A Comprehensive Risk Assessment Framework for Addressing Hormonal and Antibiotic Residues in Meat Supply Chains in the USA

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ABSTRACT

Hormonal and antibiotic residues in meat supply chains pose significant risks to public health, environmental sustainability, and regulatory compliance in the United States. This review presents a comprehensive risk assessment framework designed to address these challenges through systematic identification, evaluation, and mitigation of residue contamination across beef, poultry, and pork production systems. The framework integrates hazard identification, exposure assessment, and risk characterization to quantify potential health impacts, including antibiotic resistance and endocrine disruption, particularly among vulnerable populations. Key sources of contamination, such as growth hormones and antibiotic overuse, are analyzed alongside pathways of environmental leakage through soil and water systems. Regulatory frameworks, including those established by the Food and Drug Administration (FDA), the U.S. Department of Agriculture (USDA), and the Environmental Protection Agency (EPA), are critically reviewed to highlight compliance gaps and enforcement challenges. The review proposes enhanced surveillance programs leveraging advanced detection technologies, such as enzyme-linked immunosorbent assays (ELISA) and liquid chromatography-mass spectrometry (LC-MS/MS), to ensure residue monitoring throughout the supply chain. Strategies for mitigation emphasize preventive approaches, including alternatives to antibiotics, improved livestock management practices, and blockchain-based traceability systems to enhance transparency. Stakeholder engagement and capacity building are essential components of the framework, promoting collaboration between regulators, producers, and consumers through education and training programs. Performance metrics and continuous auditing mechanisms are also recommended to assess effectiveness and enable adaptive responses to emerging risks. This framework advocates for a balanced approach that prioritizes food safety while supporting economic efficiency and sustainable agricultural practices. Future directions include the integration of artificial intelligence for predictive analytics and the development of harmonized international standards to improve residue management globally. Ultimately, this framework aims to safeguard consumer health, protect ecosystems, and strengthen the resilience of meat supply chains in the USA.

Keywords: Risk assessment, Framework, Hormonal, Meat supply chains, USA

INTRODUCTION

The meat supply chains in the United States represent a complex network that spans from animal husbandry through to consumer distribution (Abass *et al*., 2024). These supply chains include several phases: pre-production (breeding and animal husbandry), production (feeding and growth), processing (slaughtering and packaging), and distribution (transportation to retail outlets). As one of the largest meat producers globally, the U.S. meat industry plays a crucial role in the economy, with beef, poultry, and pork as key components of the agricultural and food sectors (Ajirotutu *et al*., 2024). However, alongside its vast scale and economic significance, meat production faces critical challenges related to food safety, particularly concerning the use of hormones and antibiotics in animal farming (Bassey and Ibegbulam, 2023; Agupugo *et al*., 2024).

Food safety is a central concern for public health, as improper practices during meat production can result in the contamination of products with harmful residues (Folorunso *et al*., 2024). Such residues are of significant concern because of their potential to affect consumer health, disrupt ecosystems, and cause widespread social and economic issues. Hormonal and antibiotic residues are some of the most common contaminants in meat products. Regulatory bodies like the U.S. Food and Drug Administration (FDA) and the Department of Agriculture (USDA) have instituted guidelines to control these residues. However, the effectiveness of these measures remains a topic of concern due to inconsistencies in enforcement, evolving farming practices, and the growing public demand for safer, sustainably produced meat (Bassey, 2023; Toromade *et al*., 2024).

Hormonal and antibiotic residues in meat products are pervasive, and their prevalence continues to pose a significant risk to both public health and the environment (Abass *et al*., 2024). Hormones are used in animal husbandry to promote growth and improve feed efficiency, while antibiotics are employed to prevent disease outbreaks and promote growth. Despite regulatory limits on their use, studies show that residue levels still exceed acceptable thresholds in some cases, raising concerns about their potential health effects. Long-term exposure to these residues has been linked to a variety of health issues, including antibiotic resistance, allergic reactions, and hormone-related disruptions in human endocrine systems (Agupugo *et al*., 2022). The emergence of antibiotic-resistant bacteria is a particularly pressing issue, as it complicates the treatment of infections, potentially leading to severe health outcomes and public health crises. Environmental impacts also result from the use of hormones and antibiotics in meat production. When these substances enter water systems through runoff, they can contaminate natural ecosystems, promoting the development of antibiotic-resistant bacteria in the environment. This contamination has far-reaching implications for biodiversity, as well as the health of animals and humans exposed to these substances through the food chain (Ajirotutu *et al*., 2024). Therefore, addressing these risks is not only a matter of food safety but also a crucial component of environmental health.

The primary objective of this framework is to develop a systematic and comprehensive approach for identifying, assessing, and mitigating the risks associated with hormonal and antibiotic residues in meat production systems. By using a multi-faceted risk assessment model, this framework aims to provide a structured methodology for understanding the sources and movement of these residues throughout the supply chain, from pre-production to distribution. The framework will focus on key risk factors at each stage, incorporating regulatory guidelines to ensure compliance with federal standards set by the FDA and USDA. Another key objective is to enhance existing food safety practices by integrating innovative technologies, data collection techniques, and best practices from various sectors. The goal is to proactively reduce contamination risks and ensure that meat products remain safe for consumers. By assessing the effectiveness of current regulatory mechanisms and proposing new interventions, the framework seeks to improve overall safety standards in meat production and address emerging concerns such as antibiotic resistance (Bassey, 2023; Folorunso *et al*., 2024).

