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Cross-contamination risks and hazard analysis and critical control point (HACCP) strategies in the meat industry: A Review

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ABSTRACT

The meat industry plays a vital role in supplying animal protein; however, it also carries a high risk of cross-contamination, which poses a significant threat to food safety. Cross-contamination can occur at multiple stages of the production chain, including slaughtering, cutting, processing, storage, and distribution, with primary sources stemming from infected animals, contaminated equipment, workers, and the surrounding environment. The consequences include a higher incidence of foodborne diseases, substantial economic losses due to product recalls, and a decline in consumer confidence. To mitigate these hazards, the Hazard Analysis and Critical Control Points (HACCP) system is internationally recognized as a science-based and preventive approach. This review discusses the fundamental principles of HACCP, including hazard identification, determination of Critical Control Points (CCP), and the mechanisms of monitoring, verification, and documentation. Furthermore, it explores HACCP implementation across various meat commodities (beef, poultry, pork), highlights differences in application between developed and developing countries, and examines key factors influencing its effectiveness, such as regulatory frameworks, worker training, and the availability of production facilities. Despite persistent challenges—such as implementation costs, limited human resources, and low hygiene awareness technological advancements, including IoT-based sensors, rapid detection methods, and blockchain traceability, offer promising opportunities to strengthen HACCP systems. Integration with other standards (ISO 22000, GMP, SOP) and the move toward a digitalized, smart meat processing industry further reinforces HACCP as a pivotal strategy to ensure food safety and enhance the global competitiveness of the meat industry.

Introduction

Food safety is a global concern that has received significant attention due to its direct implications for public health, economic stability, and consumer confidence in food products (Tibebu *et al.*, 2024). Among various food commodities, meat products occupy a critical position as they are a primary source of animal protein, vitamins, and minerals essential for human health (Marina *et al.*, 2024). However, the perishable nature of meat and its high nutritional content provide favorable conditions for microbial growth (Al-Mazrouei *et al.*, 2024). Consequently, meat is classified as a high-risk food commodity, particularly vulnerable to contamination and cross-contamination, which may occur at nearly all stages of the production chain (Wibisono *et al.*, 2022).

Cross-contamination refers to the transfer of biological, chemical, or physical hazards from a contaminated source to food products, either directly or indirectly, through various intermediaries (Farag *et al.*, 2023; Possas and Perez-Rodriguez, 2023). In the meat industry, cross-contamination can take place from slaughtering to distribution (Thompson and Miller, 2025). Animals carrying pathogens in their gastrointestinal tract or on their skin can contaminate muscle tissue during cutting processes (Velebit *et al.*, 2021). Moreover, processing equipment such as knives, cutting tables, conveyors, and storage containers may act as contamination vectors if they are not adequately cleaned and sanitized (Leaman *et al.*, 2023; Khambhaty and Samidurai, 2024). Human factors, including hand hygiene, proper use of protective clothing, and compliance with sanitation protocols, also play a critical role in contamination risk (Chang *et al.*, 2021). At the distribution stage, inadequate temperature control and product-to-product contact further increase the likelihood of microbial transfer (Mahunu *et al.*, 2024).

The impact of cross-contamination is substantial. From a public health perspective, it is a major contributor to foodborne diseases (Possas and Perez-Rodriguez, 2023). Pathogens such as *Salmonella* spp., *Escherichia coli* O157:H7, *Listeria monocytogenes*, and *Campylobacter* spp. are frequently associated with food poisoning cases linked to meat products (Habib *et al.*, 2021; Schirone and Visciano, 2021; Ali and Alsayeqh, 2022). Infections caused by these microorganisms can lead to gastrointestinal disorders, systemic complications, and even fatalities among vulnerable populations, including children, the elderly, and immunocompromised individuals (Jagirdhar *et al.*, 2023; Aziz *et al.*, 2024). From an economic standpoint, cross-contamination events can lead to costly product recalls, substantial financial losses, reputational damage to the food industry, and a decline in consumer trust (Warmate and Onarinde, 2023).

