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INNOVATIVE MODELS FOR MANAGING SALMONELLA AND OTHER MICROBIAL RISKS IN EGG PROCESSING AND STORAGE IN THE USA

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ABSTRACT

The prevalence of *Salmonella* and other microbial contaminants in egg processing and storage poses significant public health and economic challenges in the United States. This review explores innovative models for managing microbial risks in egg production, processing, and distribution systems. It highlights advanced technologies and strategies that enhance food safety, regulatory compliance, and sustainability. Key approaches include ultraviolet (UV-C) and pulsed light treatments for surface decontamination, high-pressure processing (HPP) for pasteurization, and ozone-based sterilization techniques to reduce microbial loads. The integration of Internet of Things (IoT)-enabled sensors and artificial intelligence (AI)-driven predictive analytics is discussed as a transformative step for real-time monitoring and early detection of contamination. Blockchain-based traceability systems are proposed to improve transparency and accountability across supply chains. Biological interventions, such as probiotics, bacteriophages, and biofilm-disrupting agents, offer promising alternatives to traditional chemical sanitizers. Additionally, smart packaging technologies, incorporating antimicrobial coatings and freshness indicators, support safer storage and extended shelf life. We also examine regulatory frameworks, including the Food and Drug Administration (FDA) Egg Safety Rule and Hazard Analysis and Critical Control Points (HACCP) protocols, identifying gaps in enforcement and compliance. Recommendations for integrating innovative models with existing practices emphasize continuous risk assessment, workforce training, and collaborative industry partnerships. Performance metrics and adaptive monitoring systems are proposed to assess effectiveness and respond to emerging risks, such as antimicrobial resistance (AMR). Ultimately, this review provides a roadmap for modernizing microbial risk management in the U.S. egg industry, ensuring consumer safety, regulatory alignment, and operational efficiency. Future directions focus on AI-based analytics and global harmonization of standards to advance microbial safety strategies and promote sustainable practices in egg processing and storage systems.

Keywords: Salmonella, Innovative Models, Microbial Risks, Egg Processing, USA.

I. INTRODUCTION

The egg industry in the United States represents a critical sector of the agricultural economy, producing billions of eggs annually to meet domestic and international demands (Abass *et al*., 2024). Eggs are widely consumed due to their rich nutritional profile, affordability, and versatility, making them a staple in diets worldwide. However, the perishable nature of eggs and their susceptibility to microbial contamination pose significant challenges to food safety and public health (Ajirotutu *et al*., 2024; Agupugo *et al*., 2024). Microbial safety in egg processing and storage has become a central concern for producers, regulatory agencies, and consumers. Contaminants such as bacteria, fungi, and viruses can infiltrate eggs during various stages of production, processing, and storage (Bassey and Ibegbulam, 2023). Salmonella, in particular, has been identified as one of the most prevalent and dangerous pathogens associated with eggs. Ensuring microbial safety involves strict adherence to hygiene protocols, advanced monitoring techniques, and effective intervention strategies throughout the supply chain. Despite existing regulatory frameworks, outbreaks linked to contaminated eggs continue to occur, underscoring the need for enhanced safety measures and technological advancements (Folorunso *et al*., 2024; Ajirotutu *et al*., 2024).

Microbial contamination in eggs, especially due to *Salmonella enteritidis*, remains a persistent issue within the egg industry (Toromade *et al*., 2024). Studies have demonstrated that contamination can occur both externally, through eggshell contact with contaminated surfaces, and internally, through transovarian transmission from infected hens. Other pathogens, including *Escherichia coli* and *Listeria monocytogenes*, further exacerbate the risk of foodborne illnesses (Abass *et al*., 2024). Health risks associated with microbial contamination include gastrointestinal infections, severe dehydration, and, in vulnerable populations, life-threatening complications. According to the Centers for Disease Control and Prevention (CDC), Salmonella is responsible for approximately 1.35 million infections and 420 deaths annually in the United States. These statistics highlight the pressing need for improved microbial risk management practices in the egg industry to protect public health and restore consumer confidence.

