# Microbial Monitoring for Quality Assurance in Food Processing Systems

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*Abstract*—**Microbiological quality control (MQC) is a fundamental component of food safety management systems, ensuring the production of safe, high-quality and regulatory-compliant food products. Conventional culture-based methods, including total viable count and indicator organism analysis, remain essential for routine quality assessment, while rapid and molecular techniques such as polymerase chain reaction (PCR), enzyme-linked immunosorbent assay (ELISA), CRISPR and automated microbial detection systems offer improved sensitivity and reduced analysis time. The role of good manufacturing practices (GMP), hazard analysis and critical control points (HACCP) and sanitation standard operating procedures in minimizing microbial contamination is highlighted. Effective implementation of microbiological quality control not only supports compliance with international food safety standards but also reduces the risk of foodborne illnesses and product recalls. Continuous advancements in rapid detection technologies are strengthening food safety monitoring and enhancing consumer protection. However, significant obstacles remain, including high expenses, detection difficulties and the increasing resistance of harmful bacteria to antibiotics. This study reviews and evaluates key microbiological quality control practices employed in food industry, focusing on the detection, enumeration and control of pathogenic, indicator and spoilage microorganisms across the food production chain and also strategies to enhance microbiological testing and management within the food sector, ensuring that food remains safe and of high quality globally.**

*Index Terms*—**Microbial quality control, Food safety, Spoilage, HACCP, Food pathogens.**

## I. INTRODUCTION

Microbiological quality control (MQC) is an essential component of food production, ensuring that food products are safe, nutritious and of high quality. The presence of harmful microorganisms in food can lead to foodborne illnesses, spoilage and degradation of product quality. As a result, MQC systems are implemented at various stages of food production, from raw material handling to finished product packaging, to detect and control microbial contamination. The increasing complexity of global food supply chains and growing consumer demands for safer, more sustainable products, the role of MQC has become more critical.[1] Foodborne pathogens, such as *Salmonella*, *E. coli* and *Listeria*, continue to pose significant risks, making effective microbiological monitoring a vital public health measure. Additionally, consumer expectations regarding the quality, shelf life and safety of food products are higher than ever, placing further pressure on food producers to maintain rigorous microbiological standards. MQC encompasses the methodologies, technologies and practices employed to ensure the microbiological safety of food products, advantages, factors that impact on food safety, product shelf life, regulatory compliance and consumer confidence. The scope of MQC in food production with increase in detection technologies and integrated management systems. MQC practices are followed across various food sectors, starting from raw material sourcing to final product distribution, considering both developed and emerging markets.[2]

## II. MICROBIAL HAZARDS IN FOOD SYSTEMS

Maintaining the quality and safety of food is essential for attaining sustainable food security on a global scale. Molds and yeasts are the primary organisms that lead to food spoilage. These microorganisms

contribute to a range of food deterioration issues. They can induce poisoning through the various mycotoxins they release, which may adversely affect the health of consumers over time. *Campylobacter*, *Salmonella* and *Yersinia* are the culprits behind thousands of foodborne infections in humans. According to the zoonoses reports released by the European Food Safety Authority (EFSA) and the European Centre for Disease Prevention and Control (ECDC) in the "EU One Health Zoonoses Summary Report," which provides data on the origins of foodborne diseases, campylobacteriosis stands out as the most prevalent illness. In 2022, it was confirmed in 137,107 individuals across 27 EU countries, resulting in an incidence rate of 43.1 per 100,000 people. Consistent with previous years, the majority of campylobacteriosis cases were attributed to *C. jejuni*, accounting for 87.6% of identified isolates, while *C. coli* was responsible for a smaller proportion at 10.7%. Additionally, there were rare instances of illness linked to *C. fetus* (0.26%), *C. upsaliensis* (0.17%) and *C. lari* (0.12%). The second most prevalent foodborne illness is salmonellosis, which is caused by various serovars of *Salmonella enterica*, particularly *S. typhimurium* and *S. enteritidis*. In 2022, there were 65,208 confirmed cases of salmonellosis, resulting in an average incidence rate of 15.3 per 100,000 inhabitants. Infections from *Y. enterocolitica* are predominantly seen in children, with 7,912 reported cases of individuals infected with *Yersinia* who exhibited disease symptoms, leading to an incidence rate of 2.2 per 100,000 inhabitants. This marks a notable increase compared to 2021, which had 6,789 cases. Research regarding the prevalence of *L. monocytogenes* in livestock indicated that this bacterium was most commonly found in sheep and goats (5.8%) and in cattle (1.2%). *Listeria monocytogenes* was also detected in animal-derived foods, including ready-to-eat items such as fish and fish products, processed meats, as well as milk and dairy products. In a particular study involving cowpea, maize, yam chips, groundnut, melon and smoke-dried fish, the bacteria and fungi that were most frequently isolated and identified were *E. coli* and species of *Aspergillus*, respectively.[3]

## III. SOURCES AND ROUTES OF MICROBIAL CONTAMINATION IN FOOD

Microbial contamination of food can happen at various stages throughout the food supply chain, from initial production to final consumption. It is crucial to comprehend the sources and pathways of microorganisms to develop effective microbial quality control measures and reduce food safety hazards.

### 3.1. Primary Production and Raw Materials
Raw agricultural products are a significant source of microbial contamination. Fruits, vegetables, meat, milk and seafood can contain microorganisms that come from soil, water, animal gut flora and the surrounding environment. Contaminated irrigation water, organic fertilizers, animal feed and interactions with wildlife or insects greatly contribute to the introduction of pathogenic and spoilage microorganisms at the farm level.[4]

### 3.2. Animal-Origin Sources
Animal-derived foods can become contaminated during the processes of slaughtering, milking, or harvesting. Insufficient hygiene during evisceration, cross-contact with intestinal contents, contaminated hides, udders, or aquatic environments can result in the transfer of microorganisms to edible tissues. Improper handling of live animals before processing further elevates the microbial load.[4]

### 3.3. Processing Environment and Equipment
Food processing facilities serve as critical points for microbial transmission. Contaminated equipment, food-contact surfaces and processing tools can function as reservoirs for microorganisms, especially when cleaning and sanitation practices are lacking. The development of microbial biofilms on surfaces such as stainless steel, plastic and rubber presents a persistent contamination risk, allowing for the ongoing transfer of microorganisms to food products.[4]

### 3.4. Human Handling and Personnel Hygiene
Food handlers are crucial in the transmission of microorganisms. Inadequate personal hygiene, insufficient hand washing and improper use of protective gear contribute to both direct and indirect food contamination. Microorganisms can spread through hands, respiratory droplets, skin contact and

contaminated clothing, particularly in manual food processing activities.[5]

3.5. Water and Air as Contamination Vectors
Water utilized for washing, processing, or as an ingredient can act as a medium for microbial contamination if not properly treated. Likewise, the air in processing and packaging areas can carry dust, aerosols and microorganisms that may settle on food and surfaces that come into contact with food. Poor ventilation and filtration systems heighten the risks of airborne contamination.[5]

3.6. Cross-Contamination
During Processing and Storage Cross-contamination happens when microorganisms are transferred from contaminated raw materials to ready-to-eat or processed foods. Common causes include shared equipment, improper workflow design and insufficient separation between raw and cooked items. During storage and transportation, temperature abuse and inadequate packaging further encourage microbial growth and dissemination.