This framework will primarily focus on the beef, poultry, and pork supply chains, which represent the largest segments of U.S. meat production. Each of these supply chains presents unique challenges related to hormonal and antibiotic residues, with specific risks at different stages of the production process. Therefore, the framework will encompass all phases of meat production: pre-production (e.g., breeding, animal health management), production (e.g., feeding, antibiotic usage), processing (e.g., slaughter, carcass handling), and distribution (e.g., packaging, transportation). Additionally, the framework will address the complexity of managing risks at various scales, from large industrial operations to smaller farms. It will examine how each stage of the supply chain contributes to residue contamination, with a focus on identifying critical control points where interventions are most needed (Agupugo *et al*., 2022). The scope will also include the development of real-time monitoring systems, predictive models, and traceability mechanisms to track hormone and antibiotic usage, ensuring accountability and fostering consumer confidence in the safety of U.S. meat products. Through a holistic approach, this framework aims to support the meat industry in adopting safer, more sustainable practices while aligning with regulatory and public health standards.

RISK ASSESSMENT METHODOLOGY

Hazard identification is the first step in risk assessment, involving the detection of hormonal and antibiotic residues in meat products (Eruaga, 2024). Advanced screening methods are used to identify contaminants in both raw and processed meat samples. These methods include microbial inhibition tests, chemical assays, and bioassays that detect the presence of active residues by measuring microbial growth inhibition or biochemical

reactions. Modern analytical techniques have significantly enhanced residue detection accuracy and sensitivity. The Enzyme-Linked Immunosorbent Assay (ELISA) is a widely employed method for preliminary screening due to its high specificity, cost-effectiveness, and rapid turnaround time. ELISA tests detect target molecules, such as antibiotics and hormones, using antigen-antibody reactions (Toromade *et al*., 2024). For confirmatory testing, Liquid Chromatography-Mass Spectrometry (LC-MS/MS) provides high sensitivity and quantitative precision. This technology allows simultaneous detection of multiple residues at trace levels, ensuring compliance with regulatory limits. Gas Chromatography-Mass Spectrometry (GC-MS) is also used, particularly for volatile compounds. These advanced methods are essential for identifying residues in muscle tissues, fat, liver, and kidneys, which are primary sites of residue accumulation. Emerging techniques, such as biosensors and portable spectrometers, further improve field testing capabilities, enabling real-time monitoring and reducing laboratory dependence (Toromade *et al*., 2024).

Exposure assessment evaluates the potential intake of residues through dietary consumption. This process involves analyzing food consumption patterns, residue levels detected in meat products, and serving size data to estimate daily intake values (Eruaga *et al*., 2024). Food Frequency Questionnaires (FFQs) and dietary recall surveys are commonly employed to determine consumption rates of specific meat types. Mathematical models, such as the Monte Carlo Simulation, predict residue exposure levels by accounting for variability in consumption patterns, cooking practices, and contamination frequencies. These models incorporate residue degradation rates during food preparation and cooking, providing more realistic estimates of exposure. Risk thresholds are established using Acceptable Daily Intake (ADI) values, defined by regulatory agencies such as the Food and Drug Administration (FDA) and Codex Alimentarius. The Maximum Residue Limits (MRLs) set for each compound serve as benchmarks for permissible contamination levels (Adepoju *et al*., 2019). For example, the MRL for tetracycline in muscle tissue is 100 μg/kg. Exceeding these thresholds indicates a potential health hazard and necessitates intervention.

Risk characterization involves correlating exposure levels with biological effects, assessing both acute and chronic risks. Dose-response relationships determine the severity of adverse outcomes based on residue concentrations (Agupugo and Tochukwu, 2021). For antibiotics, sublethal doses may foster antibiotic-resistant bacterial strains, while higher doses can induce allergic reactions and gut microbiome disruption. Hormonal residues are assessed using endocrine-disrupting potential studies. Low-dose effects, such as altered gene expression and hormonal imbalances, highlight the non-linear dose-response relationship associated with these compounds. Benchmark Dose (BMD) modeling further refines these assessments by identifying critical thresholds for adverse effects. Acute exposure risks are evaluated based on short-term dietary intake exceeding safety thresholds. Symptoms such as nausea, vomiting, and hypersensitivity reactions may occur, necessitating immediate interventions like product recalls. Chronic exposure assessments focus on long-term health outcomes, including cancer, infertility, and immune suppression, associated with cumulative residue buildup (Eruaga *et al*., 2024). Risk Quotients (RQs) are calculated by dividing estimated dietary exposure by the Reference Dose (RfD), a safety benchmark derived from toxicological studies. An RQ value greater than 1.0 suggests unacceptable risk levels, prompting stricter regulatory oversight.

The risk assessment methodology provides a systematic approach to identifying, evaluating, and quantifying hazards associated with hormonal and antibiotic residues in meat supply chains (Bassey, 2023). Advanced screening technologies, such as ELISA and LC-MS/MS, enable accurate residue detection, while exposure assessments leverage modeling tools to estimate dietary intake levels. Dose-response evaluations and risk characterization techniques ensure that both acute and chronic health risks are comprehensively analyzed. By integrating these methodologies, stakeholders can make informed decisions to safeguard public health, improve regulatory compliance, and promote sustainable practices in meat production systems. This framework supports the development of targeted interventions and monitoring programs, ensuring the safety and quality of meat products across the U.S. supply chain.