Given the complexity of these challenges, a systematic, science-based, and preventive approach is required. One internationally recognized strategy is the Hazard Analysis and Critical Control Points (HACCP) system (Malik *et al.*, 2021; Motarjemi and Warren, 2023). HACCP is a food safety management framework that emphasizes the identification of potential hazards, determination of critical control points (CCPs), and the implementation of monitoring, verification, and documentation procedures to ensure product safety at all stages of production (Awuchi, 2023; Motarjemi and Warren, 2023). Its strength lies in its proactive approach, preventing contamination before products reach consumers, in contrast to conventional methods that rely primarily on final product inspection (Owusu-Apenten and Vieira, 2022).

In the meat industry, the implementation of Hazard Analysis and Critical Control Points (HACCP) represents a crucial strategy for mitigating risks of cross-contamination (Mustefa *et al.*, 2021). Key processes such as slaughtering, cutting, cooling, packaging, and distribution can be iden-

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tified as critical control points (CCPs) that require strict monitoring (Rebezov *et al*., 2024; Spanova *et al*., 2025). Essential elements of this monitoring include temperature control, equipment sanitation, and adherence to worker hygiene practices (Owusu-Apenten and Vieira, 2022). When consistently applied, HACCP not only reduces contamination rates but also enhances consumer confidence and improves the global competitiveness of the meat industry. Building on this background, the present review aimed to provide a comprehensive analysis of cross-contamination risks in the meat industry and to evaluate the effectiveness of HACCP as a control strategy. Furthermore, the review highlighted the challenges of HACCP implementation, particularly in developing countries, and explored opportunities for integrating modern technologies to strengthen food safety systems in the future.

Cross-contamination in the meat industry

Cross-contamination in the meat industry is a complex phenomenon that can be influenced by various factors, including raw materials, the environment, equipment, and human resources (Possas and Perez-Rodriguez, 2023). To comprehensively understand the risks and impacts, it is important to review key aspects, including the definition and mechanisms of contamination, the main sources involved in the process, and the consequences for public health and industry sustainability.

Definition and mechanism of cross-contamination

Cross-contamination is defined as the process of transferring biological, chemical, or physical hazards from one food product to another, thereby potentially compromising the quality and safety of that product (Possas and Perez-Rodriguez, 2023). In the meat industry, cross-contamination is a primary route by which foodborne pathogens enter the food chain (Wu *et al*., 2022). Transmitted hazards can include pathogenic microbes such as *Salmonella*, *Escherichia coli* O157:H7, and *Listeria monocytogenes*; chemical residues such as detergents, disinfectants, or veterinary drug residues; and physical hazards such as metal shavings, bone fragments, or plastic fragments from production equipment (Schirone and Visciano, 2021; Ali and Alsayeqh, 2022).

The mechanism of cross-contamination is complex and can occur at various points in the meat production chain (Wu *et al*., 2022). At the slaughter stage, the main risk comes from contact between muscle tissue and the contents of the digestive tract or blood contaminated with microbes (Bovay, 2023). The subsequent cutting process can increase the likelihood of contaminant transfer through the equipment used, especially if knives, tables, or containers do not undergo adequate cleaning and sanitation procedures (Leaman *et al*., 2023).

The meat processing stage is also a critical point, as the mixing of raw materials, chopping, or grinding processes can spread microbes throughout the product (Qureshi *et al*., 2024). In addition, the use of unhygienic washing water has the potential to become a medium for the spread of pathogens (Spanva *et al*., 2025). During the storage phase, temperature instability plays an important role in enabling the growth of microorganisms, while non-airtight packaging can cause cross-contamination between products (Tarawneh *et al*., 2024). Furthermore, distribution and transportation add new risks through possible packaging damage, temperature fluctuations during transport, or direct contact with other contaminated products (Karanth *et al*., 2023). Even at the retail and serving stages, cross-contamination can still occur due to unhygienic handling practices, such as using the same equipment for raw and cooked products (Lorenc, 2023).

Primary sources of cross-contamination

Cross-contamination in the meat industry can originate from various sources, both inherent in the raw materials and arising from environmental conditions and processing practices (Indriani *et al*., 2021). Identifying these primary sources is an important step in developing effective control strategies through food safety systems such as HACCP.