3.7. Distribution, Retail and Consumer Handling
Microbial contamination can also take place during distribution, retail display and consumer handling. Interruptions in the cold chain, unsanitary retail practices and improper food handling or storage by consumers can introduce or exacerbate microbial contamination, ultimately raising the risk of foodborne illnesses.[5]

## IV. ROLE OF MICROBIOLOGICAL QUALITY CONTROL IN FOOD PRODUCTION

➢ It demonstrates the key advantages of microbiological quality control in food production, including ensuring food safety, extending shelf life and to meet regulatory standards.
➢ It gives the knowledge regarding the challenges faced in microbiological quality control, such as high costs, detection limitations, antimicrobial resistance and complex global supply chains.
➢ It gives the information about the recent trends and technological advancements used in MQC, including innovations in pathogen detection methods and management systems like HACCP.

➢ In providing insights and recommendations for food producers and industry stakeholders in improving microbiological testing and implementing effective quality control practices in food production.[6]

## V. THE IMPORTANCE OF MICROBIOLOGICAL QUALITY CONTROL IN FOOD PRODUCTION

Microbiological quality control (MQC) is critical in food production as it ensures the safety, quality and longevity of food products, by detecting and controlling harmful microorganisms. MQC prevents foodborne illnesses and contamination, safeguarding public health. It also enhances the shelf life of products, minimizing the spoilage and helps companies comply with international safety standards like HACCP and ISO. Effective MQC builds consumer trust, protects brand reputation and supports global food supply chains in delivering safe, high-quality products.[7]

## VI. ADVANTAGES OF MICROBIOLOGICAL QUALITY CONTROL

6.1. Ensuring Food Safety: MQC is crucial for ensuring food safety by detecting and controlling harmful microorganisms that can cause foodborne illnesses. MQC systems are designed to identify and eliminate these microorganisms at various stages of production.

6.2. Prevention of Foodborne Illnesses: One of the primary objectives of MQC in food production is the prevention of foodborne illnesses, which pose significant risks to public health worldwide. Foodborne illnesses result from the consumption of contaminated food containing harmful microorganisms, such as bacteria, viruses, or parasites. Implementing rigorous MQC measures ensures the detection, control and elimination of these pathogens, reducing the likelihood of foodborne outbreaks.[8]

6.3. Detection of Pathogens: Microbiological quality control systems are designed to identify the presence of harmful microorganisms, such as *Salmonella*, *E. coli*, *Listeria monocytogenes* and *Norovirus*. Advanced testing methods, including polymerase chain reaction (PCR), immunoassays and whole-

genome sequencing, enable rapid and accurate detection of pathogens in raw materials, processed foods and finished products. Early detection is critical to preventing the distribution of contaminated products to consumers.

6.4. Control of Cross-Contamination: MQC plays a vital role in identifying and mitigating potential points of cross-contamination during food processing and handling. For instance, improper hygiene practices, unclean equipment, or inadequate storage conditions can introduce or spread pathogens in food production facilities. By implementing stringent sanitation protocols and routine microbial testing, food producers can significantly reduce the risk of cross-contamination.[8]

6.5. Mitigation of Foodborne Outbreaks: Outbreaks of foodborne illnesses can have severe consequences, including hospitalization and fatalities. They can also damage the reputation of food producers and lead to costly recalls. Through effective microbiological monitoring and quality assurance systems, companies can prevent contaminated products from reaching the market.

6.6. Protecting Vulnerable Populations: Certain groups, such as young children, pregnant women, the elderly and immunocompromised individuals, are particularly vulnerable to severe complications from foodborne illnesses. MQC measures are essential to protecting these high-risk populations by ensuring that food products meet the highest safety standards.

6.7. Reducing Economic Burden: Foodborne illnesses place a significant economic burden on healthcare systems and the food industry. Costs associated with treatment, lost productivity, product recalls and legal actions can be substantial. By preventing foodborne illnesses through rigorous MQC, food producers can contribute to public health while avoiding financial losses associated with contamination incidents.[8]

6.8. Reduction in Spoilage Risks:
Another critical advantage of MQC in food production is the reduction in spoilage risks, which helps ensure that food products maintain their quality and safety throughout their shelf life. Spoilage not only affects the sensory attributes of food, such as taste, smell and texture, but also poses potential safety hazards if harmful microorganisms proliferate.

6.9. Identification of Spoilage Organisms: MQC involves the routine testing of raw materials, intermediate products and finished goods for spoilage-causing microorganisms, such as yeast, molds and bacteria. Common spoilage organisms include *Pseudomonas, Lactobacillus and Clostridium perfringens,* which can cause off-flavors, discoloration and gas production in foods. Early detection of these microbes enables food producers to take corrective actions before the spoilage affects large batches of products.[9]

6.10. Maintaining Product Integrity: By employing stringent microbiological testing and control measures, producers can maintain the sensory and nutritional quality of their products, ensuring that they meet consumer expectations and regulatory standards.

6.11. Extending Shelf Life: Advanced preservation techniques, such as modified atmosphere packaging (MAP) and the use of natural antimicrobials, work in conjunction with MQC practices to inhibit spoilage organisms and extend the shelf life of perishable products like dairy, meat and fresh produce.

6.12. Sustainability Benefits: Reducing spoilage risks also contributes to sustainability efforts by minimizing food waste. Spoiled products that are discarded represent a waste of resources, including raw materials, water, energy and labor. By implementing effective MQC practices, food producers can reduce spoilage, thereby supporting global initiatives to combat food waste and improve resource efficiency.[10]

6.13. Understanding Spoilage Mechanisms: Spoilage organisms often produce metabolic byproducts, such as acids, gases, or slime, that lead to sensory and physical changes in food. MQC helps producers understand the specific mechanisms by which these microbes spoil food, enabling targeted interventions to inhibit their growth. For example, monitoring and controlling *Lactobacillus* species in dairy products can prevent souring, while controlling yeast growth can reduce the risk of fermentation in fruit juices.[11]

6.14. Ensuring Food Safety: Standards such as the

FDA's Food Safety Modernization Act (FSMA) and ISO 22000 provide comprehensive frameworks for identifying and mitigating microbiological risks in food production. These guidelines mandate the implementation of Hazard Analysis and Critical Control Points (HACCP) systems and require regular microbial testing to prevent contamination and ensure consumer safety.[11]

6.15. Facilitating Technological Advancements: International standards often promote the adoption of innovative technologies in MQC. For instance, the FDA encourages the use of rapid microbial detection methods, while ISO standards advocate for the continuous improvement of laboratory testing procedures. By aligning with these standards, food producers can stay at the forefront of technological advancements and improve their overall quality control processes.[12]