Regulatory Landscape and Compliance Requirements

The regulatory framework governing meat safety in the United States is a complex system involving multiple agencies with distinct yet complementary roles as explain in table 1 (Adeyemo *et al*., 2021). The Food and Drug Administration (FDA), U.S. Department of Agriculture (USDA), Environmental Protection Agency (EPA), and international bodies like Codex Alimentarius all contribute to the standards and enforcement mechanisms

designed to protect consumers from the risks associated with hormonal and antibiotic residues in meat products. The FDA plays a pivotal role in regulating the use of drugs and hormones in animal agriculture, including the approval of veterinary drugs and growth promoters for animals intended for human consumption. Through the Center for Veterinary Medicine (CVM), the FDA sets residue limits for various substances used in livestock, ensuring they do not exceed levels considered harmful to human health (Bassey *et al.,* 2024). The FDA also monitors and ensures the safety of animal feed ingredients, including antibiotics and hormones, under the Federal Food, Drug, and Cosmetic Act.

The USDA, through the Food Safety and Inspection Service (FSIS), is responsible for overseeing meat processing plants and ensuring that meat products meet safety standards before reaching consumers. This includes enforcing regulations related to hormone and antibiotic residues (Oyewale and Bassey, 2024). FSIS ensures that the meat produced and processed in the U.S. adheres to the maximum residue limits (MRLs) set by the FDA and maintains food safety during slaughter, processing, packaging, and storage. The USDA also plays a key role in conducting routine inspections and coordinating testing programs to detect residues in finished products. The Environmental Protection Agency (EPA) also has an important role in regulating the environmental impact of antibiotics and hormones used in animal production. The EPA is responsible for setting tolerance levels for pesticide residues in food, including those that may come from antibiotic use (Bassey, 2022). The agency monitors the potential risks to ecosystems posed by agricultural runoff, which may carry hormone and antibiotic residues into water supplies, affecting both wildlife and human populations. Internationally, the Codex Alimentarius Commission, a body established by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO), provides guidelines for food safety and residue limits in meat products. These international standards influence the regulatory landscape within the U.S. by providing harmonized benchmarks for residue limits and food safety practices. The U.S. government adheres to Codex guidelines in its trade agreements and strives to ensure its domestic standards align with international expectations to facilitate safe and equitable global trade (Bassey *et al.,* 2024).

While the regulatory framework in the U.S. is robust, challenges in enforcement persist, leading to gaps in the effectiveness of current measures to control hormonal and antibiotic residues in meat. One key issue is the inconsistency in monitoring and testing systems. While large meat processing facilities are subject to frequent inspection and regulatory oversight, smaller operations may not undergo the same level of scrutiny. Inconsistent application of rules across different states and facilities can create opportunities for non-compliance, especially in areas with fewer resources or weaker enforcement mechanisms (Folorunso, 2024). Furthermore, technological limitations in testing and monitoring systems complicate the detection of residues in meat. Despite advances in residue testing, current methods are not always capable of detecting low levels of contamination or differentiating between natural and synthetic residues. In some cases, outdated testing protocols may not fully align with emerging science, resulting in gaps in regulatory enforcement. Additionally, while large processing plants may employ advanced systems to monitor antibiotic and hormone use, smaller farms and facilities may lack the infrastructure or training to implement similar standards effectively, leading to potential risks in the supply chain. Another challenge lies in the variations in compliance across states and facilities. Regulations regarding the use of hormones and antibiotics in livestock may be enforced differently depending on state laws and local policies. Some states have stricter regulations or more rigorous testing protocols, while others may face challenges in implementing federal guidelines due to limited resources or differing political priorities. This variability creates a fragmented regulatory environment that complicates enforcement efforts and undermines uniform compliance across the country (Adepoju *et al.,* 2018).

In response to growing concerns over public health and environmental risks, there have been several recent policy developments aimed at improving the regulation of hormonal and antibiotic residues in meat. The FDA has updated its residue limits for certain substances, reflecting advances in scientific understanding and evolving concerns about the impact of hormones and antibiotics on human health (Eruaga, 2024). These updates include lower tolerance levels for certain antibiotics and a stronger emphasis on reducing the use of growth-promoting hormones, especially in light of growing concerns over antibiotic resistance. Additionally, there has been a push toward improving testing protocols, including the development of more sensitive and rapid testing technologies. The USDA has increased its focus on improving residue detection in meat products by investing in modern testing methods that can identify trace amounts of contamination. Efforts to enhance testing methods have been accompanied by calls for more frequent and comprehensive inspections, particularly in smaller or less-regulated facilities. Emerging standards for organic and antibiotic-free meat products also reflect changing consumer

preferences and the growing demand for more sustainably produced food. The USDA's National Organic Program (NOP) has set strict guidelines regarding the use of antibiotics and hormones in organic meat production, prohibiting the use of synthetic hormones and limiting antibiotic usage to only those cases where animals are seriously ill. These standards are seen as a response to consumer concerns about the safety and sustainability of conventional meat production practices, and they continue to evolve as the market for organic and antibiotic-free meat expands (Anozie *et al.,* 2024).

Table 1: Regulatory Landscape and Compliance Requirements for Hormonal and Antibiotic Residues in Meat Supply Chains in the USA (Adeyemo *et al.,* 2021)

Regulatory Body/Framework	**Key Regulations/Acts**	**Compliance Requirements**	**Purpose**
U.S. Department of Agriculture (USDA)	Federal Meat Inspection Act (FMIA)	Ensures meat is inspected for safety, labeling accuracy, and compliance with residue tolerance limits.	Protects public health by ensuring safe and properly labeled meat products.
Food Safety and Inspection Service (FSIS)	National Residue Program (NRP)	Monitors and tests for residues of antibiotics, hormones, and pesticides in meat, poultry, and egg products.	Prevents violative residues from entering the food supply chain.
Food and Drug Administration (FDA)	Food, Drug, and Cosmetic Act (FDCA)	Approves drugs and hormones for animal use, sets residue tolerance levels, and enforces withdrawal periods.	Ensures safety of veterinary drugs used in food-producing animals and establishes limits for residues in meat.
Environmental Protection Agency (EPA)	Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)	Regulates pesticides used in animal feed and sets residue tolerance levels for contaminants.	Prevents harmful chemical residues in food products.
Residue Monitoring Programs	USDA-FSIS Residue Monitoring Program	Random sampling and testing of carcasses for hormone and antibiotic residues to detect violations.	Provides ongoing surveillance to ensure compliance and detect illegal use of substances.