This aims to address the challenges posed by microbial contamination in the egg supply chain through the following objectives. By leveraging predictive modeling, advanced microbial detection systems, and data analytics, this study seeks to create more accurate and effective tools for identifying contamination risks (Bassey, 2023; IormomI *et al*., 2024). The research will explore best practices and technologies to ensure compliance with safety standards, reduce contamination incidents, and promote sustainable practices within the egg industry. The scope of this study encompasses key stages in the egg supply chain, including processing, storage, and distribution. Special attention will be given to critical control points where microbial contamination is most likely to occur. This includes. Examination of washing, sanitization, and packaging procedures. Analysis of temperature control, humidity management, and packaging materials (Agupugo,] *et al*., 2022). Evaluation of transportation conditions and supply chain logistics. These will prioritize pathogens such as Salmonella, *Escherichia coli,* and *Listeria monocytogenes* while also considering emerging microbial threats. By focusing on these phases and pathogens, the research aims to deliver targeted interventions and recommendations to strengthen microbial safety protocols (Ajirotutu *et al*., 2024; Igwe *et al*., 2024). This responds to the critical need for enhanced microbial safety in the U.S. egg industry. By addressing the prevalence of microbial contaminants, assessing health risks, and developing innovative risk management strategies, the research seeks to improve food safety, regulatory compliance, and sustainability. The findings are expected to inform industry practices, support regulatory frameworks, and ultimately protect public health.

II. MICROBIAL RISKS IN EGG PROCESSING AND STORAGE

Eggs are a staple food item consumed worldwide, yet they pose significant microbial risks during processing and storage as explain in figure 1 (Jin *et al*., 2022). Understanding the sources of contamination, pathways of microbial transmission, and health impacts is essential to developing effective mitigation strategies (Bassey, 2023; Folorunso *et al*., 2024). Microbial contamination of eggs often begins at the farm level, primarily due to infected laying hens. Pathogens such as *Salmonella enteritidis* can colonize the reproductive tracts of hens, leading to internal contamination before the eggs are even laid. Environmental factors such as contaminated feed and water also contribute to microbial risks. Inadequate hygiene practices, including the use of unclean nesting materials and improper waste management, can exacerbate contamination risks (Agupugo *et al*., 2022). The processing stage introduces additional contamination risks. Equipment used for washing, grading, and packing eggs can harbor biofilms and microbial colonies if not sanitized regularly. Human handlers may also serve as vectors for contamination through improper hand hygiene and handling practices. Cross-contamination from dirty surfaces, crates, or conveyors is another potential source, especially in facilities lacking stringent sanitation protocols. The outer eggshell serves as a barrier, but its porous nature can facilitate microbial penetration. Contamination can occur during laying when eggs come into contact with feces or dirty nesting materials (Toromade *et al*., 2024). Washing processes, if not properly controlled, may exacerbate the problem by allowing bacteria to enter through microcracks in the shell or via penetration through the cuticle a natural protective layer removed during washing. Internal contamination arises when bacteria penetrate the eggshell and infect the egg contents (Ogunyemi and Ishola, 2024). Cracks in the shell or damage to the eggshell membrane create direct pathways for microbes to enter (Eruaga, 2024). Additionally, the porous nature of shells allows for gradual microbial migration, particularly when eggs are stored under suboptimal conditions such as high humidity or fluctuating temperatures.

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The primary pathogen of concern in egg contamination is *Salmonella*, particularly *Salmonella enteritidis*. Consumption of contaminated eggs can result in foodborne illnesses, leading to symptoms such as diarrhea, vomiting, fever, and abdominal cramps (Toromade *et al*., 2024). In severe cases, *Salmonella* infections can lead to bacteremia and septicemia, which require immediate medical intervention. Certain populations are more susceptible to microbial infections, including infants, elderly individuals, pregnant women, and immunocompromised individuals. For these groups, *Salmonella* infections can be life-threatening, leading to long-term health complications. Outbreaks of foodborne illnesses linked to eggs can strain public health systems, resulting in increased healthcare costs, product recalls, and loss of consumer confidence (Eruaga *et al*., 2024; Okedele *et al*., 2024). Microbial risks in egg processing and storage pose significant challenges to food safety and public health. Contamination can occur at multiple points along the production and distribution chain, from farm-level practices to processing and storage. Addressing these risks requires stringent biosecurity measures, regular equipment sanitization, proper handling protocols, and temperature-controlled storage solutions (Adepoju *et al*., 2019; Agupugo and Tochukwu, 2021). By mitigating these risks, the food industry can enhance egg safety and protect public health.