The first source is infected animals that carry pathogenic microorganisms in their digestive tract, skin, or blood (Habib *et al*., 2021). Pathogens such as *Salmonella*, *Escherichia coli* O157:H7, and *Campylobacter* are commonly found in the intestines of slaughtered animals and can contaminate meat if the intestines leak during slaughter (Schirone and Visciano, 2021; Ali and Alsayeqh, 2022). In addition, the surface of animal skin can also contain microbes that transfer to muscle tissue through direct contact during the cutting process. This condition makes the slaughter stage a critical point in the meat production chain (Velebit *et al*., 2021; Nakamura *et al*., 2023).

The second source comes from processing equipment and the processing environment (Leaman *et al*., 2023). Equipment used in processing, such as knives, cutting tables, conveyors, and storage containers, has the potential to become a medium for microbial transfer if not properly cleaned and sanitized (Ali and Alsayeqh, 2022; Lorenc, 2023). Contaminated washing water can also increase the chance of contamination because it acts as a medium for spreading pathogens to meat surfaces and equipment (Morshdy *et al*., 2025). Production environments with low levels of cleanliness, high humidity, and poor ventilation also support the survival of microorganisms (Rai *et al*., 2021).

The third source is workers, who often act as vectors in the transfer of microbes (Das *et al*., 2025). Poor personal hygiene, including unwashed hands, long nails, or the use of unsterilized gloves, is the primary route of pathogen transfer (Bahramian *et al*., 2022). Unclean work clothes that are not changed regularly can harbor and spread microorganisms to meat products (Owusu-Apenten and Vieira, 2022). Therefore, the implementation of worker hygiene standards through training and strict supervision is a crucial part of the cross-contamination control system.

The final source is found in the distribution and storage chain (Awuchi, 2023). Meat products that are poorly packaged or stored at inappropriate temperatures are at risk of cross-contamination with other products. For example, storing raw meat alongside ready-to-eat products can lead to the transfer of pathogens that are harmful to consumers (Karanth *et al*., 2023; Bovay, 2023). During distribution, temperature fluctuations in transport vehicles also increase the growth of microorganisms and increase the likelihood of contamination (Mahunu *et al*., 2024).

The impact of cross-contamination

Cross-contamination in the meat industry has a wide-ranging impact that not only affects public health but also has implications for economic stability and the reputation of the food industry (Alves *et al*., 2024). Table 1 confirms that cross-contamination in the meat industry has multidimensional impacts, including public health, economic stability, corporate reputation, and even the credibility of a country's food system.

From a health perspective, cross-contamination is one of the main routes of transmission of foodborne diseases reported globally (Possas and Perez-Rodriguez, 2023). The most commonly identified pathogens include *Salmonella* spp., *Escherichia coli* O157:H7, *Listeria monocytogenes*, and *Campylobacter* spp.. Infections caused by these microorganisms generally attack the gastrointestinal system with symptoms such as diarrhea, nausea, vomiting, and fever, but in certain cases can develop into serious complications (Schirone and Visciano, 2021; Ali and Alsayeqh, 2022). For example, *E. coli* O157:H7 can trigger hemolytic uremic syndrome, while *Listeria monocytogenes* poses a high risk of sepsis, meningitis, and even death in vulnerable groups such as infants, the elderly, and pregnant women (Habib *et al*., 2021).

In addition to health aspects, cross-contamination also has a major impact on economic aspects (Banach *et al*., 2021). Cases of meat product contamination that cause illness are usually followed by product recalls (Warmate and Onarinde, 2023). The recall process not only causes direct financial losses due to product loss, but also adds to the cost burden on companies for testing, investigation, and production system improvements. In the long term, such incidents can damage business relationships, reduce competitiveness, and worsen the company's image in the eyes of consumers (Radu *et al*., 2023; Bovay, 2023).

Furthermore, reputational impact is also a major concern. The food industry, especially those engaged in the meat sector, is highly dependent on consumer trust (Wu *et al*., 2021). Once a widespread cross-contamination case occurs, reputation recovery requires a long time and large investments, often resulting in loss of market share (Schrobback *et al*., 2023). On a macro scale, repeated cases of cross-contamination can also undermine the credibility of a country's food surveillance system, thereby affecting export market access and international trade stability (Radu *et al*., 2023). Figure 1 shows the main sources of cross-contamination in the meat industry, including infected animals, contaminated processing equipment, workers with poor hygiene, and improper distribution and storage conditions.