While significant progress has been made in establishing regulatory standards to control hormonal and antibiotic residues in the U.S. meat supply chain, challenges remain in enforcement, particularly with regard to variations in compliance and gaps in monitoring systems. Recent policy developments, including updates to residue limits and improvements in testing protocols, reflect a growing commitment to addressing these issues (Folorunso, 2024). Furthermore, emerging standards for organic and antibiotic-free meat align with consumer demand for safer, more sustainable production practices and are likely to play an increasingly important role in shaping future regulatory landscapes.

Sources and Pathways of Residue Contamination

Growth hormones are commonly used in livestock production to enhance growth rates, improve feed efficiency, and increase lean muscle mass. Among the most widely used hormones are estrogen, progesterone, trenbolone acetate, and zeranol (Itua *et al.,* 2024). These compounds are administered to cattle through implants, injections, or feed additives to regulate growth cycles and improve meat quality. While these hormones are effective for production efficiency, their residues can accumulate in animal tissues, posing potential risks to human health. Hormonal residues primarily accumulate in adipose tissues, liver, and kidneys due to their lipophilic (fat-soluble) nature. When administered, hormones metabolize within the animal's body, but incomplete metabolism can leave

active residues stored in tissues. For example, trenbolone acetate is metabolized into 17-alpha-trenbolone, which can persist in the muscle and fat of treated animals. Additionally, excretion through urine and feces can release unmetabolized hormones into the environment, further contaminating soil and water sources. Hormonal implants and injections may also result in uneven absorption, contributing to localized accumulation near administration sites, such as ears or injection zones (Folorunso e al., 2024). Improper withdrawal periods time allowed between hormone administration and slaughter can exacerbate residue retention, increasing the likelihood of contaminated meat entering the supply chain.

Antibiotics are widely used in animal agriculture for three primary purposes: disease treatment, disease prevention, and growth promotion. Common antibiotics include tetracyclines, sulfonamides, penicillin's, macrolides, and aminoglycosides, all of which can leave residues in edible tissues if not managed properly (Agupugo *et al*., 2024). The prophylactic (preventative) use of antibiotics in livestock operations is a major contributor to residue buildup. In confined animal feeding operations (CAFOs), where animals are raised in close quarters, antibiotics are routinely administered to prevent outbreaks of bacterial diseases. While effective for disease control, this practice often results in excessive antibiotic usage, leading to the accumulation of residues in muscle tissue, liver, kidneys, and bones. Antibiotics are also used as growth promoters, particularly in poultry and swine production, to enhance feed conversion efficiency and accelerate weight gain (Avwioroko, 2023). This non-therapeutic application raises concerns because it not only contributes to residue buildup but also fosters antibiotic resistance in both animals and humans.

Improper dosing, failure to observe withdrawal periods, and off-label drug use further increase the risk of contamination. Inconsistent monitoring and testing programs exacerbate the issue, allowing undetected residues to enter the meat supply chain. Residue contamination is not limited to direct administration within animals; it can also occur through environmental pathways, which amplify the spread of residues beyond farm boundaries.

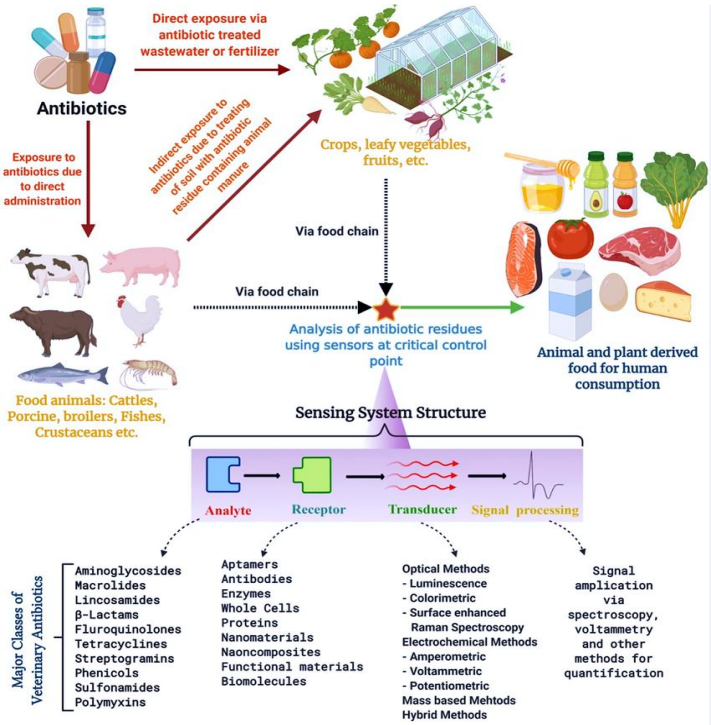

Figure 1: Sources of antibiotic residues in food and how sensors are used to find them at key food chain control points (Liu *et al*., 2022)