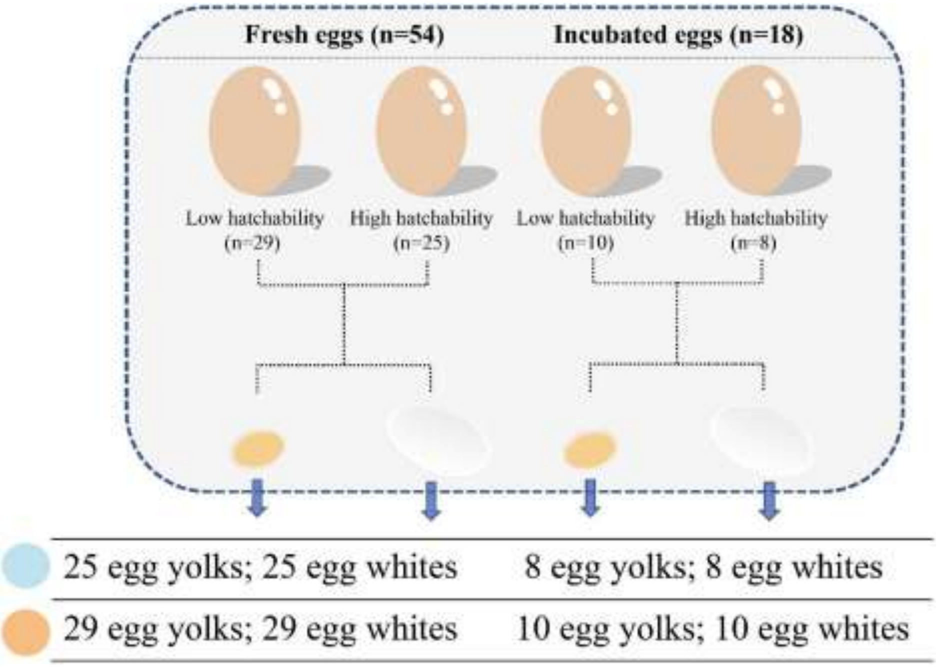

Figure 1: The microbial makeup of egg components and how they relate to laying hens' capacity to hatch (Jin *et al*., 2022)

2.1 Regulatory Framework and Compliance Standards

Regulatory frameworks and compliance standards play a pivotal role in ensuring food safety and protecting public health. The food industry is governed by a combination of national regulations, international standards, and industry-specific protocols (Eruaga *et al*., 2024). This examines the current regulatory environment, challenges in enforcement, and global best practices. The FDA Egg Safety Rule is a crucial component of U.S. food safety regulations. Enforced since 2010, this rule mandates preventive measures to reduce Salmonella Enteritidis contamination in shell eggs during production, storage, and transportation. Key provisions include refrigeration requirements, environmental testing, and biosecurity measures to mitigate risks (Bassey, 2023). The USDA provides comprehensive guidelines to ensure food safety and quality. Its Food Safety and Inspection Service (FSIS) oversees the inspection of meat, poultry, and egg products, ensuring adherence to sanitary processing standards. The USDA also promotes educational programs to inform producers and consumers about safe handling practices. HACCP is a systematic preventive approach to food safety that identifies potential hazards and implements critical control measures. Adopted widely across industries, HACCP protocols focus on identifying biological, chemical, and physical hazards, thereby ensuring process control and reducing risks of contamination.