6.16. Adapting to Regional Variations: While international standards provide a global framework, they also allow for adaptations based on local regulations and cultural practices. For example, some countries may have stricter guidelines for certain pathogens or food types. By incorporating both international and regional standards, food producers can ensure compliance across diverse markets.[13]

6.17. Consumer Confidence - Microbiological quality control plays a significant role in building and maintaining consumer confidence in food products. With increasing awareness of food safety issues, consumers are more concerned about the safety and quality of the food they consume. MQC helps ensure that food products are safe, nutritious and free from harmful microorganisms, which strengthens consumer trust.[14]

6.18. MQC in Maintaining Brand Reputation: MQC plays a pivotal role in safeguarding a food producer's brand reputation by ensuring the consistent delivery of safe, high-quality products. In today's highly competitive and interconnected market, even a single incident of microbial contamination can severely damage a company's reputation, leading to loss of consumer trust, financial repercussions and long-term harm to brand equity.[14]

6.19. Gaining Competitive Advantage: A strong reputation for microbiological safety can differentiate a brand in the market. Food producers known for their rigorous MQC practices are often preferred by consumers, retailers and distributors, giving them a competitive edge.[15]

6.20. Promoting Corporate Social Responsibility (CSR): Prioritizing food safety through MQC aligns with broader CSR objectives, as it reflects a company's responsibility toward consumer health and well-being. This positive association enhances the brand image and strengthens its position in the market.[16]

## 7. CHALLENGES IN MICROBIOLOGICAL QUALITY CONTROL

7.1. High Costs: One of the major challenges in MQC is the significant investment required for advanced equipment, testing procedures and skilled personnel. The cost of microbiological testing, including the purchase of high-tech diagnostic tools, laboratory maintenance and training staff, can be prohibitive for smaller food producers. Additionally, frequent and rigorous testing for pathogens or spoilage organisms, especially in large-scale operations, can lead to increased operational costs. These expenses may impact overall profitability, especially for companies with limited resources. Skilled personnel, including microbiologists and laboratory technicians, must be hired and trained, which further increases expenses.[17]

7.2. Detection Limitations: Despite advancements in microbiological testing methods, there are still significant limitations in detection techniques. Traditional methods, such as plating and culturing, while reliable, can take several days to yield results, delaying decision-making and increasing the potential risk of food contamination. While newer techniques like polymerase chain reaction (PCR) provide faster results, they may still face issues like insufficient sensitivity or the inability to detect low-level contamination, especially in complex food matrices such as dairy products, meats, or ready-to-eat foods. Additionally, some tests may provide false positives, leading to unnecessary recalls or destruction of good products, which incurs financial losses. Moreover, the detection of certain pathogens in foods with complex

compositions can be hindered by the presence of interfering substances, complicating testing efforts. The variability in microbial types across different food products further complicates the development of universal detection systems, requiring food producers to adopt multiple testing methods, each with its limitations.[18]

7.3. Antimicrobial Resistance: Antimicrobial resistance (AMR) among foodborne pathogens is a growing global concern, significantly complicating microbiological quality control. The widespread use of antibiotics in agriculture, particularly in livestock, has contributed to the development of resistant strains of bacteria, which can enter the food supply. Resistant pathogens are harder to eliminate through traditional antimicrobial treatments, making contamination control more difficult. This is particularly problematic in environments where food producers rely on antibiotics to manage bacterial growth or preserve product quality. AMR not only makes foodborne illnesses more severe but also challenges the effectiveness of conventional food safety protocols, requiring the food industry to innovate with more sophisticated antimicrobial strategies and resistance monitoring systems.[19]

7.4. Risk of Spread to Humans: Resistant strains of pathogens in the food supply can be transferred to humans through consumption of contaminated food products. This can result in more severe and prolonged illnesses, which require more complex and expensive treatments. In some cases, antimicrobial-resistant infections can be fatal if left untreated or if effective treatment options are not available.[20]

7.5. Regulatory and Public Health Concerns: Governments and international organizations such as the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) are increasingly focusing on AMR as a public health issue. As a result, food producers are facing stricter regulations on the use of antibiotics in food production. This adds another layer of complexity for food producers who must navigate the regulatory landscape while ensuring the safety and quality of their products.[21]

7.6. Impact on Food Safety and Production: It increases the risk of contamination in food products,

especially in meats, dairy and other animal-based products. To address this, food producers must implement more rigorous surveillance systems to detect resistant strains and adopt alternative antimicrobial interventions such as bacteriophage therapy, probiotics, or stricter hygiene and sanitation practices.

As food producers expand their reach to international markets, they face a range of obstacles that can compromise the uniformity of microbiological safety across various stages of production, processing and distribution.[22]

7.7. Varying Environmental Conditions: Different geographical regions have varying climates, which directly impact the types of microorganisms present in food products. For instance, warmer and more humid environments may favor the growth of specific spoilage bacteria or pathogens, which might not be as prevalent in cooler or drier regions. This variation in microbial risks can result in differing quality control needs, requiring localized testing methods and interventions.[22]

7.8. Inconsistent Hygiene Standards and Practices: Hygiene practices can differ significantly across countries or even between facilities within the same company. For example, the level of sanitation in food processing plants may be more advanced in certain regions, while others may struggle with adequate hygiene practices due to resource constraints. This disparity can lead to variations in microbial contamination levels, making it difficult to maintain consistent quality control across all operations.[23]

7.9. Cultural and Operational Differences: Companies operating in different regions may face challenges due to cultural differences or operational constraints. For example, workers in various countries may have different levels of training or awareness regarding food safety practices. In some regions, food safety may be given higher priority, while in others, it may be overlooked due to cost-cutting measures or lack of awareness. This inconsistency in operational practices can lead to significant discrepancies in the microbiological safety of food products produced in different regions.[24]

7.10. Complex Supply Chains - The complexity of global food supply chains presents a significant challenge for MQC. Food products often pass through multiple stages of processing, transportation and storage, each involving different environmental conditions that can contribute to contamination. Factors such as varying levels of hygiene, temperature fluctuations and exposure to cross-contamination during transportation can lead to inconsistent microbiological quality across different regions and suppliers. Furthermore, food products may be sourced from diverse geographical locations, each with its own microbial risks, making it difficult to standardize safety protocols.[24]

As food production increasingly becomes globalized, maintaining consistent MQC across various regions and operations has become a significant challenge. Global operations face multiple hurdles in ensuring that the same high standards of microbiological safety are upheld across all production sites, regardless of geographic location. These challenges can stem from environmental factors, local practices, regulations and logistical issues.[25]

7.11. Impact on Global Trade and Market Access: These regulatory inconsistencies can complicate international trade, especially in regions with highly regulated food safety standards. When food producers attempt to export products to countries with stricter food safety requirements, they may face significant hurdles in meeting those standards. In some cases, this may result in delays in market access, product recalls, or even the rejection of shipments.[25]