One of the most significant environmental pathways is water runoff from livestock operations. Animal manure, which often contains hormones and antibiotics, is commonly used as fertilizer in agricultural fields (Ajirotutu *et al*., 2024). Rainfall or irrigation can wash these substances into nearby rivers, streams, and groundwater systems. Studies have detected traces of estradiol and tetracyclines in surface water, posing risks to aquatic ecosystems and drinking water supplies. Soil serves as another reservoir for residue accumulation. When manure or wastewater containing residues is applied to farmland, these substances can bind to soil particles, leading to long-term contamination. Microbial degradation of antibiotics in soil is often incomplete, enabling residues to persist for months and potentially leach into groundwater. Moreover, hormones such as trenbolone acetate can undergo

chemical transformations in soil, forming metabolites that may retain biological activity and toxicity. Feed is a critical pathway for introducing residues into the meat supply chain. Contaminated feed ingredients, such as fishmeal, soybean meal, or crop silage treated with pesticides or antibiotics, can transfer residues to animals (Ijomah *et al*., 2024). For example, ionophores, a class of antibiotics used in feed additives, are not metabolized completely and may accumulate in tissues. Cross-contamination during feed processing or storage can further amplify the risk, especially in facilities handling multiple feed formulations. Feed contamination is also influenced by storage conditions. Mold growth in improperly stored feed can lead to the production of mycotoxins, which may interact with antibiotics or hormones, creating combined toxic effects.

The sources and pathways of hormonal and antibiotic residues in meat supply chains present a multifaceted challenge requiring rigorous oversight and intervention strategies. Hormonal residues primarily accumulate in animal tissues due to incomplete metabolism and improper withdrawal periods, while antibiotic residues result from excessive use in disease prevention and growth promotion (Toromade *et al*., 2024). Environmental pathways, including water runoff, soil contamination, and feed sources, further complicate the issue by spreading residues beyond their initial points of application as shown as explain in figure 1 (Liu *et al*., 2022). Addressing these challenges necessitates a holistic framework that integrates stringent monitoring, improved residue detection technologies, and sustainable farming practices. Effective regulatory enforcement, combined with ongoing research into residue degradation and mitigation, is critical to safeguarding food safety and public health in the U.S. meat industry.

Risk Identification and Characterization

The presence of hormonal and antibiotic residues in meat products poses significant threats to human health, primarily through antibiotic resistance and endocrine disruption. One of the most pressing concerns is the role of antibiotic residues in promoting antimicrobial resistance (AMR). Residual antibiotics in meat products can expose consumers to subtherapeutic doses of these drugs, enabling bacteria to develop resistance (Eruaga *et al*., 2024). Resistant bacterial strains, such as Escherichia coli and Salmonella, may colonize the gut and transfer resistance genes to other pathogens, reducing the effectiveness of antibiotics used in human medicine. This phenomenon exacerbates global health crises by limiting treatment options for bacterial infections and increasing morbidity and mortality rates. Hormonal residues, including estrogens and androgens, act as endocrine disruptors, interfering with the body's hormonal balance. Chronic exposure to these substances, even at low doses, has been linked to reproductive issues such as infertility, early puberty, and developmental abnormalities. Hormonal contaminants are also associated with hormone-dependent cancers, including breast and prostate cancer, highlighting their potential long-term carcinogenic effects. Prolonged consumption of contaminated meat may lead to bioaccumulation of residues in human tissues, amplifying health risks over time. Studies suggest that residues of trenbolone acetate and zeranol may stimulate abnormal cell growth, increasing cancer risks. Additionally, chronic exposure to antibiotic residues can trigger allergic reactions, gastrointestinal disorders, and immune suppression, making individuals more susceptible to infections (Folorunso *et al*., 2024).

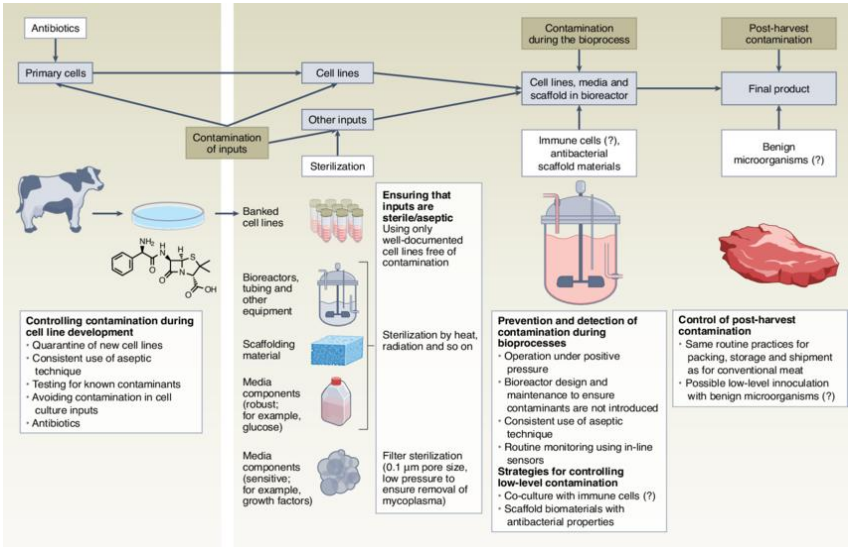

Figure 2: Techniques and approaches to stop microbiological contamination at different phases of the CM manufacturing process (McNamara and Bomkamp, 2022)

Residue contamination extends beyond human health, affecting ecosystems through residue leakage and bioaccumulation in food webs. Hormonal and antibiotic residues discharged into the environment via animal manure, wastewater runoff, and fertilizer application can disrupt natural ecosystems. Residues entering aquatic environments may mimic natural hormones, causing endocrine disruption in fish and amphibians. For example, 17-beta-estradiol has been shown to feminize male fish, impairing reproduction and altering population dynamics. In terrestrial ecosystems, residues affect soil microbial communities, inhibiting beneficial bacteria involved in nitrogen cycling and organic matter decomposition (Toromade *et al*., 2024). This disruption reduces soil fertility and ecosystem resilience. Antibiotics and hormones can persist in environmental matrices such as soil, sediments, and water bodies, where they are absorbed by plants and ingested by herbivores, entering the food web. Bioaccumulation leads to magnification of residues at higher trophic levels, including humans, exacerbating exposure risks. The persistence of these substances poses long-term challenges for ecosystem restoration and sustainability.