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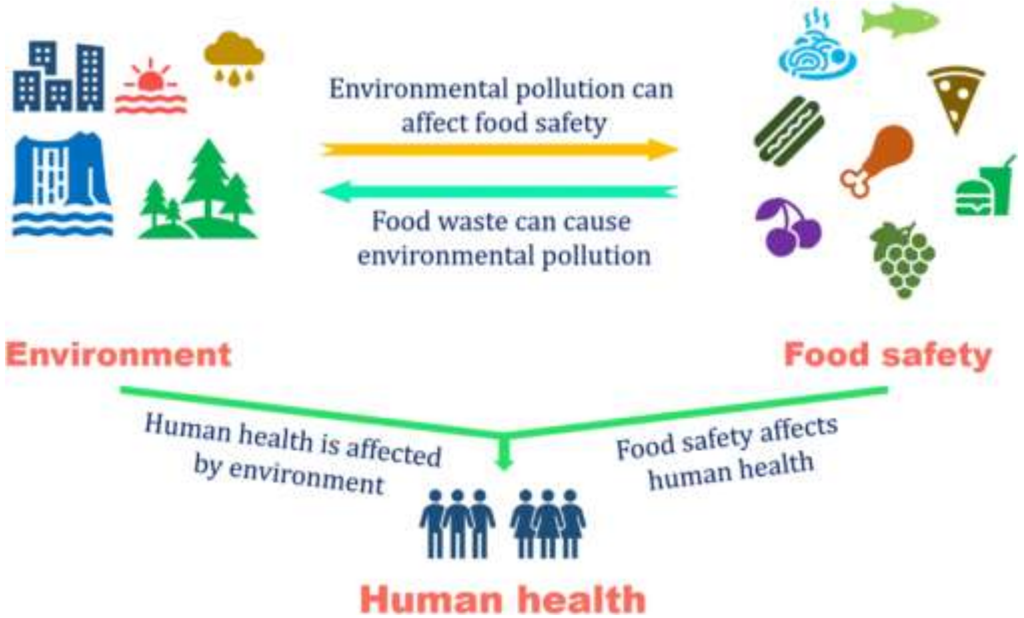

Figure 2: An example of how food safety and the environment are related, and how this affects human health (Castro *et al.*, 2021)

One major challenge is the inconsistency in compliance practices across different regions and facilities. Variability may arise due to differences in interpretation, resource availability, and technological capabilities as illustrated in figure 2 (Castro *et al.*, 2021; Bassey *et al.*, 2024). Smaller producers often face difficulties meeting stringent requirements, which can lead to gaps in compliance. Despite rigorous standards, enforcement remains challenging due to inadequate monitoring systems. Resource limitations and staffing shortages may result in infrequent inspections, thereby allowing non-compliant practices to persist. Moreover, the lack of standardized reporting mechanisms further complicates regulatory oversight. The Codex Alimentarius, established by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO), provides international guidelines for food safety and quality. Its standards cover various aspects, including hygiene practices, labeling, and contaminants, serving as a benchmark for harmonizing regulations globally. Efforts to harmonize food safety standards globally are gaining momentum. The Global Food Safety Initiative (GFSI) aligns with Codex principles to create a unified framework. Such harmonization simplifies compliance for multinational companies and enhances consumer confidence by ensuring uniform safety measures worldwide. Regulatory frameworks and compliance standards are fundamental to safeguarding public health and ensuring food safety (Oyewale and Bassey, 2024). While regulations like the FDA Egg Safety Rule, USDA guidelines, and HACCP protocols provide robust frameworks, challenges persist in enforcement and monitoring. International standards, such as those established by Codex Alimentarius, offer valuable guidelines for harmonization and best practices. Strengthening compliance mechanisms and fostering global cooperation will be vital to addressing existing gaps and achieving safer food systems (Bassey, 2022).

