to analyze vast and complex datasets from the supply chain to identify patterns indicative of fraudulent activity. AI algorithms can be trained to detect anomalies in shipping logs, batch numbers, and sales data that might signal the diversion or introduction of counterfeit products [22]. For instance, an AI system could flag a shipment that deviates from its expected route or a batch of drugs appearing in a market where it was not intended for sale. Furthermore, ML models can be applied to the visual inspection of pharmaceutical packaging. By analyzing images of labels, holograms, and barcodes, these systems can learn to distinguish authentic packaging from sophisticated forgeries with greater speed and accuracy than human inspectors [23].

4.3. The Internet of Things (IoT) for Real-Time Monitoring

The Internet of Things (IoT) involves a network of physical devices embedded with sensors and connectivity, enabling them to collect and exchange data in real time. In the pharmaceutical supply chain, IoT can be leveraged for granular, real-time tracking of individual drug packages [24]. Smart packaging equipped with sensors can monitor and report on critical environmental conditions, such as temperature and humidity, which is vital for ensuring the stability and efficacy of sensitive biologics and vaccines. RFID tags and scannable QR codes on each package provide a unique digital identity, allowing for automated verification at each node of

the supply chain. This constant stream of data not only secures the product against theft and diversion but also provides an auditable record of its handling, ensuring that quality is maintained throughout its journey [25].

Table 2. Comparison of Technological Interventions for Integrity of Supply Chain

Technology	Primary Function	Benefits	Major Challenges
Blockchain	Decentralized, immutable ledger for traceability.	High security and resistance to tampering. Creates a transparent, verifiable chain of custody. Enhances trust among stakeholders.	High initial cost. Complexity of integration with legacy systems. Scalability and data privacy concerns.
Artificial Intelligence (AI) / Machine Learning (ML)	Anomaly detection and data analysis.	Can identify complex fraudulent patterns in large datasets. Automates visual inspection of packaging. Predictive analytics for risk assessment.	Requires large, high-quality datasets for training. Potential for algorithmic bias. High computational resource requirements.
Internet of Things (IoT)	Real-time tracking and environmental monitoring.	Provides granular, real-time location data. Ensures product quality by monitoring temperature/humidity. Enables rapid alerts for diversion or tampering.	Investment in sensors, smart tags, and network infrastructure. Data security for connected devices. Lack of universal standards.

5. Institutional Policies

While technology provides the tools to secure the supply chain, its effectiveness is contingent upon a robust and harmonized policy and regulatory environment. Combating the transnational crime of pharmaceutical counterfeiting requires coordinated action at the global, regional, and national levels.

5.1. Strengthening Global and Regional Governance

International organizations are crucial for setting standards and coordinating the global response. The WHO's Global Surveillance and Monitoring System collects data on substandard and falsified medical products from member states, helping to map the scale of the problem and target interventions [3]. Law enforcement bodies like INTERPOL lead international operations to dismantle the criminal networks behind the production and trafficking of these illicit goods [11]. Regional regulatory bodies, such as the European Medicines Agency (EMA) and the African Medicines Regulatory Harmonization (AMRH) initiative, play a vital role in aligning standards and practices across countries. Harmonizing drug registration requirements, quality control testing, and post-market surveillance makes it more difficult for falsified products to exploit regulatory loopholes by moving across borders [26].

Table 3. Global and Regional Policy and Enforcement Bodies

Organization / Initiative	Primary Role in Combating Falsified Medicines & AMR	Activities & Programs
World Health Organization (WHO)	Sets global norms and standards; surveillance and data collection.	Global Surveillance and Monitoring System (GSMS) for substandard/falsified products. Global Action Plan on AMR. Prequalification of Medicines Programme.
INTERPOL	International criminal police organization; coordinates cross-border law enforcement.	Operation Pangea: An annual global operation targeting illicit online sale of medicines. Dismantling transnational criminal networks involved in pharmaceutical crime.
European Medicines Agency (EMA)	Regulatory body for the European Union.	Centralized marketing authorization. Falsified Medicines Directive (FMD), requiring safety features on packaging (e.g., 2D barcode).
African Medicines Regulatory Harmonization (AMRH)	African Union initiative to harmonize medicine regulation across the continent.	Supporting Regional Economic Communities to standardize regulatory processes. Building capacity of National Regulatory Authorities (NRAs). Paving the way for the African Medicines Agency (AMA).