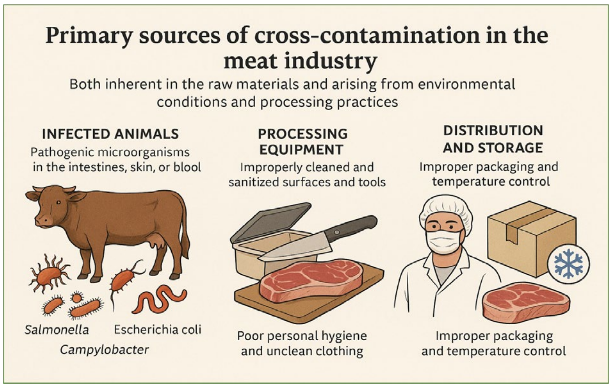

Figure 1. Sources and mechanisms of cross-contamination in the meat industry.

HACCP principles in cross-contamination control

Efforts to prevent cross-contamination in the meat industry cannot rely solely on general hygiene procedures but require a structured, systematic, and risk-based control system (Ferri *et al*., 2023). In this context, Hazard Analysis and Critical Control Points (HACCP) is an internationally recognized approach as the main standard in ensuring food safety. This system emphasizes preventive measures through hazard identification, determination of critical control points, and implementation of consistent monitoring and documentation mechanisms (Blagojevic *et al*., 2021; Nagel-Alne *et al*., 2022). To understand the effectiveness of HACCP in minimizing the risk of cross-contamination, it is necessary to explain its basic concepts, the hazard analysis process, the determination of critical control points, and the monitoring and verification procedures that complement it (Motarjemi and Warren, 2023).

Basic concepts of HACCP

Hazard Analysis and Critical Control Points (HACCP) is a food safety management system developed to prevent biological, chemical, and physical hazards in food products, including meat (Awuchi *et al*., 2023). This concept was first introduced in the 1960s by the Pillsbury Company in collaboration with the National Aeronautics and Space Administration (NASA) and the U.S. Army Natick Laboratories, to ensure food safety for astronauts during space missions (Reelfs, 2022). As it developed, HACCP was then widely adopted in the food industry and recognized by international institutions, including the Codex Alimentarius Commission, as a global standard in food safety management systems (Radu *et al*., 2023).

The general principles of HACCP are based on seven key steps, namely: (1) conducting a hazard analysis, (2) determining critical control points, (3) establishing critical limits, (4) developing monitoring procedures, (5) determining corrective actions, (6) establishing verification procedures, and (7) documenting the entire process. These seven principles form a systematic framework for identifying, evaluating, and controlling potential hazards that may arise throughout the meat production chain (Owusu-Apenten and Vieira, 2022; Awuchi, 2023).

One of the main advantages of HACCP is its preventive rather than reactive nature. This system not only detects contamination after the final product is produced, but rather emphasizes prevention from the early stages of production (Motarjemi and Warren, 2023). By identifying critical points in the processing flow, such as slaughtering, cutting, cooling, and packaging, HACCP enables the industry to minimize the chances of cross-contamination (Awuchi, 2023). This differs from the traditional approach, which focuses more on inspecting the final product, which in

Table 1. The impact of cross-contamination on the meat industry.

Impact aspects	Form of impact	Concrete example	Source
Public Health	Foodborne illness with gastrointestinal symptoms (diarrhea, nausea, vomiting, fever) and serious complications	*E. coli* O157:H7 → hemolytic uremic syndrome; *Listeria monocytogenes* → sepsis, meningitis, death in infants/the elderly/pregnant women	(Schirone and Visciano, 2021; Ali and Alsayeqh, 2022)
Economy	Financial losses due to product recalls, investigations, testing, and production system improvements; decreased competitiveness	The case of contaminated meat recall that caused the loss of millions of dollars worth of products	(Warmate and Onarinde, 2023)
Industry Reputation	Loss of consumer confidence, damage to the company's image, decline in market share	The meat industry experienced a decline in sales after a major contamination case; export access was restricted.	(Bovay, 2023)
National/Global Level	Declining credibility of a country's food control system, barriers to international trade	Meat exporting countries face import bans due to repeated contamination cases	(Radu *et al*., 2023)

Table 2. Hazard classification in the meat industry.