2.2 Innovative Models for Risk Management

Risk management is an essential aspect of modern industries, ensuring safety, quality, and compliance. Innovative models integrating advanced technologies and methodologies are transforming risk mitigation strategies (Bassey *et al.*, 2024). This explores cutting-edge approaches categorized into technological interventions, automation and monitoring systems, biological approaches, and packaging innovations. UV-C light and pulsed light technologies offer effective solutions for surface decontamination. UV-C light utilizes short-wavelength ultraviolet radiation to disrupt microbial DNA, rendering pathogens inactive. Pulsed light delivers high-intensity energy bursts, effectively eliminating contaminants without chemical residues, making these techniques suitable for food processing and healthcare environments. HPP is a non-thermal pasteurization technique that uses high hydrostatic pressure to inactivate pathogens and spoilage organisms. This method preserves nutritional quality and flavor, making it ideal for food preservation while ensuring safety and extending shelf life. Ozone gas acts as a strong oxidizing agent, effectively breaking down microbial cell walls. Plasma treatments generate reactive species that disinfect surfaces and liquids (Folorunso, 2024). Both approaches are environmentally friendly and reduce reliance on chemical sanitizers.

Internet of Things (IoT)-enabled sensors facilitate real-time microbial detection and monitoring. These sensors detect pathogens and contamination levels, enabling prompt responses to potential threats (Adepoju *et al*., 2018). They support continuous monitoring, enhancing safety protocols. Blockchain technology improves supply chain transparency by providing immutable records of product movement and conditions. It ensures traceability and accountability, minimizing fraud and contamination risks.

Artificial intelligence (AI) processes vast datasets to predict and assess risks. Machine learning algorithms analyze trends, identify vulnerabilities, and forecast outcomes, enabling proactive decision-making and resource optimization (Eruaga, 2024).

Probiotics, beneficial microorganisms, inhibit pathogen growth by competing for nutrients and producing antimicrobial substances. Bacteriophages, viruses that target specific bacteria, offer precise microbial control without affecting beneficial flora. These natural antimicrobials present sustainable alternatives to chemical treatments. Biofilms, microbial communities embedded in protective matrices, pose challenges in industrial and healthcare settings. Enzymatic and chemical agents, as well as physical disruption methods, break down biofilms, reducing microbial persistence and contamination risks (Anozie *et al*., 2024).

Antimicrobial coatings incorporate active agents that inhibit microbial growth, providing extended protection. Modified atmosphere packaging (MAP) alters gas compositions within packaging to slow spoilage, preserving product freshness. Smart packaging integrates sensors and indicators that monitor freshness, temperature, and contamination. These systems provide real-time information, ensuring product integrity and improving consumer confidence. Innovative risk management models leverage technological advancements, automation, biological solutions, and packaging innovations to address microbial contamination and safety concerns. These approaches enhance efficiency, sustainability, and reliability across industries. Future research and development in these domains promise further improvements in risk mitigation strategies, safeguarding public health and operational stability (Folorunso, 2024; Itua *et al*., 2024).

2.3 Implementation Strategies

Effective implementation strategies for food safety management rely heavily on comprehensive risk assessment methodologies as illustrated in figure 3. This involves hazard identification and microbial load quantification to ensure food safety, especially in high-risk products like eggs. Hazard identification focuses on recognizing biological, chemical, and physical agents that can compromise food quality and safety (Folorunso *et al*., 2024). Microbial load quantification assesses the concentration of pathogens, including Salmonella spp., to establish contamination levels and potential health risks. Exposure assessment and risk modeling play a crucial role in predicting and managing risks. Exposure assessment evaluates the probability and magnitude of human exposure to hazards during production, processing, and consumption stages. Risk modeling integrates data from hazard identification and exposure assessments to predict outcomes and enable proactive control measures. Quantitative microbial risk assessment (QMRA) is often employed to estimate infection risks, providing a scientific basis for setting critical limits and corrective actions in food safety systems (Agupugo *et al*., 2024).

Ensuring food safety requires a coordinated approach across the entire supply chain, from farm-to-fork. Supply chain integration emphasizes seamless collaboration among stakeholders, including farmers, processors, distributors, retailers, and consumers. Implementing traceability systems and real-time monitoring technologies ensures transparency and quick responses to contamination events. Adopting Good Agricultural Practices (GAP) and Good Manufacturing Practices (GMP) forms the backbone of supply chain integration. GAP focuses on safe farming practices, including proper animal husbandry, sanitation, and pest control, to minimize contamination at the source.