## VIII. MODERN ADVANCEMENTS IN MICROBIAL DETECTION TECHNIQUES

Recent advancements in microbiological detection techniques have significantly transformed microbiological quality control (MQC) in food production. These innovations offer improved sensitivity, speed a nd reliability, allowing food producers to detect microbial contaminants more efficiently and prevent potential risks.[26]

8.1. CRISPR-Based Detection Tools
Speed and Cost Efficiency: These tools can deliver results within 30–60 minutes, making them ideal for on- site testing. Their simplicity and affordability are particularly beneficial for resource-limited settings.[27]
Precision and Specificity: CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) technology, originally developed for gene editing, is now being applied to detect microbial pathogens. CRISPR-based assays target specific DNA or RNA sequences of microorganisms with unparalleled precision, enabling the rapid identification of pathogens such as Salmonella and E.coli.[27]
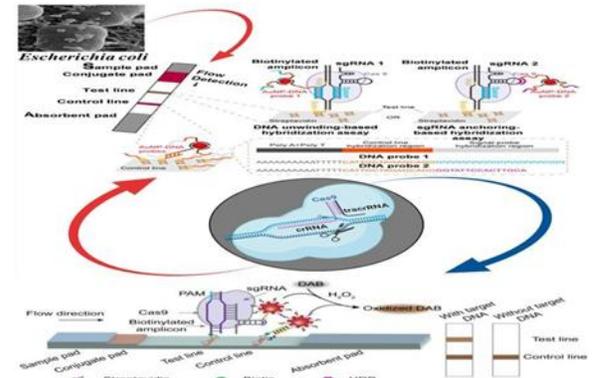


Fig 1: Crisper based detection for food-borne pathogens.[28]

8.2. Next-Generation Sequencing (NGS)
Comprehensive Microbial Profiling: NGS allows for the simultaneous detection of multiple microorganisms, including bacteria, viruses, fungi and parasites. Unlike traditional methods, which target specific pathogens, NGS provides a complete microbial profile of a food sample.[29]
Application in Traceability: NGS is being used to trace contamination sources during outbreaks, enabling food producers to identify the origin of microbial contaminants and implement corrective actions effectively.[29]
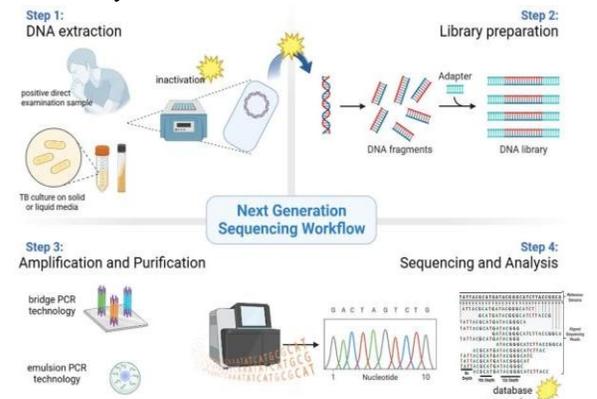


Fig 2: NGS in sample analysis.[30]

Automation and Scalability: Advances in NGS automation have made it more accessible for routine quality control, especially in large-scale food production facilities.

## 8.3. Biosensors and Lab-on-a-Chip Devices:

Real- Time monitoring and Lab-on-a-Chip Devices: Biosensors are evolving to include lab-on-a-chip technologies, which integrate multiple detection processes into a single, portable device. These tools allow for real-time microbial monitoring during food production and storage.31



Fig 3: Lab-on-a-chip device.[32]

Enhanced Sensitivity: Lab-on-a-chip devices use nanotechnology to detect extremely low concentrations of microbial contaminants, ensuring high accuracy. Applications: These devices are being widely adopted for detecting spoilage organisms and pathogens in fresh produce, meat and dairy products.34
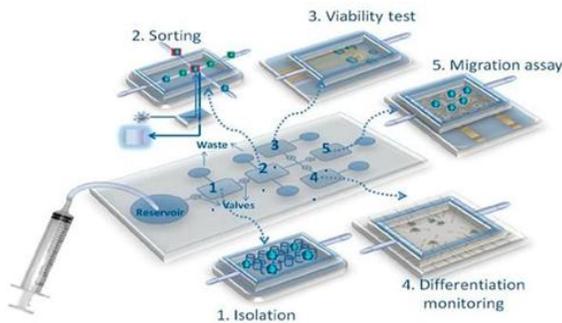


Fig 4: Biosensor for pathogens detection.[33]

## 8.4. Artificial Intelligence (AI) and Machine Learning (ML)

Data Analysis: AI-powered algorithms can analyze vast amounts of microbial data quickly, identifying contamination patterns and predicting potential risks. Automation: ML models are being trained to identify microbial colonies in culture-based methods, reducing

human error and improving efficiency.
Integration with IOT: AI-enabled devices connected via the Internet of Things (IoT) allow for continuous monitoring of food safety parameters and instant alerts when abnormalities are detected.35

## 8.5. Rapid Immunological Techniques

Enzyme-Linked Immunosorbent Assay (ELISA): Modern ELISA kits are designed to provide faster and more accurate results for detecting specific pathogens, toxins, or allergens in food.
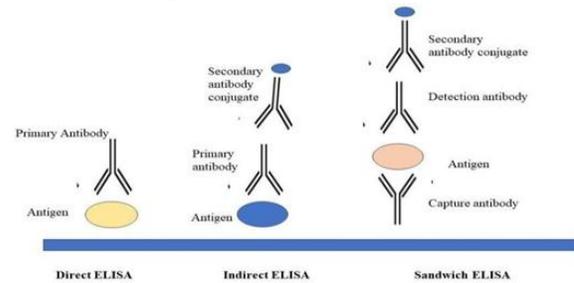


Fig 5: ELISA used for detection of various components present in food.[36]

Lateral Flow Assays: These portable, user-friendly tools are gaining popularity for quick onsite testing of microbial contaminants. They are especially useful for detecting pathogens like *Listeria* or *Campylobacter* in raw and processed foods.37

## 8.6. Automation and Robotics

High-Throughput Systems: Automated systems now handle large volumes of samples simultaneously, reducing the time required for microbial analysis.
Robotic Sample Handling: Robots are increasingly being used for sample collection, preparation and analysis, minimizing contamination risks and improving consistency in MQC processes.38



Fig 6: Robots in food preparation.[39]

## IX. BENEFITS OF ADVANCES IN DETECTION TECHNIQUES ENHANCED FOOD SAFETY

Faster and more accurate detection reduces the likelihood of contaminated products reaching consumers.

Cost and Time Efficiency: These techniques lower the overall costs associated with recalls, wastage and lengthy testing procedures.