Certain populations are disproportionately vulnerable to the health effects of residue contamination due to biological susceptibility and dietary habits (Eruaga *et al*., 2024). Children, pregnant women, elderly individuals, and immunocompromised patients are at elevated risk. Children's developing endocrine systems make them particularly sensitive to hormonal disruptions, potentially leading to developmental delays and growth abnormalities. Immunocompromised individuals, including those undergoing chemotherapy or living with HIV/AIDS, face higher risks of infection from antibiotic-resistant bacteria (Ajirotutu *et al*., 2024). Pregnant women are also vulnerable, as residues can cross the placental barrier, affecting fetal development. For instance, exposure to synthetic estrogens during pregnancy has been linked to birth defects and hormonal imbalances in offspring.

Dietary habits and meat consumption patterns influence exposure levels. High meat intake, particularly in regions with intensive livestock farming, elevates the risk of residue ingestion. The popularity of fast-food diets and processed meats further exacerbates exposure among lower-income populations, who may rely on inexpensive meat products with limited oversight. Geographic and cultural factors also play a role. Regions with higher consumption of red meat and organ meats which tend to accumulate residues are more likely to experience elevated exposure risks. Consumers seeking organic or antibiotic-free meat may mitigate risks, but limited access and higher costs pose barriers to widespread adoption (Avwioroko, 2024). The identification and characterization of risks associated with hormonal and antibiotic residues highlight the multifaceted nature of the challenge. Human health risks, such as antibiotic resistance, endocrine disruption, and cancer, underscore the urgency for stricter residue monitoring and mitigation strategies. Environmental impacts, including ecosystem disruption and bioaccumulation, further emphasize the need for sustainable waste management and residue control practices. Vulnerable populations, including children, immunocompromised individuals, and frequent meat consumers, face heightened risks, necessitating targeted public health interventions and consumer awareness campaigns (Bature *et al*., 2024). A comprehensive risk assessment framework must integrate surveillance, early detection, and regulatory compliance to safeguard both public health and environmental integrity in the U.S. meat supply chain as explain in figure 2 (McNamara and Bomkamp, 2022).

Mitigation Strategies and Control Measures

Ensuring the safety of meat products in the U.S. requires a multifaceted approach to mitigate the risks posed by hormonal and antibiotic residues (Toromade and Chiekezie, 2024). Effective strategies encompass prevention, monitoring, regulatory compliance, and emergency response protocols. To reduce reliance on antibiotics and growth hormones, researchers are exploring natural alternatives such as probiotics, prebiotics, and plant extracts. Probiotics, like Lactobacillus spp., enhance gut health, reduce pathogen colonization, and improve nutrient absorption, leading to better growth rates without antibiotic supplementation. Plant-based phytochemicals, including essential oils and polyphenols, exhibit antimicrobial properties, minimizing infections and the need for antibiotic treatments as explain in figure 3 (Suganya *et al*., 2022). Adopting biosecurity measures, vaccination programs, and optimized feeding regimes can reduce disease outbreaks and improve overall animal health, minimizing the demand for pharmaceutical interventions. Practices such as rotational grazing, sanitation protocols, and genetic selection for disease resistance are instrumental in preventing contamination at the source. Emphasizing animal welfare through stress-reduction techniques also curtails hormonal imbalances, thereby lowering residue levels in meat products (Udo *et al*., 2024).

Comprehensive residue testing programs are critical for early detection of contaminants. Routine sampling and laboratory analysis using technologies like ELISA and LC-MS/MS ensure compliance with regulatory limits. Regular audits of processing facilities and supply chains further reinforce accountability (Folorunso, 2024). Modern technologies, such as Blockchain and the Internet of Things (IoT), enable real-time tracking and traceability of meat products from farm to fork. Blockchain provides tamper-proof data logs, documenting every stage of production, processing, and distribution. IoT sensors monitor temperature, storage conditions, and feed quality, facilitating prompt identification of deviations that could lead to contamination. These systems enhance supply chain transparency, streamline inspections, and bolster consumer confidence.

Voluntary certification programs, such as the USDA Organic and Certified Humane labels, establish standards for antibiotic-free and hormone-free meat. These programs incentivize producers to adopt sustainable practices while offering consumers informed choices (Adewale *et al*., 2024). Certification also requires regular audits and third-party verifications, ensuring compliance with established protocols. Developing SOPs tailored to specific production systems is crucial for minimizing residue contamination. SOPs include feed management protocols, withdrawal periods before slaughter, and sanitation guidelines for equipment and facilities. Training programs for farmers and processors further reinforce adherence to these procedures, reducing contamination risks at multiple stages.