GMP addresses hygienic handling, processing, and packaging practices to maintain product integrity throughout production. These practices are reinforced through Hazard Analysis and Critical Control Points (HACCP) frameworks, which identify and mitigate risks at critical points (Avwioroko, 2023).

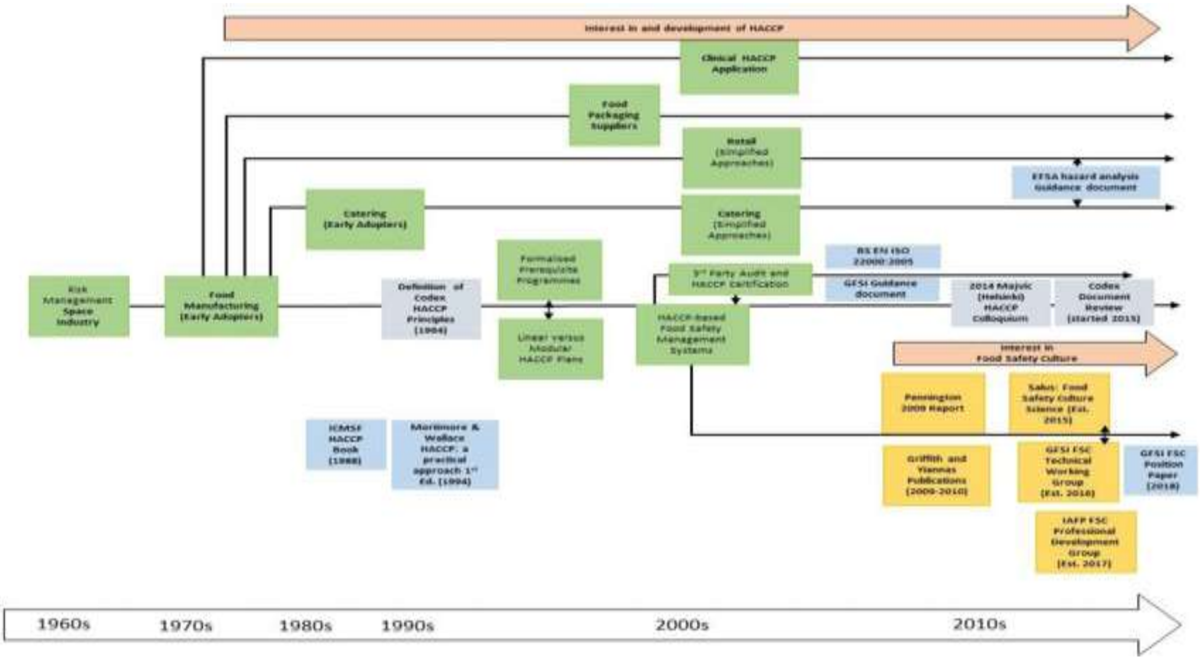

Figure 3: Adoption schedule for HACCP-based methods of food safety management (Malik *et al*., 2021)

Training and education programs are pivotal for strengthening food safety implementation strategies. Workforce development focuses on equipping employees with the knowledge and skills necessary to adhere to food safety protocols. Regular training sessions on hygiene practices, contamination prevention, and emergency response procedures ensure consistent compliance with safety standards (Ajirotutu *et al*., 2024). Certification programs further validate workforce competency and enhance accountability. Consumer education also plays an integral role in minimizing risks associated with food handling and storage. Awareness campaigns and informational materials educate consumers on proper egg handling, refrigeration, and cooking practices to reduce exposure to pathogens. Promoting simple strategies, such as avoiding cross-contamination and cooking eggs thoroughly, helps lower the risk of foodborne illnesses. Implementing effective food safety strategies necessitates a multi-faceted approach involving risk assessment methodologies, supply chain integration, and training programs. Hazard identification, microbial load quantification, and risk modeling form the foundation for proactive hazard control. Coordinated supply chain practices, reinforced by GAP and GMP, ensure safety across production and distribution channels (Ijomah *et al*., 2024). Finally, workforce and consumer education programs enhance compliance and awareness, reducing overall risks. Together, these strategies contribute to a robust framework for safeguarding food safety and public health.