Proactive Risk Management: Real-time monitoring and predictive capabilities enable food producers to address potential issues before they escalate.[40]

## X. IMPORTANCE OF HACCP IN FOOD PRODUCTION

The Hazard Analysis and Critical Control Points (HACCP) system is a globally recognized framework for ensuring food safety through systematic identification and management of microbiological risks. By integrating HACCP into microbiological quality control (MQC), food producers can establish proactive measures to prevent contamination, ensuring safe food production and compliance with regulatory standards.[41]

10.1. Systematic Risk Identification and Mitigation
Hazard Analysis: HACCP begins with identifying potential microbiological hazards, such as pathogens (*E. coli, Listeria, Salmonella*), toxins, or spoilage organisms, at each stage of food production.
Critical Control Points (CCPs): Once hazards are identified, CCPs are established where controls can be applied to prevent, eliminate, or reduce these hazards to acceptable levels. For example, pasteurization is a CCP for controlling microbial growth in dairy products.[42]

10.2. Preventive Rather than Reactive
Unlike traditional quality control methods that focus on end- product testing, HACCP emphasizes preventive measures. By addressing risks during the production process, HACCP reduces the likelihood of contamination, minimizing reliance on final product testing. This proactive approach enhances food safety and reduces waste.[43]
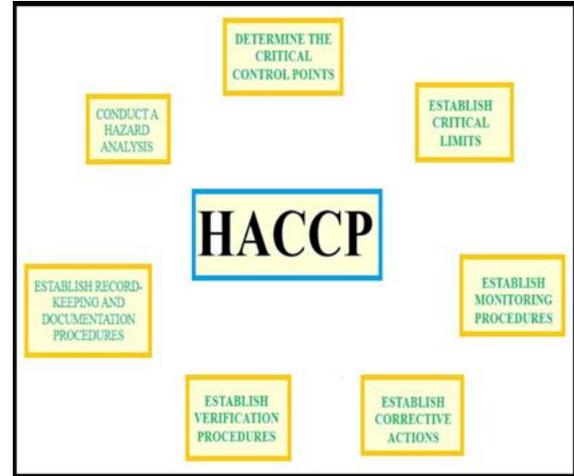


Fig 7: Principles of HACCP

10.3. Compliance with Global Standards
Regulatory Requirements: Many countries mandate the implementation of HACCP for food businesses to comply with safety regulations. For instance, the U.S. FDA and the European Food Safety Authority (EFSA) require HACCP-based systems for various food sectors.
Harmonization of Practices: HACCP provides a standardized framework that facilitates consistency across global supply chains, enabling food producers to meet international standards and export requirements.[44]

10.4. Integration with Other Quality Management Systems
HACCP complements other food safety management systems, such as ISO 22000, which incorporates HACCP principles into a broader framework. This integration ensures comprehensive monitoring and control of food safety risks across all stages of production, processing and distribution.[44]

10.5. Continuous Monitoring and Documentation
Real-Time Control: HACCP involves continuous monitoring of CCPs, ensuring immediate detection and correction of deviations. For instance, temperature logs in cold storage help maintain conditions that inhibit microbial growth.
Traceability and Accountability: The system emphasizes detailed documentation of processes and corrective actions, enhancing traceability and accountability. This is invaluable during audits or foodborne illness investigations.[45]

10.6. Economic and Operational Benefits

Cost Efficiency: Preventing contamination through HACCP reduces the costs associated with recalls, legal actions and loss of consumer trust.

Enhanced Productivity: By streamlining processes and identifying inefficiencies, HACCP contributes to smoother operations and better resource management.[46]

10.7. Challenges in Implementation

While HACCP offers numerous benefits, its successful implementation requires:

Trained Personnel: Staff must be trained to identify hazards, monitor CCPs a nd maintain records accurately.

Investment in Infrastructure: Adequate resources, such as testing equipment and monitoring tools, are essential for effective HACCP implementation.

Adaptation to Diverse Products and Processes: Customizing HACCP plans for different food products and production systems can be complex.[47]

10.8. Training and Education

Continuous Professional Development for Personnel - Effective microbiological quality control (MQC) in food production relies heavily on the knowledge, skills and competencies of personnel involved in the process. Continuous professional development (CPD) and regular training programs ensure that employees remain updated with the latest advancements, practices and regulatory requirements, contributing to a robust food safety management system.

## XI. IMPORTANCE OF TRAINING IN MICROBIOLOGICAL QUALITY CONTROL

11.1. Role of HACCP

Understanding Microbiological Risks: Training equips personnel with a clear understanding of microbial hazards, including their sources, transmission and potential impacts on food safety.

Skill Development: Hands-on training helps workers acquire the technical skills needed to operate advanced detection methods, such as PCR or biosensors and implement systems like HACCP effectively.

Awareness of Regulations: Regular education ensures staff stay informed about changing food safety standards and compliance requirements, such as FDA or ISO guidelines.[48]

11.2. Benefits of Continuous Professional Development (CPD):

Enhanced Performance: CPD ensures that employees maintain and improve their competencies, leading to better decision-making and problem-solving in MQC practices.

Adaptation to Technological Advancements: As new technologies like CRISPR or AI based tools emerge, ongoing training enables personnel to adopt and utilize these innovations effectively.

Improved Workplace Culture: A well-trained workforce fosters a culture of accountability, vigilance and commitment to food safety, reducing errors and enhancing overall quality.[49]

11.3. Training Focus Areas:

Hygiene and Sanitation Practices: Personnel must be trained in proper hygiene protocols, including hand washing, equipment cleaning and facility maintenance, to minimize contamination risks.

Critical Control Point Monitoring: Training ensures that employees understand how to identify and manage CCPs effectively within HACCP frameworks.

Use of Detection Technologies: Practical sessions on operating rapid detection tools, such as real-time PCR, lateral flow assays, or biosensors, enhance technical expertise.

Incident Management: Training programs should include procedures for handling contamination incidents, conducting recalls and communicating effectively with stakeholders.[50]

11.4. Strategies for Effective Training and Education:

Customized Training Programs: Tailoring training content to specific roles and responsibilities ensures relevance and engagement. For instance, microbiologists may require advanced analytical training, while line workers focus on hygiene practices.

Regular Refresher Courses: Periodic refresher sessions help reinforce key concepts and address gaps in knowledge or skills.

On-the-Job Training: Practical, hands-on training in real production environments enhances retention and applicability of knowledge.

E-Learning and Online Resources: Digital platforms enable flexible learning, providing access to webinars, tutorials and case studies on emerging topics in MQC. Certification Programs: Encouraging employees to pursue certifications, such as ISO 22000 or HACCP qualifications, boosts expertise and credibility.[51]

11.5. Challenges in Implementing Training Programs Cost and Resource Constraints: Investing in training programs, especially for small-scale producers, can be challenging due to limited budgets. Resistance to Change: Employees may resist adopting new practices or technologies, highlighting the need for effective communication about the benefits of training.
Retention of Knowledge: Without regular reinforcement, employees may forget critical concepts, underscoring the importance of ongoing education.

