



Enhancing milk safety in the USA: A holistic framework for controlling aflatoxin M1 and pathogenic microorganisms in dairy supply chains

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Abstract

Milk safety is a critical public health concern in the United States due to the potential presence of aflatoxin M1 and pathogenic microorganisms, such as *Escherichia coli*, *Salmonella*, and *Listeria monocytogenes*. These contaminants pose severe health risks, including carcinogenic effects and foodborne illnesses, while threatening consumer confidence and economic stability in the dairy industry. This review proposes a holistic approach for controlling aflatoxin M1 and microbial hazards in dairy supply chains through integrated preventive, monitoring, and intervention strategies. The framework emphasizes enhanced feed quality management to mitigate aflatoxin B1 contamination at the source, coupled with advanced detection technologies, including enzyme-linked immunosorbent assays (ELISA) and high-performance liquid chromatography (HPLC) for rapid and accurate testing. Microbial risks are addressed through modern decontamination techniques such as ultraviolet (UV-C) light, ozonation, and high-pressure processing (HPP). Additionally, blockchain-enabled traceability systems and Internet of Things (IoT)-based real-time monitoring are proposed to ensure transparency and compliance throughout production, processing, and distribution. These also highlights the role of Hazard Analysis and Critical Control Points (HACCP) systems and the Pasteurized Milk Ordinance (PMO) in aligning practices with regulatory standards. We advocate for workforce training, capacity building, and consumer awareness programs to reinforce safety measures at multiple levels. By integrating cutting-edge technologies with existing best practices, this framework aims to modernize dairy supply chains, enhance regulatory compliance, and reduce contamination risks. The review concludes with recommendations for future research into AI-driven predictive models and adaptive safety systems to further strengthen milk safety. Ultimately, this comprehensive approach ensures sustainable dairy production, protects public health, and promotes consumer confidence in the U.S. milk supply.

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Introduction

Milk is a vital component of human nutrition, providing essential nutrients such as proteins, vitamins, and minerals (Ishola *et al.*, 2024) ^[46]. Its consumption spans all age groups, making it a cornerstone of dietary recommendations worldwide. Ensuring milk safety is crucial for protecting public health and sustaining consumer confidence. Contaminated milk can pose serious health risks, especially to vulnerable populations such as infants, pregnant women, and immunocompromised individuals (Adewale *et al.*, 2024; Toromade *et al.*, 2024) ^[8, 58]. The significance of milk safety extends beyond health concerns, influencing economic stability and international trade compliance.

In the United States, the dairy industry operates through a complex supply chain involving production, processing, storage, and distribution. The sector includes small-scale farms, industrial processing units, and extensive transportation networks, all of which play integral roles in delivering safe and high-quality milk to consumers (Okedele *et al.*, 2024; Toromade and Chiekezie, 2024) ^[54, 58]. Despite stringent regulations and technological advancements, challenges persist in maintaining consistent safety standards due to potential contamination risks at various stages of the supply chain (Ishola *et al.*, 2024) ^[46].

The presence of aflatoxin M1 and pathogenic microorganisms in milk poses significant threats to both public health and economic stability. Aflatoxin M1, a toxic metabolite derived from aflatoxin B1, can contaminate milk through the consumption of contaminated feed by dairy animals (Anjorin *et al.*, 2024; Eruaga *et al.*, 2024) ^[19, 32]. This compound is classified as a potential human carcinogen, leading to severe health outcomes, including liver cancer, immune suppression, and developmental impairments. Similarly, pathogenic microorganisms, such as *Escherichia coli*, *Salmonella* spp., and *Listeria monocytogenes*, can cause foodborne illnesses, resulting in hospitalization and, in severe cases, fatalities (Ogunyemi and Ishola, 2024; Adefila *et al.*, 2024) ^[46, 4].

Beyond health implications, contamination incidents can lead to extensive economic losses due to product recalls, reduced consumer confidence, and trade restrictions. Regulatory bodies, such as the U.S. Food and Drug Administration (FDA) and the Environmental Protection Agency (EPA), enforce strict safety standards. However, achieving compliance remains a persistent challenge due to variability in detection methods, inconsistent monitoring practices, and evolving microbial threats (Adefila *et al.*, 2024) ^[4].