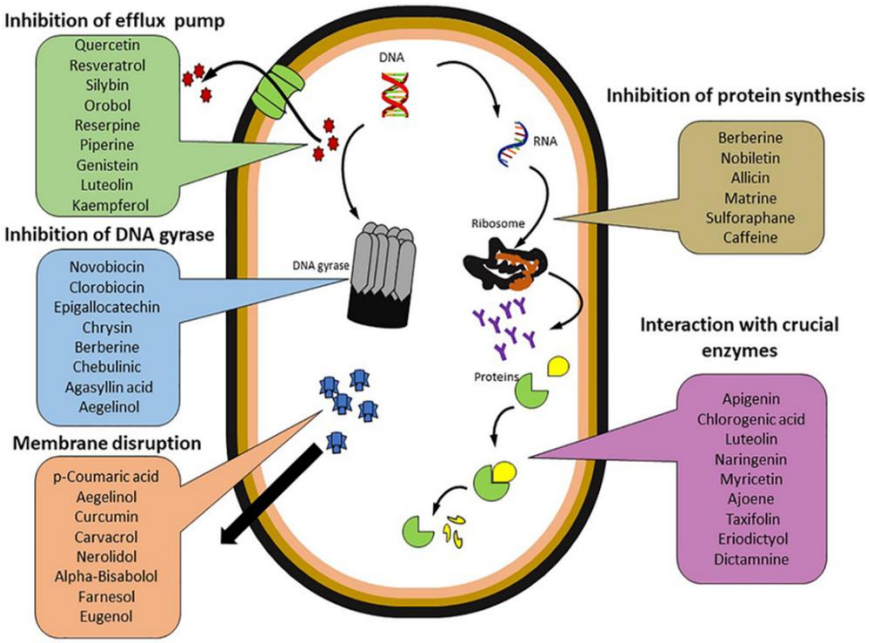

Figure 3: Promising phytochemicals against Multi Drug Resistant bacteria (Suganya *et al*., 2022)

In cases of contamination, rapid recall systems are vital for preventing the distribution of unsafe products. Centralized databases, such as the FDA's Reportable Food Registry, streamline reporting and response efforts. Automated consumer alert systems, including mobile notifications and online databases, ensure the public receives timely information about affected products. Effective incident management protocols involve containment measures, root-cause analysis, and corrective actions to address contamination sources (Ogunyemi and Ishola, 2024). Facilities should maintain contingency plans for managing recalls, including product quarantines, disinfection procedures, and re-testing programs before resuming operations. Establishing communication channels with regulators and stakeholders ensures coordinated responses to minimize health risks and financial losses. Mitigating hormonal and antibiotic residues in meat supply chains demands a holistic strategy integrating prevention, monitoring, regulatory compliance, and emergency response measures. Alternatives to antibiotics, including probiotics and plant-based additives, provide sustainable options for promoting animal health. Enhanced monitoring systems, leveraging Blockchain and IoT technologies, enable traceability and real-time surveillance of contaminants. Regulatory compliance tools, such as certification programs and SOPs, further promote safe practices and consumer trust. Moreover, emergency response protocols ensure swift action in the event of contamination, protecting public health and maintaining market stability. By implementing these strategies, the U.S. meat industry can address residue risks effectively, enhancing food safety and sustainability in the supply chain (Ishola, 2024).

Stakeholder Engagement and Capacity Building

Addressing the risks of hormonal and antibiotic residues in meat supply chains requires a coordinated effort involving diverse stakeholders. Effective engagement and capacity building strategies empower participants across the supply chain to implement sustainable practices, ensure compliance, and promote food safety. This outlines the roles of key stakeholders, education and training programs, and collaborative partnerships essential for strengthening the meat industry's capacity to mitigate residue contamination (Avwioroko and Ibegbulam, 2024). Farmers and producers are the first line of defense in preventing residue contamination. They influence feeding practices, antibiotic usage, and animal husbandry, making their engagement vital for residue mitigation. Providing incentives for adopting sustainable practices, such as organic farming and reduced antibiotic use, motivates producers to prioritize food safety.

Processors and distributors ensure that meat products meet regulatory standards before reaching consumers. Their role includes testing for residues, maintaining traceability, and implementing standard operating procedures (SOPs). Collaboration with processors helps enforce compliance and integrate monitoring technologies like Blockchain and IoT. Regulatory bodies such as the Food and Drug Administration (FDA) and the U.S. Department of Agriculture (USDA) oversee compliance, testing, and enforcement. Their role extends to policy development, conducting inspections, and updating residue limits to reflect emerging risks. Strengthening regulatory frameworks ensures consistent monitoring and enforcement across states. Consumers play an influential role through demand for safe, antibiotic-free products (Ogunyemi and Ishola, 2024). Awareness programs empower them to make informed purchasing decisions, encouraging producers to adopt residue-free practices. Consumer advocacy groups also push for stricter regulations and greater transparency in labeling.

Training farmers and producers on alternative practices, such as using probiotics and plant-based supplements, reduces dependence on antibiotics and hormones. Workshops cover topics like biosecurity, vaccination protocols, and sanitation practices, providing practical tools for residue prevention. Educational programs targeting processors focus on residue detection techniques, including ELISA and LC-MS/MS. Inspectors receive specialized training on sampling protocols, compliance audits, and risk assessment methodologies to improve monitoring systems. Public education initiatives highlight the risks associated with residue contamination and emphasize the benefits of consuming certified organic or antibiotic-free meat (Ajirotutu *et al*., 2024). Outreach efforts, including media campaigns and school programs, promote safer consumption patterns and encourage advocacy for better regulations.

Partnerships between universities, research institutions, and non-governmental organizations (NGOs) foster research and innovation in residue mitigation. Universities contribute expertise in risk modeling and testing technologies, while NGOs facilitate community engagement and policy advocacy. Collaborative research programs develop sustainable alternatives to antibiotics and hormones, bridging the gap between science and practice (Iommi *et al*., 2024). Engaging the private sector, including meat processors, retailers, and technology providers, promotes the adoption of smart technologies for monitoring and traceability. Companies investing in Blockchain systems and IoT devices enhance transparency and accountability across supply chains. Global partnerships with organizations like the World Health Organization (WHO) and the Codex Alimentarius Commission help harmonize residue standards and regulations. Sharing best practices and technological advancements across countries promotes consistent safety standards for international trade and imports. Effective stakeholder engagement and capacity building are fundamental to mitigating the risks of hormonal and antibiotic residues in meat supply chains. Engaging farmers, processors, regulators, and consumers ensures a collective approach to food safety. Education and training programs equip stakeholders with the knowledge and tools to implement sustainable practices and monitoring systems. Collaborative efforts, including cross-sector partnerships and international cooperation, foster research, innovation, and harmonized standards. By strengthening stakeholder capacity and promoting collaboration, the U.S. meat industry can enhance residue control, ensuring public health and sustainability (Igwe *et al*., 2024).