5.2. National Strategies for Enforcement and Stewardship

At the national level, the foundation of drug safety is a strong, well-funded National Regulatory Authority (NRA). NRAs are responsible for enforcing laws related to pharmaceutical quality, inspecting manufacturing facilities, and monitoring the distribution chain. However, in many LMICs, these agencies are hampered by insufficient funding, a lack of trained personnel, and inadequate legal frameworks, which criminals exploit [8, 18]. Beyond enforcement against falsified drugs, national policy must also address the demand side of the AMR crisis. Public health strategies centered on antimicrobial stewardship are essential. These programs promote the appropriate use of antimicrobials by healthcare professionals and patients, implement surveillance systems to track resistance patterns, and advocate for improved infection prevention and control in healthcare settings to reduce the overall need for antimicrobials [12, 13].

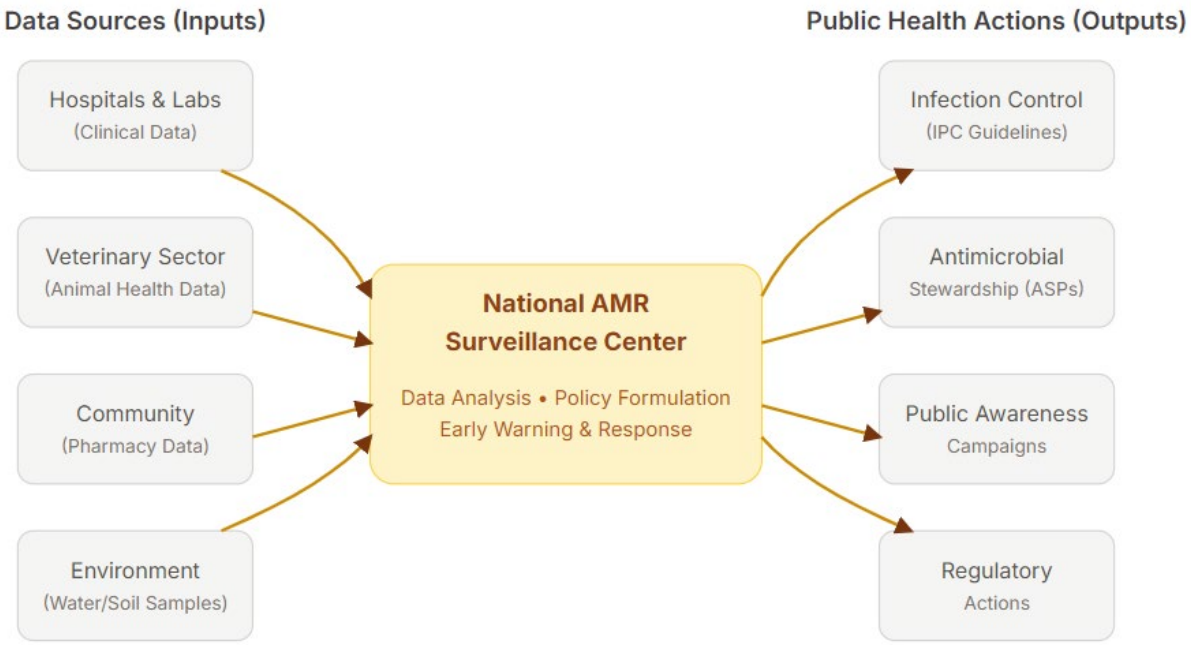

Figure 3. National AMR Surveillance and Response

6. Challenges and Barriers to Implementation

Despite the promise of technological and policy solutions, significant obstacles hinder the global effort to combat falsified medicines and AMR. These challenges are multifaceted, spanning regulatory, financial, and socio-economic domains.

6.1. Enforcement Hurdles

The globalized nature of the pharmaceutical market creates profound enforcement challenges. Illicit actors exploit inconsistencies between national regulations to traffic falsified products across borders with relative ease [11]. In many jurisdictions, particularly in LMICs, legal frameworks are either outdated or inadequately enforced due to corruption, a lack of political will, or insufficient resources for inspection and prosecution [27]. This creates a permissive environment where counterfeiters can operate with a low risk of being held accountable.