This study aims to develop a comprehensive framework for controlling contaminants in milk, specifically focusing on aflatoxin M1 and microbial contamination. Designing preventive strategies to minimize contamination risks during production and processing stages. Implementing robust monitoring systems for early detection of contaminants. Establishing effective intervention protocols to mitigate contamination and ensure regulatory compliance. Promoting awareness and training programs for stakeholders involved in the dairy supply chain. The scope of this study encompasses the entire dairy supply chain, addressing contamination risks in both raw and processed milk. Particular emphasis is placed on aflatoxin M1 and microbial contamination, as these hazards represent critical safety concerns. Assessing feed quality, animal health, and milking practices. Evaluating pasteurization efficacy and hygienic handling procedures. Investigating temperature control and storage conditions to prevent microbial growth. Analyzing transportation methods and packaging integrity (Ishola, 2024; Folorunso *et al.*, 2024) ^[38, 46]. This holistic approach provides insights into potential vulnerabilities and opportunities for strengthening milk safety protocols. By integrating preventive, monitoring, and intervention strategies, this study aims to enhance public health protection and support sustainable dairy industry practices (Toromade *et al.*, 2024) ^[58].

Risks Associated with Aflatoxin M1 and Pathogenic Microorganisms

Food safety is a critical concern globally, particularly regarding contaminants such as Aflatoxin M1 and pathogenic microorganisms. These hazards pose significant health risks and present challenges in detection and regulation. This section discusses their sources, health impacts, regulatory frameworks, and public health implications as explained in figure 1 (Abrehame *et al.*, 2023) ^[3]. Aflatoxin M1 is a metabolite derived from Aflatoxin B1, a toxin produced by *Aspergillus flavus* and *Aspergillus parasiticus* fungi (Ogunyemi and Ishola, 2024) ^[46]. Livestock ingest contaminated feed containing Aflatoxin B1, which is subsequently metabolized in the liver and excreted into milk as Aflatoxin M1. This toxin is highly stable and can persist even after pasteurization and processing, making it a major concern in dairy products. Aflatoxin M1 is classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC). Chronic exposure is linked to hepatocellular carcinoma (liver cancer), severe liver damage, and immunotoxicity, impairing the immune system's ability to combat infections. Infants and children, due to their reliance on milk, are particularly vulnerable to these adverse effects, raising concerns about developmental toxicity (Eruaga *et al.*, 2024) ^[32].

To mitigate risks, regulatory authorities such as the European Union (EU) and the U.S. Food and Drug Administration (FDA) have established maximum permissible limits for Aflatoxin M1 in milk: 0.05 µg/kg in the EU and 0.5 µg/kg in the U.S. However, accurate detection poses challenges due to the low concentrations of Aflatoxin M1 in milk (Okedele *et al.*, 2024) ^[54]. Advanced analytical techniques like High-Performance Liquid Chromatography (HPLC) and Enzyme-Linked Immunosorbent Assays (ELISA) are commonly employed, though cost and accessibility can limit widespread monitoring (Ajrotutu *et al.*, 2024) ^[15].

Pathogenic microorganisms that contaminate milk and dairy products include *Escherichia coli*, *Salmonella*, *Listeria monocytogenes*, and *Campylobacter*. These bacteria are significant contributors to foodborne illnesses, posing severe health risks, especially for immunocompromised individuals (Avwioroko *et al.*, 2024) ^[21]. Infected animals may directly shed pathogens into milk through mastitis or fecal contamination during milking. Inadequate pasteurization, poor hygiene, and cross-contamination during handling and storage can introduce or amplify microbial contamination. Ingestion of contaminated milk can lead to outbreaks of foodborne illnesses. For example, *Escherichia coli* can cause severe diarrhea, hemolytic uremic syndrome, and kidney failure. *Salmonella* infections may result in gastroenteritis, typhoid fever, and systemic infections (Abass *et al.*, 2024) ^[1]. *Listeria monocytogenes* is associated with listeriosis, characterized by meningitis, septicemia, and miscarriages. *Campylobacter* species are leading causes of bacterial gastroenteritis, often linked to Guillain-Barré syndrome. The persistence of these pathogens in raw milk and improper handling underscores the need for strict hygiene practices and advanced detection methods.