2.4 Evaluation and Continuous Improvement

Evaluation and continuous improvement are fundamental processes in ensuring the effectiveness of interventions aimed at enhancing health, safety, and environmental standards (Toromade *et al*., 2024). These processes rely on performance metrics, feedback mechanisms, and the ability to adapt to emerging risks. This review explores these elements, emphasizing their role in optimizing microbial contamination control and addressing antimicrobial resistance (AMR). Performance metrics serve as critical tools for evaluating the success of interventions. Two essential indicators are the reduction in microbial contamination rates and compliance rates with established protocols. Tracking microbial contamination rates is a primary measure of intervention effectiveness. Lower contamination levels indicate successful implementation of control strategies, including sanitation protocols, sterilization techniques, and antimicrobial agents. Quantitative data collected through periodic sampling and laboratory testing enable precise measurement of changes over time, providing insights into intervention performance. Compliance rates reflect adherence to regulatory standards and internal protocols, serving as proxies for organizational discipline and commitment to safety (Eruaga *et al*., 2024). Regular audits assess conformity with standard operating procedures (SOPs) and identify gaps requiring corrective actions. High compliance rates correlate with improved outcomes, while audit findings guide refinements to processes and training programs.

Effective feedback and monitoring systems underpin continuous improvement by enabling dynamic performance evaluation and protocol enhancement. Continuous auditing mechanisms ensure real-time assessment of intervention efficacy (Folorunso *et al*., 2024). Automated data collection systems, such as sensors and IoT devices, facilitate continuous monitoring, providing timely alerts for deviations from expected performance levels. This proactive approach minimizes risks by enabling immediate remediation. Scientific advancements and technological innovations necessitate periodic updates to protocols. Emerging findings, such as improved sterilization techniques or novel antimicrobial compounds, must be integrated into existing frameworks (Toromade *et al*., 2024; Eruaga *et al*., 2024). Regular reviews of literature and collaboration with research institutions enable organizations to remain at the forefront of best practices.

The dynamic nature of microbial threats, including the rise of antimicrobial resistance (AMR), highlights the need for adaptive strategies that leverage advanced technologies. Addressing Antimicrobial Resistance (AMR) poses a significant challenge to infection control, necessitating a multifaceted approach. Surveillance programs monitor resistance patterns, guiding the selection of effective treatments (Ajirotutu *et al*., 2024). Stewardship programs promote judicious antimicrobial use, minimizing the emergence of resistance. Furthermore, research into alternative therapies, such as bacteriophages and probiotics, expands the arsenal against resistant strains. Advanced data analytics, including machine learning and artificial intelligence, enhance the capacity for early detection of contamination and resistance trends. Predictive models analyze patterns in large datasets, identifying potential outbreaks before they escalate. These insights inform preemptive measures, reducing the likelihood of adverse outcomes. Evaluation and continuous improvement are indispensable for sustaining effective microbial contamination control and combating AMR. Performance metrics provide quantifiable evidence of success, while feedback and monitoring systems ensure ongoing optimization. Adaptation to emerging risks through advanced analytics and updated protocols safeguards public health and environmental integrity. By integrating these elements, organizations can achieve sustained improvements and resilience in microbial safety management (Avwioroko, 2023).

2.5 Methodology

Effective management of microbial risks, particularly Salmonella, in egg processing and storage is a critical component of food safety in the USA. This aims to develop and evaluate innovative models to mitigate microbial contamination, focusing on integrating advanced detection techniques, risk assessment frameworks, and intervention strategies. The methodology combines laboratory experimentation, data analytics, and regulatory evaluations to develop comprehensive management approaches (Bature *et al*., 2024). The study employs a mixed-methods approach, integrating quantitative and qualitative techniques. The quantitative methods include microbiological assays and statistical modeling, while qualitative methods encompass observational analysis, interviews with industry stakeholders, and surveys. The research design ensures the incorporation of both empirical data and contextual insights. Sampling is conducted at multiple stages in the egg supply chain, including farms, processing facilities, and storage units. Samples are collected randomly from eggs, equipment surfaces, and environmental swabs to ensure representativeness. A stratified sampling method is employed to capture variations in geographical regions, facility sizes, and operational practices (Toromade and Chiekezie, 2024; Ogunyemi and Ishola, 2024). Standard microbiological protocols are followed to isolate and quantify Salmonella and other pathogens. Techniques include: Enrichment broths and selective agars are used for isolating Salmonella strains. Rapid identification of genetic markers specific to Salmonella. Detailed characterization of microbial strains to track transmission routes and resistance patterns. Broader microbial profiling to identify co-contaminants and microbial ecosystems (Udo *et al*., 2024).