Evaluation and Continuous Improvement

Implementing a comprehensive framework for mitigating hormonal and antibiotic residues in meat supply chains necessitates ongoing evaluation and continuous improvement. This process ensures that the framework remains effective, adapts to emerging risks, and sustains compliance with evolving regulatory standards (Ogunyemi and

Ishola, 2024). Key areas of focus include performance metrics, auditing mechanisms, and integration of innovative technologies for risk adaptation.

Establishing measurable performance indicators is critical for assessing the framework's success. Metrics should evaluate residue reduction levels, regulatory compliance rates, and testing accuracy. Measured through periodic sampling and testing programs to detect hormone and antibiotic concentrations. Reduction trends indicate the efficacy of preventive and monitoring strategies. Tracking adherence to FDA, USDA, and EPA standards ensures alignment with legal and safety requirements. Evaluating the performance of testing methods, such as enzyme-linked immunosorbent assays (ELISA) and liquid chromatography-mass spectrometry (LC-MS/MS), ensures early and accurate detection of residues (Okedele *et al*., 2024). Measuring response times to contamination incidents evaluates readiness and effectiveness in managing emergencies. Comparative analysis of residue levels over time demonstrates the impact of mitigation strategies. Increasing compliance rates across facilities and states highlights widespread adoption of best practices. Key metrics also include rates of non-compliance violations and the frequency of recalls, reflecting the need for corrective actions.

Regular audits verify that established protocols are followed, identify gaps, and recommend corrective measures. Evaluating practices from feed sourcing to processing and distribution to ensure residue prevention. Reviewing testing accuracy, sample collection processes, and laboratory performance to maintain data integrity. Inspecting compliance with Standard Operating Procedures (SOPs) and certification programs for antibiotic-free products. Transparency in reporting fosters trust among stakeholders, including regulators and consumers. Publish audit outcomes and compliance data through accessible platforms. Share recall alerts and corrective action plans to demonstrate accountability (Adefila *et al*., 2024). Provide progress updates on achieving performance targets, promoting continuous improvement.

Modernizing detection systems enhances the framework's capacity to address evolving risks. Biotechnology advancements, such as biosensors and genetic markers, improve residue detection sensitivity. AI-based tools streamline data analysis, enabling real-time predictions and anomaly detection. Technologies like Blockchain enhance traceability, while IoT-enabled devices monitor feed and water quality, identifying contamination risks early. Monitoring the introduction of new drugs and their residues to adapt standards accordingly. Evaluating how environmental shifts affect residue pathways, such as runoff patterns and bioaccumulation (Toromade and Chiekezie, 2024). Aligning U.S. practices with Codex Alimentarius and international standards to ensure safety in global supply chains. Framework updates should incorporate findings from risk assessments and pilot studies. Adaptive strategies must also address consumer preferences, including rising demand for organic and antibiotic-free products, by supporting certification programs and sustainable practices.

Evaluating and improving the framework for residue control ensures ongoing protection of public health and environmental sustainability. Performance metrics track progress, while auditing and transparent reporting mechanisms hold stakeholders accountable. Incorporating biotechnology, AI-based monitoring, and blockchain systems strengthens adaptability to emerging risks and technological advancements (Ogunyemi and Ishola, 2024). The framework's capacity for continuous improvement supports regulatory compliance, reduces contamination risks, and enhances public trust. By fostering data-driven decision-making and embracing innovations, the U.S. meat supply chain can achieve long-term resilience and sustainability.

CONCLUSION

This review highlights the pressing need for a comprehensive risk assessment framework to address hormonal and antibiotic residues in meat supply chains across the United States. Key insights emphasize the importance of balancing food safety, animal welfare, and economic interests to ensure sustainable and ethical production practices. Residue contamination poses serious risks to public health and the environment, necessitating coordinated efforts to enhance detection, monitoring, and mitigation strategies. A holistic framework, integrating technological advancements and regulatory compliance, offers a structured approach to minimize these risks and safeguard consumer health.

A call-to-action urges policymakers, researchers, and industry stakeholders to strengthen regulatory enforcement and invest in advanced research. Enhanced monitoring systems, such as real-time predictive technologies, can improve early detection and response to contamination incidents. Promoting consumer awareness about residue

risks and supporting sustainable livestock practices are essential for fostering public trust and driving market demand for safer, antibiotic-free products. Additionally, investment in capacity building programs, including training workshops and public outreach campaigns, is critical for empowering farmers and processors to adopt best practices and regulatory standards.

Future directions should prioritize the integration of predictive analytics and AI-driven tools to forecast risks and improve decision-making processes. Leveraging biotechnology and blockchain-based traceability will enhance transparency and accountability in supply chains. Furthermore, expanding global cooperation through partnerships with international organizations can align U.S. standards with Codex Alimentarius and promote safer, harmonized food systems worldwide.

Addressing hormonal and antibiotic residues requires a multifaceted strategy that combines scientific innovation, policy reforms, and stakeholder collaboration. By continuously adapting to emerging risks and technological advancements, the U.S. can build a resilient meat supply chain that prioritizes health, sustainability, and consumer confidence.

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