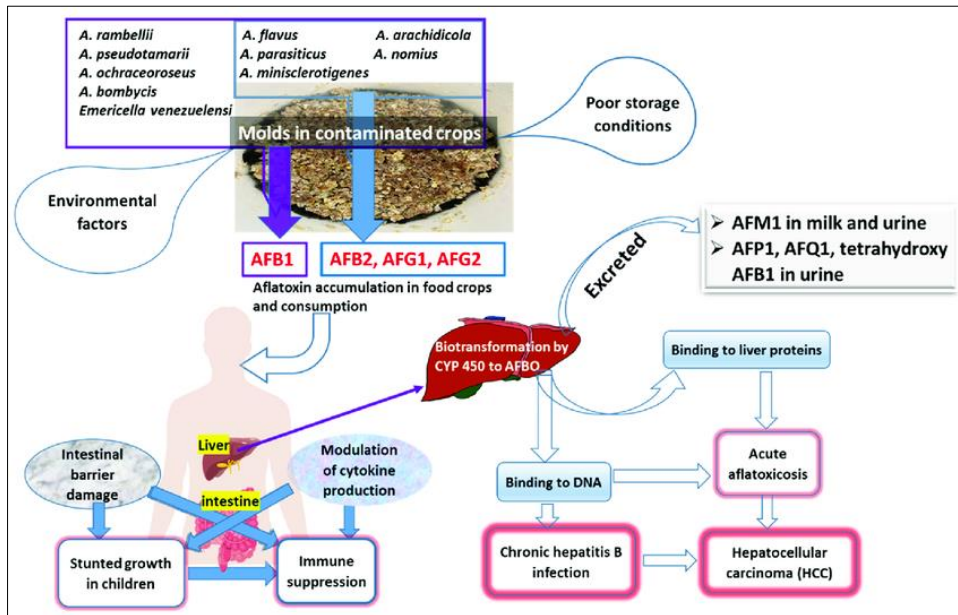


Fig 1: Aflatoxin sources, exposure, and the pathogenic pathway (Abrehame *et al.*, 2023) [3]

Aflatoxin M1 and pathogenic microorganisms in milk represent serious threats to public health due to their carcinogenic, immunotoxic, and infectious properties (Avwioroko, 2023) [21]. While regulatory frameworks and detection technologies help mitigate these risks, enforcement and accessibility remain challenges. Continued research and innovations in monitoring and control strategies are essential to ensure food safety and protect public health globally (Ajirrotutu *et al.*, 2024) [15].

Regulatory Framework and Compliance Standards

Ensuring food safety and quality requires robust regulatory frameworks and compliance standards. These frameworks set permissible limits for contaminants, enforce microbial safety guidelines, and promote harmonization across international markets (Agupugo *et al.*, 2024) [10]. This explores existing U.S. regulations, enforcement challenges, and international standards for food safety. The United States has implemented stringent regulatory measures to control foodborne contaminants and ensure public health safety. One critical

regulation is the FDA standard for aflatoxin limits, which permits a maximum aflatoxin concentration of 0.5 parts per billion (ppb) in dairy products intended for human consumption. Aflatoxins, produced by *Aspergillus* fungi, pose significant health risks, including carcinogenic effects, making their strict regulation imperative.

Another key regulation is the Pasteurized Milk Ordinance (PMO), which establishes microbial safety guidelines for milk and milk products. The PMO mandates pasteurization processes that effectively eliminate harmful pathogens, such as *Salmonella* and *Listeria monocytogenes* as illustrated in figure 2 (Pendyala *et al.*, 2022; Basseg and Ibegbulam, 2024; Bature *et al.*, 2024) [31, 57, 29, 23]. Additionally, it outlines sanitary requirements for dairy processing equipment and storage facilities to prevent contamination during production and distribution. These regulations form the cornerstone of food safety enforcement in the U.S., protecting consumers from hazardous substances and microbial contamination (Folorunso *et al.*, 2024) [38].