6.2. Technological and Financial Barriers

The implementation of advanced technologies like blockchain and IoT requires substantial upfront investment in digital infrastructure, software, and training. For many healthcare systems and pharmaceutical companies in resource-limited settings, these costs are prohibitive [28]. Furthermore, issues of data privacy, security, and the lack of universal standards for interoperability between different technological platforms can slow down adoption. Without a concerted effort to ensure equitable access to these technologies, there is a risk of creating a "digital divide" that leaves the most vulnerable supply chains even further behind [29].

6.3. Compounded Challenges in Resource-Limited Settings

The problems of falsified medicines and AMR are acutely magnified in LMICs. Overburdened and underfunded health systems struggle to provide consistent access to affordable, quality-assured medicines. This drives patients to informal markets, where falsified products are rampant [8]. A lack of access to diagnostic tools often leads to empirical prescribing of broad-spectrum

antibiotics, while a scarcity of healthcare professionals limits opportunities for patient education on correct antimicrobial use. This creates a perfect storm where falsified drugs can readily contribute to AMR, and the resulting drug-resistant infections overwhelm a healthcare system that is already fragile [30].

Table 4. Challenges in Resource-Limited Settings

Challenge Domain	Specific Manifestations in Low- and Middle-Income Countries (LMICs)	Impact on Falsified Medicines	Impact on Antimicrobial Resistance (AMR)
Economic	High cost of legitimate medicines. Limited patient purchasing power. Underfunded healthcare systems.	Drives demand for cheaper, often falsified, products from unregulated markets.	Prevents access to full courses of appropriate antibiotics, leading to treatment stoppage and resistance.
Regulatory & Governance	Weak or under-resourced National Regulatory Authorities (NRAs). Porous borders and inconsistent enforcement. Corruption.	Creates a low-risk environment for traffickers. Allows falsified products to easily enter the legal supply chain.	Leads to the uncontrolled sale of antibiotics without prescriptions. Hampers surveillance of resistance patterns.
Healthcare Infrastructure	Shortage of trained healthcare professionals. Lack of diagnostic capacity. Fragmented and insecure supply chains.	Reduces capacity to identify and report suspicious products. Creates numerous entry points for counterfeiters.	Encourages empirical prescribing of broad-spectrum antibiotics. Limits infection prevention and control measures.
Social & Educational	Low public awareness of the dangers of falsified drugs. Limited health literacy regarding correct antibiotic use.	Patients unknowingly purchase and consume dangerous products.	Fosters misuse and overuse of antibiotics by the public, directly fueling resistance.

7. Recommendations

Addressing the intertwined threats of falsified medicines and AMR requires a sustained, multi-stakeholder commitment to action. A forward-looking strategy must integrate global policy, technological innovation, and community engagement.

7.1. Global Collaboration

A robust international treaty or convention specifically targeting the crime of falsified medicines, similar to frameworks for other transnational crimes, could strengthen global cooperation and harmonize legal responses. Increased funding and technical support for NRAs in LMICs, facilitated through public-private partnerships, is essential to build local capacity for regulation and enforcement [26, 31]. High-level political commitment, such as that seen at the United Nations General Assembly, must be translated into tangible resources and national action plans that address both supply chain security and antimicrobial stewardship.

7.2. Investing in Sustainable and Accessible Technology

Future innovation should focus on developing scalable, cost-effective technological solutions that are appropriate for resource-limited settings. This could include mobile-based authentication systems that allow consumers to verify a product's legitimacy using a simple text message or app [32]. International donors and development partners have a role to play in subsidizing the initial costs of implementing traceability systems in high-burden countries. Establishing global standards for data exchange will be critical to ensure that different systems can communicate, creating a truly interconnected and secure global supply chain.

7.3. Empowering Communities through Education

Public awareness campaigns are vital for educating patients and consumers about the dangers of purchasing medicines from unregulated sources and the importance of appropriate antibiotic use [33]. Training programs for healthcare professionals, from doctors and nurses to community pharmacists and drug vendors, should emphasize the identification of falsified products and the principles of antimicrobial stewardship. Empowering local communities with knowledge is one of the most effective long-term strategies for reducing demand for falsified medicines and promoting responsible health-seeking behaviors.