11.6. Long-Term Benefits of Training and Education
Reduced Contamination Risks: A well-trained workforce is better equipped to prevent, identify and address microbial contamination, ensuring safer food production.
Improved Operational Efficiency: Skilled personnel contribute to smoother workflows, fewer errors and reduced downtime.
Demonstrating a commitment to employee development reflects positively on the company's dedication to quality and safety, enhancing consumer trust. Continuous professional development and targeted training programs are essential for maintaining high standards in microbiological quality control. By equipping personnel with the knowledge and skills needed to adapt to evolving challenges and technologies, food producers can ensure the consistent production of safe, high-quality food products. Training is not just an investment in employees but also a crucial step toward safeguarding public health and achieving long-term success in the food industry.[52]

## XII. FUTURE DIRECTION

The integration of AI with advanced detection methods is expected to further improve speed and accuracy. Research into portable, low-cost devices will make cutting-edge technologies more accessible to small-scale producers. Combining traditional methods with advanced tools will offer a balanced approach to ensuring comprehensive microbiological quality control.[53]

## XIII. APPLICATIONS OF MICROBIAL QUALITY CONTROL

Microbial quality control strategies are customized to fit the distinct characteristics, processing conditions and risk profiles of various food sectors. Monitoring and control measures that are specific to each sector are crucial for maintaining food safety, ensuring product quality and adhering to regulatory standards.

13.1. Dairy Industry
Chowdhury et al., 2025, reviewed comprehensive approaches for preventing and detecting microbial contamination in the dairy industry, highlighting both traditional and advanced detection methods to safeguard dairy product safety and quality. A recent Foods journal special issue includes research on microbial dynamics and hygiene concerns related to dairy products, emphasizing the importance of controlling spoilage and pathogenic microorganisms. Yalew et al., 2024, provided an updated review on detection and control strategies for psychrotrophic bacteria in milk, which are key spoilage organisms in dairy supply chains.[54]

13.2. Meat and Poultry
Sivamaruthi et al., 2025 comprehensively reviewed lactic acid bacteria applications in the meat industry, including implications for food safety, bacteriocin use and preservation strategies.
The Foods journal special issue "Meat Quality and Microbial Analysis" contains studies on bacterial community dynamics and hygienic control measures in RTE meat products. A systematic review by Gizaw et al. confirms the high prevalence of pathogenic bacteria in RTE foods and highlights the need for rigorous microbial monitoring and control.[55]

13.3. Fresh Produce
A narrative review focusing on fresh produce compiles the latest detection technologies and control strategies for ensuring microbial safety, such as plasma-activated water and CRISPR diagnostics, showcasing advanced research from 2000 to 2024.[55] The review in Trends in Food Science & Technology emphasizes the

use of AI/ML for detecting spoilage and assessing quality in perishable items, including fruits and vegetables.[56]

13.4. Smart Food Safe Ready-to-Eat (RTE) Foods
Afrifa-Tettey *et al*., 2025 examined the technological progress in the processing, safety and quality management of RTE meals, addressing microbial risks and control methods like high-pressure processing. Systematic reviews concerning RTE food contamination highlight the public health threats posed by pathogens such as *E. coli*, *Salmonella* and *Staphylococcus aureus*, emphasizing the urgent need for microbial quality control strategies.[57]

13.5. Cross-Sector and General Food Safety
A systematic literature review from 2025 reveals the most recent technologies for detecting food contaminants, regulatory changes and microbial hazards that are pertinent across various sectors.[58]

## XIV. CONCLUSION

Microbiological quality control (MQC) is a critical aspect of food production, ensuring the safety, quality and integrity of food products. By monitoring and controlling microbial contamination, MQC prevents the spread of foodborne illnesses, reduces spoilage risks and helps maintain the shelf life of food products. As the food industry faces increasing pressure to meet safety standards, comply with regulations and satisfy consumer demands for high quality products, effective microbiological quality control remains indispensable. Throughout this review, we have highlighted both the advantages and challenges of MQC. The advantages include ensuring food safety, enhancing product shelf life and maintaining consumer confidence through the adoption of advanced technologies, such as PCR and biosensors. However, challenges such as high costs, detection limitations, antimicrobial resistance, complex supply chains and regulatory variations continue to pose significant hurdles to achieving optimal MQC standards. By overcoming these challenges, the food industry can not only improve its quality control practices but also drive innovation in food safety and production. Adopting emerging technologies like nanotechnology, blockchain and predictive microbiology offers the potential to revolutionize how microbial risks are managed. In addition, integrating sustainable practices into MQC can align food safety goals with environmental and social responsibilities. Ensuring the safety and quality of food products is not just about meeting regulatory requirements it is about fostering a safer and more sustainable food system for the future.

## REFERENCES

[1] Caleb, O. J., Mahajan, P. V., Al-Said, F. A.-J., & Opara, U. L. (2013). Modified atmosphere packaging technology of fresh and fresh-cut produce and the microbial consequences—A review. Food and Bioprocess Technology, 6(2), 303–329. https://doi.org/10.1007/s11947-012-0932-4

[2] Kaur, N., & Singh, A. (2023). Role of microorganisms in the food industry, Springer Nature Singapore. 1-23. https://doi.org/10.1007/978-981-99-4784-3_1

[3] Maestre, F. T., Sole, R., & Singh, B. K. (2017). Microbial biotechnology as a tool to restore degraded drylands. Microbial Biotechnology, 10(5), 1250-1253. https://doi.org/10.1111/1751-7915.12832

[4] Rinken, T., & Kivirand, K. (2019). Biosensors for environmental monitoring. IntechOpen.

[5] Ma, Z., Meliana, C., Munawaroh, H. S. H., Karaman, C., Karimimaleh, H., Low, S. S., & Show, P. L. (2022). Recent advances in the analytical strategies of microbial biosensor for detection of pollutants. Chemosphere, 306, https://doi.org/10.1016/j.chemosphere.2022.1355 15

[6] Silva, I. F., Rezende-Lago, N. C. M. D., Marchi, P. G. F. D., Messias, C. T., & Silva, L.A. (2023). Microbiological quality of food. In COLLECTION OF INTERNATIONAL TOPICS IN HEALTH SCIENCE. 1(7), 1-120. https://doi.org/10.56238/colleinternhealthscienv

[7] Ljevakovic-Musladin, I., Lakic, M., & Kozacinski, L. (2019). Microbiological quality assessment of ready- to-eat vegetables in dubrovnik-neretva county, croatia. Universal Journal of Agricultural Research, 7(1), 1-6. https://doi.org/10.13189/ujar.2019.070101

[8] Postollec, F., Falentin, H., Pavan, S., Combrisson, J., & Sohier, D. (2011). Recent advances in

quantita56+ive PCR applications in food microbiology. Food Microbiology, 28(5), 848-861. https://doi.org/10.1016/j.fm.2011.02.008

[9] Bal, B., Naya, S., & Das, A. P. (2017). Recent advaces in molecular techniques for the diagnosis of foodborne diseases. In Nanotechnology Applications in Food. Elsevier. https://doi.org/10.1016/B978-0-12-811942-6.00013-3

[10] Shuba, A. A., Bogdanova, E. V., Anokhina, E. P. (2025). Current trends in the determination of microbiological indicators of dairy products. J Food Sci Technol, 62, 453-470. https://doi.org/10.1007/s13197-025-06207-0