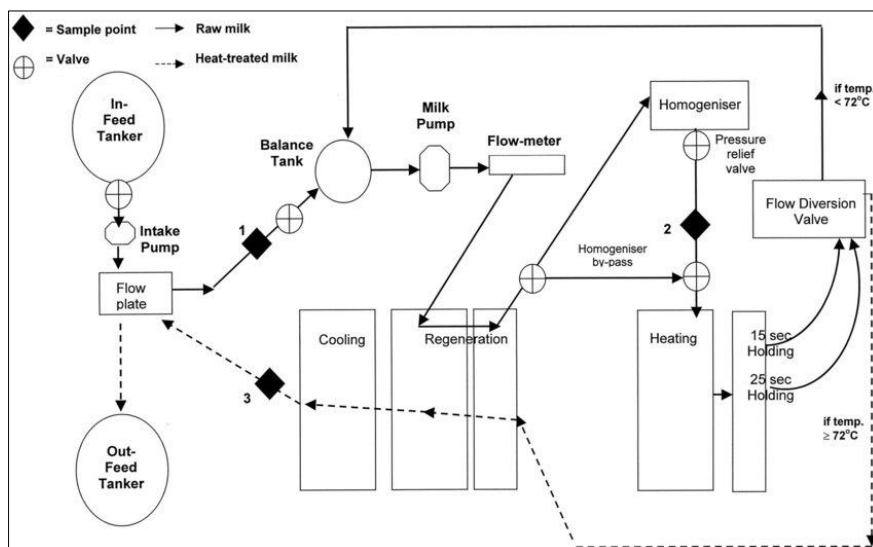


Fig 2: Schematic displaying the locations of the raw and pasteurized milk sampling ports as well as the design of the pasteurization and homogenization plant (Pendyala *et al.*, 2022) [57]

Despite having comprehensive regulations, enforcement faces several challenges, particularly related to inconsistent compliance practices across regions. Variations in enforcement arise due to differences in resource allocation, training, and monitoring capabilities among states and municipalities (Toromade *et al.*, 2024) ^[58]. Smaller food producers may lack the infrastructure to meet regulatory requirements, leading to uneven enforcement and compliance gaps. Another pressing issue is the need for better detection and traceability systems. Current testing methods often require extensive laboratory analysis, which can delay responses to contamination events. Implementing advanced detection technologies, such as biosensors and real-time monitoring systems, would significantly improve enforcement by enabling rapid identification and containment of food safety hazards. Furthermore, enhancing traceability systems using blockchain technology could streamline record-keeping and improve transparency throughout the supply chain (Abass *et al.*, 2024) ^[1]. Globally, food safety standards are guided by frameworks such as the Codex Alimentarius, developed by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO). The Codex establishes safety thresholds for contaminants, including aflatoxins, and provides guidelines for food handling, labeling, and hygiene practices (Bassey, 2023) ^[26]. These standards serve as international benchmarks, facilitating trade and ensuring consumer protection. In the European Union (EU), regulations are similarly stringent, with a maximum aflatoxin limit of 0.05 ppb in dairy products far stricter than U.S. standards. The EU also mandates Hazard Analysis and Critical Control Points (HACCP) systems to identify and manage food safety risks throughout production processes. Efforts to harmonize standards globally are crucial for facilitating trade and improving food safety practices. Global collaboration initiatives, such as the International Food Safety Authorities Network (INFOSAN), promote knowledge sharing and coordinated responses to foodborne outbreaks. By aligning regulations and fostering international partnerships, countries can better address emerging food safety challenges. Regulatory frameworks and compliance standards are fundamental to safeguarding public health and maintaining food quality. In the U.S., regulations like FDA limits on aflatoxins and the PMO provide essential protections, though enforcement challenges persist due to inconsistencies and technological limitations. International standards, such as Codex Alimentarius and EU regulations, complement these efforts by fostering harmonization and encouraging global cooperation (Agupugo *et al.*, 2022) ^[10].

Strengthening enforcement mechanisms and advancing detection technologies will be critical to addressing future food safety challenges and ensuring compliance in an increasingly interconnected world.