8. Conclusion

The convergence of falsified medicines and antimicrobial resistance is an escalating threat to global health security. The vulnerabilities within the pharmaceutical supply chain do more than just permit the circulation of fraudulent products; they actively undermine the efficacy of modern medicine by fueling the development of drug-resistant pathogens. While the challenges are formidable, particularly in resource-limited settings, they are not insurmountable. The pathway forward requires a paradigm shift from siloed interventions to an integrated strategy. Technological advances like blockchain, AI, and IoT offer powerful tools for creating transparent and resilient supply chains, but they must be implemented as part of a broader ecosystem of strengthened regulatory oversight, harmonized international policies, and robust enforcement. Simultaneously, public health efforts must continue to champion antimicrobial stewardship and educate communities to build a culture of responsible medicine use. A dedicated and collaborative global effort along with sustained political will and equitable investment, is imperative to secure the integrity of our medicines, preserve the effectiveness of life-saving antimicrobials, and protect the health of future generations.

References

[1] Uthayakumar J, K M, N, V, T, P. Pharmaceutical Supply Chain Management: A New Perspective. In: Advances in Production and Industrial Engineering. Singapore: Springer Nature Singapore; 2021. p. 419–27.

[2] World Health Organization. Substandard and falsified medical products. [Internet]. 2018 [cited 2025 Aug 23]. Available from: https://www.who.int/news-room/fact-sheets/detail/substandard-and-falsified-medical-products

[3] World Health Organization. A study on the public health and socioeconomic impact of substandard and falsified medical products. Geneva: World Health Organization; 2017.

[4] Lawal OP, Babatunde JO, Owusu-Ansah S, Ani CP, Adegbesan AC, Hashim H, et al. Antibiogram and Molecular Characterization of Extended-Spectrum Beta-Lactamase-Producing Klebsiella pneumoniae in a Nigerian Teaching Hospital. Microbes, Infection and Chemotherapy. 2025 Mar 24;5:e2305–e2305

[5] O'Neill J. Tackling drug-resistant infections globally: final report and recommendations. The Review on Antimicrobial Resistance. 2016.

[6] Mehralian G, Rangchian M, Javadein SRA, Peikanpour M. A systematic literature review on pharmaceutical supply chain: A glimpse of manufacturer-to-patient journey. J Pharm Policy Pract. 2021 Dec;14(1):82.

[7] Nittas V, Lun P, Ehrler F, Puhan MA, Myli D, Mavridis D, et al. Electronic technologies for the authentication of medicines: a systematic review and network meta-analysis. Lancet Digit Health. 2019 Aug;1(4):e182–91.

[8] Ozawa S, Evans DR, Bessias S, Haynie DG, Yemeke TT, Laing SK, et al. Prevalence and Estimated Economic Burden of Substandard and Falsified Medicines in Low- and Middle-Income Countries: A Systematic Review and Meta-analysis. JAMA Netw Open. 2018 Aug 3;1(4):e181662.

[9] Kaur H, Clarke S, Lalani M, Phanouvong S, Ferreira PE, St-Jean M, et al. A review of the quality of selected antimalarial medicines in circulation in the tropics. Malar J. 2022 Dec;21(1):151.

[10] Nayyar GML, Breman JG, Newton PN, Herrington J. Poor-quality antimalarials in southeast Asia and sub-Saharan Africa. Lancet Infect Dis. 2012 Jun;12(6):488–96.

[11] United Nations Office on Drugs and Crime (UNODC). Trafficking in fraudulent medicine. Vienna: UNODC; 2019.

[12] Ventola CL. The antibiotic resistance crisis: part 1: causes and threats. P T. 2015 Apr;40(4):277–83.

[13] Murray CJL, Ikuta KS, Sharara F, Swetschinski L, Aguilar GR, Gray A, et al. Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. The Lancet. 2022 Feb;399(10325):629–55.

[14] Andersson DI, Hughes D. Microbiological effects of sublethal levels of antibiotics. Nat Rev Microbiol. 2014 Jul;12(7):465–78.