[11] Wilcock, A., Ball, B., & Fajumo, A. (2011). Effective implementation of food safety initiatives: Managers', food safety coordinators' and production workers' perspectives. Food Control, 22(1), 27-33. https://doi.org/10.10166/j.foodcont.2010.06.005

[12] Arne Reis. (2025). HACCP Explained: Ensuring Food Safety from Farm to Fork. Flowdit. https://flowdit.com

[13] Murat Karaoglu, M., Gurbuz Kotancilar, H., & Gurses, M. (2005). Microbiological Characteristics of Part-Baked White Pan Bread During Storage. International Journal of Food Properties, 8(2), 355-365. https://doi.org/10.1081/JFP-200060239

[14] Basu, S., Pal., & Desai, P. (2005). Quality control of culture media in a microbiology laboratory. Indian Journal of Medical Microbiology, 23(3), 159. https://doi.org/10.4103/0255-0857.16586

[15] Alok Chaurasia. (2023). The Importance of Microbiological Quality Control in Food Industry. Ghaziabad Testing Laboratories Pvt. Ltd. https://www.gtllab.org

[16] Bolton, F. J. (1998). Quality assurance in food microbiology-A novel approach. International Journal of Food Microbiology, 45(1), 7-11. https://doi.org/10.1016/S0168-1605(98)00139-1

[17] Sharma, V., Garg, M., Talukdar, D., Thakur, P., Henkel, M., Sharma, D., & Kumar, G. (2018). Preservation of microbial spoilage of food by biosurfactant-based coating. Asian Journal of Pharmaceutical and Clinical Research, 11(14), 98. https://doi.org/10.22159/ajpcr.2018.v11s2.28592

[18] Sagar, N. A., & Pareek, S. (2020). Safe storage and preservation techniques in commercialization agriculture. In Nature Remedies for Pest, Disease and Weed Control. Elsevier. 221-234. https://doi.org/10.1016/B978-0-12-819304-4.00019-1

[19] Chu, Z., Wang, H., & Dong, B. (2024). Research on food preservation based on antibacterial technology: Progress and future prospects. Molecules, 29(14), 3318. https://doi.org/10.3390/molecules29143318

[20] Aakriti Guleria. (2025). Microbiological Spoilage: A Major Contributor to Food Waste and Safety Concerns. International Journal of Research Publication and Reviews. 6(2), 3525-3533. www.ijrpr.com ISSN 2582-7421

[21] Trias, M., Mutiara, A. V., Edna, E., Evi, L., Corrienna, A. T. (2022). Best practices and challenges in implementing healthy food environment at school setting toward prevention of obesity in Indonesia and Malaysia. Oamjms. 10. https://doi.org/10.3889/oamjms.2022.8998

[22] Murali, A. P., Trzaskowska, M., & Trafialek, J. (2023). Microorganisms in organic food-issues to be addressed. Microorganisms, 11(6), 1557. https://doi.org/10.3390/microorganisms11061557

[23] Kvenberg, J. E., & Schwalm, D. J. (2000). Use of microbial data for hazard analysis and critical control point verification- Food and drug administration perspective. Journal of Food Protection, 63(6), 810-814. https://doi.org/10.4315/0362-028X-63.6.810

[24] A. Bukhari, M., M. Banasser, T., El-Bali, M., A. Bulkhi, R., A. Qamash, R., Trenganno, A., Khayyat, M., A. Kurdi, M., Al Majrashi, A., & Bahewareth, F.(2021). Assessment of microbiological quality of food preparation process in some restaurants of Makkah city. Saudi Journal of Biological Sciences, 28(10), 5993-5997. https://doi.org/10.1016/j.sjbs.2021.06.050

[25] Olayiwola, Olusola. (2015). Microbiological Quality Assessment and Antibiogram of the Bacteria Isolated from Fish Feed, Oyo, South-West Nigeria. Journal of Animal Science Advances. 5(3), 1218. https://doi.org/10.5455/jasa.20150315015415

[26] Mayahi, T. (2024). Ensuring food safety: Risk assessment and microbiological quality control in food microbiology. J Food Microbiol. 8(5), 226. https://doi.org/10.35841/aafmy-8050226

[27] Os, Job, et al. (2024). Nanotechnology in Water Quality: Assessment Application for Microbial Detection and Control. Open Access Journal of Microbiology & Biotechnology, 9(4), 1-4. https://doi.org/10.23880/oajmb-16000308

[28] Degpal Singh, Anit Kumar and Amandeep Singh. (2018). HACCP IN CLEAN FOOD PRODUCTION. International Journal of Research, 6(12), 128-134. https://doi.org/10.5281/zenodo.2532392

[29] Gholami-Shabani, M., Shams-Ghahfarokhi, M., & Razzaghi-Abyaneh, M. (2024). Food microbiology: Application of microorganisms in food industry. Recent Developments and Trends in Food Sector. IntechOpen. https://doi.org/10.5772/intechopen.109729

[30] Shah, A. S., Bhat, S. V., Muzaffar, K., Ibrahim, S. A., & Dar, B. N. (2022). Processing technology, chemical composition, microbial quality and health benefits of dried fruits. Current Research in Nutrition and Food Science Journal, 10(1), 71-84. https://www.foodandnutritionjournal.org/volume 10number1/processing- technology-chemical-composition-microbial-quality-and-health-benefits-of-dried-fruits/

[31] Kayla Murray, Fan Wu, John Shi, Sophia Jun Xue, Keith Warriner. (2017). Food quality and Safety. Oxford Academic. 1(4), 289-30. https://doi.org/10.1093/fqsafe/fyx027

[32] Graham, A. E., & LEDESMA-AMARO, R. (2023). The microbial food revolution. Nature Communications, 14(1), 2231. https://doi.org/10.1038/s41467-023-37891-1

[33] BECK, K. L., HAIMINEN, N., CHAMBLISS, D. et al. (2021). Monitoring the microbiome for food safety and quality using deep shotgun sequencing. 5(3). https://doi.org/10.1038/s41538-020-00083-y

[34] Mafe, A. N., Edo, G. I., Makia, R. S., Joshua, O. A., Akpoghelie, P. O., Gaaz, T. S., Jikah, A. N., Yousif, E., Isoje, E. F., Igbuku, U. A., Ahmed, D. S., Essaghah, A. E. A., & Umar, H. (2024). A review on food spoilage mechanisms, food borne diseases and commercial aspects of food preservation and processing. Food Chemistry Advances, 5, 100852. https://doi.org/10.1016/j.focha.2024.100852

[35] Jia, Z., Zhou, J., Wang, W., Liu, D., Zheng, X., Hu, M., Jiang, Y., & Lv, R. (2024). Optimization of vaccum freeze-drying process and quality evalution of stropharia rugosoannulata. Applied Sciences, 14(22), 10158. https://doi.org/10.3390/app142210158

[36] Bhattacharjee, R., Nandi, A., Mitra, P., Saha, K., Patel, P., Jha, E., Panda, P. K., Singh, S. K., Dutt, A., Mishra, Y. K., Verma, S. K., & Suar, M. (2022). Theragnostic application of nanoparticle and CRISPR against food-borne multi-drug resistant pathogens. Materials Today Bio, 15, 100291. https://doi.org/10.1016/j.mtbio.2022.100291