Holistic Framework for Risk Management

Effective risk management in agricultural and food production systems demands a comprehensive and integrated approach. A holistic framework combines preventive strategies, detection and monitoring systems, intervention technologies, and data-driven methodologies to mitigate risks effectively as illustrated in figure 3 (Moradi and Groth, 2020; Ajirotutu *et al.*, 2024) ^[5, 15]. This outlines these components, emphasizing strategies to enhance safety and sustainability. Ensuring feed quality is fundamental to preventing contamination and ensuring livestock health. Mycotoxin management in livestock feed is critical, given its impact on animal health and food safety. Strategies include rigorous testing for contaminants and integrating additives to inhibit mold growth. Proper storage practices, such as maintaining optimal temperature and humidity, significantly reduce mold proliferation, minimizing mycotoxin production. *Hygiene and Sanitation Protocols* Adherence to Good Agricultural Practices (GAP) and Good Manufacturing Practices (GMP) ensures hygiene throughout the food production chain. These protocols emphasize proper handling, cleaning, and sanitization to minimize microbial contamination. Biosecurity measures, such as controlled farm access, disinfection points, and quarantine areas, further protect livestock from infections and environmental hazards (Folorunso *et al.*, 2024) ^[38]. Advanced analytical techniques, including Enzyme-linked Immunosorbent Assays (ELISA) and High-Performance Liquid Chromatography (HPLC), provide accurate detection of aflatoxins in feed and food products. ELISA offers rapid, cost-effective screening, while HPLC delivers high precision for confirmatory testing (Bassey, 2023) ^[26]. Microbial contamination is monitored using Polymerase Chain Reaction (PCR)-based detection for pathogen identification and culture-based enumeration for quantifying microbial loads. These methods ensure timely detection and response to microbial threats. The integration of Internet of Things (IoT) sensors enables continuous monitoring of critical parameters, such as temperature, humidity, and pH, during food processing and storage (Agupugo *et al.*, 2022) ^[10]. Real-time data collection facilitates prompt corrective actions to prevent spoilage and contamination.

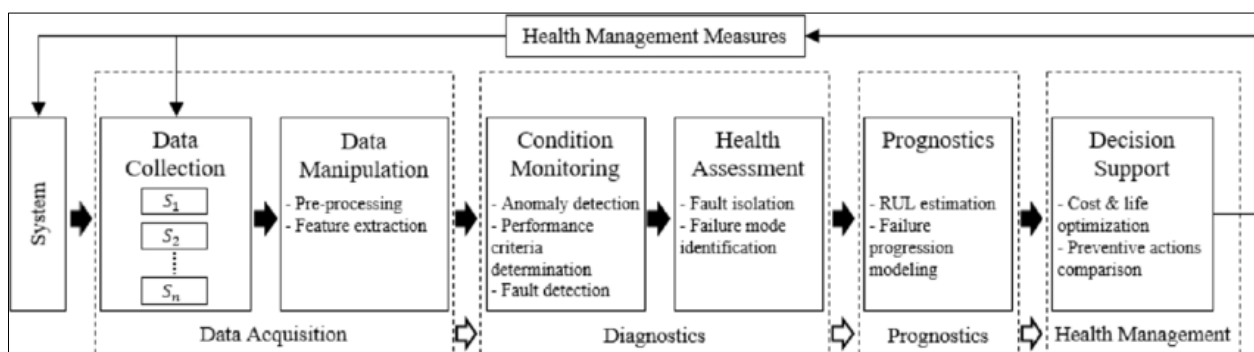


Fig 3: A comprehensive PHM structure. Data acquisition, diagnostics, prognostics, and health management are its four main processes, which are delineated by dashes (Moradi and Groth, 2020) ^[50].

Innovative decontamination methods, such as ozonation, UV-C light, and lactoperoxidase systems, effectively reduce microbial loads without compromising food quality. These methods are increasingly favored for their sustainability and efficiency. Thermal treatments like pasteurization are widely used for microbial inactivation, ensuring product safety. Non-thermal methods, such as High-Pressure Processing (HPP), retain nutritional quality while achieving microbial reduction, offering a viable alternative for heat-sensitive products (Toromade *et al.*, 2024) ^[58]. To mitigate aflatoxin contamination, binders like bentonite clay are incorporated into feed processing. These adsorbents effectively sequester aflatoxins, reducing their bioavailability and toxicity. Blockchain technology enhances traceability across the supply chain by securely recording transactions and data points. This transparency ensures accountability, enabling rapid identification and containment of contamination sources. Artificial Intelligence (AI) and Machine Learning (ML) tools analyze large datasets to predict risks and optimize decision-making. These technologies identify patterns, assess vulnerabilities, and recommend preventive measures, improving overall risk management. A holistic framework for risk management integrates preventive strategies, advanced detection systems, intervention technologies, and data-driven approaches to safeguard food safety and quality (Eruaga, 2024) ^[32]. By leveraging innovations such as IoT sensors, AI, and blockchain, agricultural and food production systems can proactively address risks, ensuring sustainability and consumer confidence. Continuous improvement and adoption of emerging technologies are essential for maintaining resilience against evolving threats.