Quantitative microbial risk assessment (QMRA) models are developed to estimate contamination probabilities and potential health impacts (Avwioroko and Ibegbulam, 2024). The steps include. Characterizing Salmonella serotypes present in the samples. Estimating contamination levels at various processing and storage stages. Evaluating infection probabilities based on consumption patterns. Integrating data to model overall risks and identify critical control points (Folorunso, 2024). The review tests various intervention methods, including. Assessing pasteurization efficacy at different temperature-time combinations. Evaluating the use of UV light for surface disinfection. Measuring antimicrobial effectiveness of ozone in reducing microbial loads. Testing antimicrobial coatings and modified atmosphere packaging to inhibit microbial growth. Assessing temperature control measures and their impact on microbial proliferation. Statistical software (e.g., SPSS, R) is used for data processing and modeling. Multivariate analyses determine correlations between processing practices and contamination levels. Predictive modeling tools are employed to simulate microbial behavior under various scenarios, allowing the optimization of intervention strategies (Adewale *et al*., 2024). This evaluates compliance with U.S. Food and Drug Administration (FDA) regulations, particularly the Egg Safety Rule. It assesses gaps in existing guidelines and provides recommendations for updates based on findings. Industry practices are benchmarked against international standards to ensure global competitiveness. Prototypes of the proposed models are implemented in selected facilities for validation. Pilot studies monitor the performance of interventions under real-world conditions, ensuring scalability and feasibility (Ishola, 2024). Feedback from stakeholders informs final model refinements. This methodology integrates cutting-edge microbiological techniques, risk modeling, and intervention assessments to develop innovative approaches for managing Salmonella and microbial risks in egg processing and storage (Ogunyemi and Ishola, 2024). The outcomes are expected to enhance food safety standards, reduce public health risks, and support regulatory frameworks in the USA.

III. CONCLUSION

This highlights the transformative role of technological advancements and integrated approaches in modern egg processing. Innovations such as automated systems, advanced pasteurization techniques, and real-time monitoring tools have significantly improved efficiency, safety, and sustainability. These technologies not only streamline production but also address critical challenges related to microbial contamination and quality assurance. By balancing safety with operational efficiency and environmental responsibility, the egg processing industry is advancing toward more sustainable practices.

To sustain and enhance these improvements, industry stakeholders should prioritize the adoption of cutting-edge technologies, including AI-driven quality control systems and Internet of Things (IoT)-based monitoring devices. Such tools enable predictive maintenance, contamination detection, and optimized resource management. Additionally, strengthening regulatory frameworks and investing in collaborative research will ensure continuous innovation and compliance with global food safety standards. Partnerships between regulatory bodies, research institutions, and manufacturers can accelerate the development and implementation of best practices.

The integration of artificial intelligence (AI) and machine learning (ML) represents a promising frontier for the egg processing industry. These technologies can improve predictive analytics, optimize processing workflows, and enhance traceability systems. Future research should focus on refining AI algorithms to identify microbial risks and predict potential hazards in real time. Furthermore, fostering global partnerships is essential for developing standardized microbial risk management strategies. Such collaborations will facilitate knowledge-sharing and drive innovations that can be implemented across diverse processing environments. The convergence of advanced technologies, strategic regulations, and global partnerships offers a pathway for the egg processing industry to achieve higher standards of safety, efficiency, and sustainability. Continued investments in research and development will be crucial for maintaining this momentum and addressing emerging challenges in the food processing sector.

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