[15] Lawal O, Oyebamiji HO, Kelenna IJ, Chioma FJ, Oyefeso E, Adeyemi BI, et al. A Review on Usage of Digital Health Literacy to Combat Antibiotic Misuse and Misinformation in Nigeria: Review Article. Journal of Pharma Insights and Research. 2025 Apr 5;3(2):258–69.

[16] The WWARN Antimalarial Quality Surveyor Study Group. The quality of artemisinin-containing antimalarials in Tanzania: results of a nationally representative survey. Malar J. 2015 Dec;14(1):475.

[17] Dondorp AM, Nosten F, Yi P, Das D, Phyo AP, Tarning J, et al. Artemisinin Resistance in Plasmodium falciparum Malaria. N Engl J Med. 2009 Jul 30;361(5):455–67.

[18] Okeke IN, Lamikanra A, Edelman R. Socioeconomic and behavioral factors leading to acquired bacterial resistance to antibiotics in developing countries. Emerg Infect Dis. 1999;5(1):18–27.

[19] Kshetri N. Blockchain and pharmaceutical supply chains in developing countries. Soc Sci Med. 2021 Mar;272:113746.

[20] Mackey TK, Kuo TT, Gummadi B, Clauson KA, Church G, Grishin D, et al. "Fit-for-purpose?" – challenges and opportunities in applications of blockchain technology in the future of healthcare. BMC Med. 2019 Dec;17(1):68.

[21] Krawiec RJ, White M. Blockchain: A new tool to prevent counterfeit drugs. J Am Pharm Assoc. 2016;56(4):e1.

[22] Torky M, Hassanein AE. Integrating blockchain and artificial intelligence in the internet of things for a smart pharmaceutical supply chain. Arab J Sci Eng. 2021 Jul 1;46(7):6911–28.

[23] Ghafurian S, Lotfian R, Khosravi-Farsani M. A survey on counterfeit drug detection methods using AI. J Supercomput. 2021 Jul 1;77(7):6995–7028.

[24] Musamih A, Salah K, Jayaraman R, Yaqoob I, Al-Hammadi Y, Omar M. A Blockchain-Based Approach for Drug Traceability in the Healthcare Supply Chain. IEEE Access. 2021;9:9728–43.

[25] Svedkauskaite S, Tamosiunas V, Ragaisis K, Lukosevicius A. Smart packaging technologies for pharmaceuticals: a review. Sensors. 2023;23(4):2268.

[26] Olaitan OF, Akatakpo ON, Victor CO, Emejulu CJ, Ayoola TM, Olayiwola DE, et al. Secure and Resilient Industrial IoT Architectures for Smart Manufacturing: A Comprehensive Review. Journal of Engineering Research and Reports. 2025 Jun 21;27(6):331–44.

[27] Mackey TK, Liang BA. Combating counterfeit medicines: a proposed framework and new global treaty. J Law Med Ethics. 2011;39(3):304–20.

[28] Tagde P, Tagde S, Bhattacharya T, Tagde P, Chopra H, Akter R, et al. Blockchain and artificial intelligence technology in e-Health. Environ Sci Pollut Res. 2021 Oct 1;28(38):52810–31.

[29] World Health Organization. Global strategy on digital health 2020-2025. Geneva: World Health Organization; 2021.

[30] Ayukekbong JA, Ntemgwa M, Atabe AN. The threat of antimicrobial resistance in developing countries: causes and control strategies. Antimicrob Resist Infect Control. 2017 Dec;6(1):47.

[31] Wirtz VJ, Hogerzeil HV, Gray AL, Bigdeli M, de Joncheere CP, Ewen MA, et al. Essential medicines for universal health coverage. The Lancet. 2017 Jan;389(10067):403–76.

[32] Koutkias VG, McNair P. A systematic review on mobile-based systems for medication adherence. J Biomed Inform. 2020 Sep;109:103525.

[33] Gualano MR, Gili R, Scaioli G, Bert F, Siliquini R. The role of the media in shaping public opinion and behaviors towards antimicrobial resistance. J Public Health Res. 2015 Mar 31;4(1):443.