Implementation and Integration

Risk assessment forms the foundation of effective implementation and integration strategies for ensuring food safety, particularly in milk production and handling. Hazard identification involves recognizing biological, chemical, and physical contaminants that may compromise milk quality. Examples include bacterial pathogens like *Salmonella* and *Listeria monocytogenes*, chemical residues from veterinary drugs, and physical contaminants such as metal fragments (Toromade *et al.*, 2024) ^[58]. Exposure assessment evaluates the likelihood and levels of exposure to these hazards, considering factors such as processing methods, transportation, and storage conditions. Risk characterization integrates hazard and exposure assessments to quantify potential health impacts and guide mitigation efforts.

The Hazard Analysis and Critical Control Point (HACCP) system is a proactive approach for identifying and controlling hazards. Critical control points (CCPs) are established at key stages in milk production, such as pasteurization, packaging, and storage. Monitoring parameters, including temperature, time, and microbial counts, ensure compliance with safety standards (Eruaga *et al.*, 2024) ^[32]. Corrective actions are predefined to address deviations promptly, minimizing risks of contamination and spoilage. HACCP principles enhance traceability and accountability, facilitating continuous improvement and compliance with regulatory requirements. Effective supply chain coordination requires seamless integration of farm-to-fork monitoring systems. Technologies such as blockchain and Internet of Things (IoT) sensors enable real-time tracking of milk production, transportation, and distribution (Adepoju *et al.*, 2019) ^[6].

These systems monitor temperature fluctuations, storage conditions, and processing timelines, ensuring data integrity and transparency. Automated alerts facilitate timely interventions to prevent contamination and reduce foodborne illnesses. Collaboration across the supply chain is vital for achieving comprehensive food safety. Strengthening partnerships between farmers, processors, and regulatory bodies fosters shared responsibility and accountability. Regular audits, joint training sessions, and data-sharing platforms enhance communication and coordination (Agupugo and Tochukwu, 2021) ^[10]. Establishing standard operating procedures (SOPs) ensures uniform safety practices, while collaborative efforts streamline compliance with local and international food safety standards.

Training programs targeting milk producers, handlers, and processors are crucial for minimizing contamination risks. Education on best practices for hygiene, equipment sanitation, and microbial testing equips workers with the skills to detect and address hazards proactively (Eruaga *et al.*, 2024) ^[32]. Hands-on workshops and certifications reinforce the importance of adhering to HACCP principles and using advanced diagnostic tools for quality assurance. Raising public awareness about safe milk handling practices complements workforce training efforts. Campaigns highlighting proper storage, boiling techniques, and hygienic practices reduce risks of contamination at the consumer level. Informational materials distributed through schools, community centers, and media platforms empower consumers to make informed decisions about milk safety. Public engagement initiatives also foster trust in regulatory systems and promote consumer confidence in the milk supply chain (Bassey, 2023) ^[26]. The implementation and integration of risk assessment methodologies, supply chain coordination, and training programs are critical for enhancing milk safety. A structured approach involving hazard identification, CCP establishment, and collaborative supply chain management ensures compliance with food safety standards. Workforce education and public awareness campaigns further reinforce these efforts, safeguarding public health and promoting sustainable practices. Effective integration of these strategies establishes a resilient framework for mitigating risks and ensuring the delivery of safe, high-quality milk products.

Methodology

This employs a mixed-methods approach, integrating quantitative and qualitative techniques to develop and validate a holistic framework for enhancing milk safety in the USA. This approach facilitates a comprehensive analysis of both chemical and microbiological contaminants in dairy supply chains. The research design consists of field studies, laboratory experiments, and stakeholder interviews to ensure robust data collection and triangulation.

A stratified sampling method is employed to ensure representation across different segments of the dairy supply chain, including farms, processing plants, and retail distribution centers. Samples are collected from diverse geographic regions in the USA to capture variations in contamination risks due to climatic and operational differences. Specific sampling includes raw milk, processed milk, and environmental swabs from processing facilities (Toromade and Chiekezie, 2024) ^[58]. Milk samples are centrifuged to separate fat content, and the supernatant is extracted for analysis. AFM1 concentrations are quantified using HPLC coupled with fluorescence detection to achieve

high sensitivity. A rapid screening method is used for preliminary identification of AFM1 contamination. Results from ELISA (Enzyme-Linked Immunosorbent Assay) are validated against HPLC (High-Performance Liquid Chromatography) findings to ensure accuracy.