[37] Beviere, M., Reissier, S., Penven, M., Dejoies, L., Guerin, F., Cattoir, V., & Piau, C. (2023). The role of next-generation sequencing (Ngs) in the management of tuberculosis: Practical review for implementation in routine. Pathogens, 12(8), 978. https://doi.org/10.3390/pathogens12080978

[38] Rainbow, J., Sedlackova, E., Jiang, S., Maxted, G., Moschou, D., Richtera, L., & Estrela, P. (2020). Integrated electrochemical biosensors for detection of waterborne pathogens in low-resource settings. Biosensors, 10(4), 36. https://doi.org/10.3390/bios10040036

[39] Attaluri, S., & Dharavath, R. (2023). Novel plant disease detection techniques-a brief review. Molecular Biology Reports, 50(11), 9677–9690. https://doi.org/10.1007/s11033-023-08838-y

[40] Charlotte Stonestreet. (2020). CONTROLS, DRIVES & AUTOMATION

[41] EFSA and ECDC (European Food Safety Authority and European Centre for Disease Prevention and Control). The European Union One Health 2022 zoonoses report. EFSA J. 2023, 21, e8442. [Google Scholar] [CrossRef]

[42] Bala, I., Eunice, B., Saka, H., Donatus, U., & Ahmad, F. (2025). Quality and safety evaluations of commonly consumed foods stuff from Dawanau market, Kano State, Nigeria. Journal of Food Safety and Hygiene. https://doi.org/10.18502/jfsh.v10i2.17684

[43] Alegbeleye, O. O., Singleton, I., & Sant'Ana, A. S. (2018). Sources and contamination routes of microbial pathogens to fresh produce during field cultivation: A review. Food microbiology, 73, 177–208. https://doi.org/10.1016/j.fm.2018.01.003

[44] Masotti, F., Cattaneo, S., Stuknytė, M., & De Noni, I. (2019). Airborne contamination in the

food industry: An update on monitoring and disinfection techniques of air. Trends in Food Science & Technology, 90, 147–156. https://doi.org/10.1016/j.tifs.2019.06.006

[45] Mohammad, Z.H., Arias-Rios, E.V., Ahmad, F., Juneja, V.K. (2024). Microbial Contamination in the Food Processing Environment. In: Ahmad, F., Mohammad, Z.H., Ibrahim, S.A., Zaidi, S. (eds) Microbial Biotechnology in the Food Industry. Springer, Cham. https://doi.org/10.1007/978-3-031-51417-3_2

[46] Loveniers, P.-J., Devlieghere, F., & Sampers, I. (2024). Towards tailored guidelines for microbial air quality in the food industry. International Journal of Food Microbiology, 421, 110779. https://doi.org/10.1016/j.ijfoodmicro.2024.110779

[47] Arki, A., Rohn, K., Lemke, B., Röpper, D., Plötz, M., Jessberger, N., & Siekmann, L. (2025). Influence of takeout packaging systems and storage conditions on microbiological, chemical and sensory properties of turkey meat. Journal of Food Protection, 100682. https://doi.org/10.1016/j.jfp.2025.100682

[48] Al-Mazrouei, M. A., Al-Kharousi, Z. S., Al-Kharousi, J. M., & Al-Barashdi, H. M. (2024). Microbiological evaluation of local and imported raw beef meat at retail sites in Oman with emphasis on spoilage and pathogenic psychrotrophic bacteria. Microorganisms, 12(12), 2545. https://doi.org/10.3390/microorganisms12122545

[49] Chowdhury, M. A. H., Reem, C. S. A., Rahman, S. M., & Sarkar, F. (2025). Comprehensive approaches for ensuring microbial safety in the dairy industry: Monitoring systems, inhibitory strategies and future prospects. Food Control, 168, 110894. https://doi.org/10.1016/j.foodcont.2024.110894

[50] Pheepakpraw, J., Sinchao, C., Sutheeworapong, S., Sattayawat, P., Panya, A., Tragoolpua, Y., & Chitov, T. (2025). Cytotoxicity and genome characteristics of an emetic toxin-producing Bacillus cereus group sp. isolated from raw milk. Foods, 14(3), 485. https://doi.org/10.3390/foods14030485

[51] Yalew, K., Pang, X., Huang, S., Zhang, S., Yang, X., Xie, N., Wang, Y., Lv, J., & Li, X. (2024). Recent development in detection and control of psychrotrophic bacteria in dairy production: Ensuring milk quality. Foods, 13(18), 2908. https://doi.org/10.3390/foods13182908

[52] Sivamaruthi, B. S., Kesika, P., Rafeek, S. B. S., Sivakumar, K., Ramasamy, S. P., Chaiaysut, C., Fukngoen, P., & Alagarsamy, K. (2025). Lactic acid bacteria in the meat industry: Flavor, function and food safety. Frontiers in Microbiology, 16, 1703213. https://doi.org/10.3389/fmicb.2025.1703213

[53] Qiu, M., Xiao, X., Xiao, Y., Ma, J., Yang, H., Jiang, H., Dong, Q., & Wang, W. (2022). Dynamic changes of bacterial communities and microbial association networks in ready-to-eat chicken meat during storage. Foods, 11(22), 3733. https://doi.org/10.3390/foods11223733

[54] Mengistu, D. A., Belami, D. D., Tefera, A. A., & Alemeshet Asefa, Y. (2022). Bacteriological quality and public health risk of ready-to-eat foods in developing countries: Systematic review and meta-analysis. Microbiology Insights, 15, 11786361221113916. https://doi.org/10.1177/11786361221113916

[55] Elbehiry, A., Marzouk, E., Alzaben, F., Almuaither, A., Abead, B., Alamri, M., Almuzaini, A. M., & Abu-Okail, A. (2025). Emerging technologies and integrated strategies for microbial detection and control in fresh produce. Microorganisms, 13(7), 1447. https://doi.org/10.3390/microorganisms13071447

[56] Rashvand, M., Ren, Y., Sun, D.-W., Senge, J., Krupitzer, C., Fadiji, T., Miró, M. S., Shenfield, A., Watson, N. J., & Zhang, H. (2025). Artificial intelligence for prediction of shelf-life of various food products: Recent advances and ongoing challenges. Trends in Food Science & Technology, 159, 104989. https://doi.org/10.1016/j.tifs.2025.104989

[57] Zhang, Z., Xu, G., & Hu, S. (2025). A comprehensive review on the recent technological advancements in the processing, safety and quality control of ready-to-eat meals. Processes, 13(3), 901. https://doi.org/10.3390/pr13030901

[58] Duan, K., Pang, G., Duan, Y., Onyeaka, H., & Krebs, J. (2025). Current research development on food contaminants, future risks, regulatory regime and detection technologies: A systematic

literature review. Journal of Environmental Management, 381, 125246. https://doi.org/10.1016/j.jenvman.2025.125246