Traditional plating methods are used to isolate common pathogens such as *Escherichia coli*, *Salmonella* spp., and *Listeria monocytogenes*. Molecular methods are employed to detect and confirm pathogenic DNA in suspected samples. Advanced sequencing technologies are applied for metagenomic analysis to identify microbial communities and potential pathogens (Udo *et al.*, 2024)^[65].

A Quantitative Microbial Risk Assessment (QMRA) model is developed to estimate the exposure and risk levels associated with microbial contamination (Folorunso, 2024)^[38]. A parallel deterministic model evaluates the dietary exposure risk to AFM1 based on consumption patterns and contamination levels. Testing animal feed for aflatoxins to reduce AFM1 occurrence in milk. Evaluating the effect of probiotics on inhibiting pathogenic bacteria in cattle. Assessing the impact of heat treatments on pathogen reduction. Testing advanced filtration systems and adsorbent materials for AFM1 removal. Structured interviews and surveys are conducted with dairy farmers, processors, regulators, and consumers to gather insights into current practices, challenges, and perceptions of milk safety. This qualitative data informs the design of practical interventions and policy recommendations. Quantitative data are analyzed using statistical software, employing ANOVA and regression techniques to assess relationships and identify significant variables. Qualitative data from stakeholder interviews are coded thematically to extract key insights. The proposed framework is validated through pilot implementation in selected dairy supply chains (Adewale *et al.*, 2024)^[8]. Feedback from stakeholders and performance metrics, such as reductions in contamination rates, guide refinements to the framework. Ethical approval is obtained for all sampling and data collection procedures. Informed consent is secured from stakeholders, and data confidentiality is maintained in compliance with regulatory standards (Ogunyemi and Ishola, 2024)^[46]. Acknowledging potential limitations, such as sample size constraints and variability in testing conditions, the study outlines directions for future research, including long-term monitoring and evaluation of intervention efficacy. This methodology ensures a comprehensive and practical approach to controlling AFM1 and pathogenic microorganisms, ultimately improving milk safety in the USA.

Evaluation and Continuous Improvement

In the food industry, particularly within dairy production, ensuring the safety and quality of products is of paramount importance. Evaluation and continuous improvement processes help maintain high standards of safety and quality while adapting to emerging challenges (Bassey *et al.*, 2024)^[29]. This explores the key components of evaluating and improving dairy safety, focusing on performance indicators, monitoring and feedback mechanisms, and adaptation to emerging challenges.

Performance indicators are essential tools for assessing the success of safety protocols and identifying areas for improvement in dairy production. Two critical performance indicators in dairy safety are the reduction in aflatoxin M1 levels and microbial contamination rates, as well as

compliance with regulatory standards (Oyewale and Bassey, 2024)^[29]. Aflatoxins, produced by certain fungi in crops such as maize, can contaminate dairy products, posing a significant risk to human health. Aflatoxin M1, a metabolite of aflatoxin B1, is commonly found in milk and dairy products. Therefore, monitoring aflatoxin M1 levels is a crucial performance indicator in dairy safety. Reduction in aflatoxin M1 levels can be achieved through better feed quality control, improved storage conditions, and effective veterinary practices. Consistent reduction in aflatoxin levels is indicative of the effectiveness of these control measures and provides a quantitative measure of progress. The presence of harmful microorganisms such as *Salmonella*, *Listeria*, and *Escherichia coli* in dairy products is another key performance indicator. Microbial contamination poses direct health risks, leading to foodborne illnesses. Monitoring microbial contamination rates provides a clear indication of the success of sanitation and hygiene practices in dairy processing plants (Bassey *et al.*, 2024)^[29]. A consistent reduction in microbial contamination rates is a vital sign of the effectiveness of safety protocols and practices. Adherence to local and international food safety regulations, such as those established by the U.S. Food and Drug Administration (FDA) or the European Food Safety Authority (EFSA), is a fundamental performance indicator. Compliance ensures that dairy products meet the required safety standards, mitigating potential risks to consumers. Regular assessments of compliance rates can indicate the need for additional training or updates to protocols (Bassey, 2022)^[25].

To maintain and improve dairy safety, it is essential to implement effective monitoring and feedback mechanisms. These mechanisms facilitate the ongoing assessment of safety practices and help identify areas that require corrective actions or improvements (Folorunso, 2024)^[38]. Audits and assessments are vital for evaluating the effectiveness of safety protocols. Regular internal and external audits ensure that production processes comply with established safety standards and identify gaps or inefficiencies. Audits may include reviewing records, inspecting facilities, and conducting interviews with personnel (Adepoju *et al.*, 2018)^[7]. These assessments help pinpoint areas where practices are falling short and provide data for developing strategies for improvement. The dairy industry is constantly evolving, with new technologies and emerging threats impacting food safety. For instance, advancements in sensor technology for detecting contaminants in milk or the development of faster diagnostic tools for microbial pathogens require ongoing adjustments to safety protocols. Updating protocols based on these technological advancements ensures that dairy production systems remain up-to-date and resilient to emerging risks, such as the introduction of novel pathogens or the discovery of new contaminants (Eruaga, 2024; Anozie *et al.*, 2024)^[32].

The dairy industry faces an array of evolving challenges that require constant adaptation. Two major concerns in recent years are antimicrobial resistance (AMR) and the impact of climate change on dairy safety (Folorunso, 2024)^[38]. The widespread use of antibiotics in livestock farming, including dairy cows, has contributed to the rise of antimicrobial resistance (AMR), which poses a significant threat to public health. Resistance to antibiotics makes infections harder to treat and increases the risk of foodborne illnesses. Dairy producers must adopt strategies to minimize antibiotic use and ensure that any necessary antibiotics are used

responsibly. This includes implementing strict regulations around veterinary drug use, monitoring antimicrobial residues in milk, and promoting alternative health practices for livestock, such as improving animal welfare and hygiene (Itua *et al.*, 2024). Continued surveillance and adjustments to practices based on emerging AMR trends are critical for mitigating the risks associated with antimicrobial resistance. Climate change is altering environmental conditions, including temperature fluctuations, precipitation patterns, and the prevalence of pests and diseases. These changes can impact dairy production, including milk quality and safety. For example, extreme temperatures may increase the growth rate of pathogens, while changes in crop patterns may affect feed quality. To address these challenges, dairy producers must adapt their practices to mitigate the effects of climate change (Ijomah *et al.*, 2024). This could involve enhancing the resilience of production systems, adjusting feed formulations, improving animal health management, and investing in climate-resistant infrastructure (Folorunso *et al.*, 2024)^[38]. By monitoring and adjusting practices to respond to these emerging climate-related threats, the dairy industry can ensure that safety standards are upheld. Evaluation and continuous improvement are integral to ensuring dairy safety. By focusing on performance indicators such as aflatoxin M1 reduction, microbial contamination rates, and regulatory compliance, dairy producers can assess the effectiveness of their safety measures (Avwioroko, 2023; Agupugo *et al.*, 2024)^[10, 21]. Regular audits, assessments, and updates to protocols based on technological advancements and emerging threats play a key role in monitoring and feedback. Furthermore, the adaptation to emerging challenges, such as antimicrobial resistance and climate change, is crucial for maintaining dairy safety in an evolving landscape. Through ongoing evaluation and improvement, the dairy industry can continue to provide safe and high-quality products to consumers (Ajiroto *et al.*, 2024)^[15].

Conclusion

In conclusion, ensuring dairy safety requires an integrated approach that combines advanced technologies, rigorous safety protocols, and continuous improvement efforts. Key findings highlight the importance of leveraging modern technologies to monitor and control risks such as aflatoxin M1 contamination and microbial threats. Furthermore, balancing safety, efficiency, and economic sustainability remains crucial in achieving long-term success in dairy production. By implementing comprehensive safety measures and adopting emerging technologies, dairy producers can effectively manage risks while ensuring the sustainability of their operations.

To enhance dairy safety, several recommendations for policy and practice can be made. Strengthening regulations and surveillance systems is essential to ensure that dairy products meet the highest safety standards. Developing more robust traceability mechanisms will help identify and manage contamination risks from farm to table. Moreover, promoting research and fostering technological advancements will drive innovation in dairy safety practices, enabling producers to stay ahead of emerging threats.

Looking ahead, the future of dairy safety lies in AI-driven predictive models for contamination risk assessment. These models can analyze vast datasets to identify potential contamination risks before they materialize, allowing for more proactive management strategies. Additionally,

fostering global partnerships will play a critical role in improving dairy safety practices worldwide. Collaborative efforts between governments, industries, and research institutions will help standardize practices, share knowledge, and develop more resilient dairy production systems, ensuring a safer and more sustainable future for the industry.

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