Hazard category	Specific examples	Primary source	Impact on consumers	Source
Biology	*Salmonella* spp., *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Campylobacter* spp., Hepatitis E virus, *Toxoplasma gondii*	Infected animals, cross-contamination during slaughter, poor sanitation	Foodborne illnesses (diarrhea, gastroenteritis, systemic complications)	(Schirone and Visciano, 2021; Ali and Alsayeqh, 2022)
Chemistry	Antibiotic residues, growth hormones, cleaning agents, disinfectants	Veterinary drugs without withdrawal periods, use of substandard chemicals	Toxic effects, risk of antimicrobial resistance, and long-term health problems	(Bogdanova *et al*., 2021)
Physics	Metal fragments, glass shards, plastic fragments, bone fragments	Damaged equipment, unsafe packaging, negligence in the production process	Mechanical injuries (choking, gastrointestinal tract injuries), product quality deterioration	(Sogore *et al*., 2024)

practice is not always effective because hazards can already have entered the distribution chain (Jubayer *et al*., 2022).

Hazard analysis in the meat industry

Hazard analysis is a crucial initial step in implementing the HACCP system, as it determines the direction of control strategies to be implemented at each point in the production process (Motarjemi and Warren, 2023). In the meat industry, hazards that need to be identified can generally be categorized into three main groups, namely biological, chemical, and physical (Mustefa, 2021). Table 2 summarizes the three main categories of hazards that can arise in the meat industry.

Biological hazards are a major concern because meat is a medium that is highly conducive to the growth of pathogenic microorganisms. Bacteria such as *Salmonella* spp., *Escherichia coli* O157:H7, *Listeria monocytogenes*, and *Campylobacter* spp. are often associated with cases of food poisoning originating from meat (Schirone and Visciano, 2021; Ali and Alsayeqh, 2022). In addition to bacteria, viruses such as Hepatitis E virus and parasites such as *Toxoplasma gondii* can also contaminate meat products through contact with infected animals or unhygienic processing practices (Zdolec and Kiš, 2021). These biological hazards can cause foodborne illnesses with varying degrees of severity, from mild gastrointestinal symptoms to serious systemic complications (Mainardi and Bidoia, 2024).

Chemical hazards also play an important role in reducing the safety of meat products. One form of this is veterinary drug residues, such as antibiotics and growth hormones, which can remain in animal tissue if withdrawal times are not adhered to Bogdanova *et al*. (2021). In addition, cleaning and disinfecting chemicals used in the sanitation of processing equipment and environments have the potential to contaminate products if not applied according to standards (Ezzatpanah *et al*., 2022). The presence of chemical residues in meat not only poses a risk of toxic effects on consumers, but also contributes to the emergence of antimicrobial resistance, which is a global issue (Okpala and Korzeniowska, 2023).

Meanwhile, physical hazards often arise due to negligence in the production process. Metal fragments from equipment, glass shards, plastic fragments from packaging, and bone fragments left in meat products can directly endanger consumers through the risk of choking, injuries to the digestive tract, or other injuries (Sogore *et al*., 2024). Although physical hazards do not always have an impact on microbiological aspects, their presence still reduces product quality and safety, while also lowering consumer confidence in the meat processing industry (Rebezov *et al*., 2024).

Determination of Critical Control Points (CCP)

The determination of Critical Control Points (CCP) is central to the implementation of the HACCP system, as these points represent stages in the meat production chain where identified hazards can be prevented, eliminated, or reduced to an acceptable level (Mustefa, 2021). CCP identification must be carried out systematically by considering product characteristics, process conditions, and the potential for cross-contamination that may occur (Wilson *et al*., 2017). The most crucial first stage is slaughter. At this stage, one of the biggest risks is leakage of intestinal contents, which can contaminate the carcass surface with pathogenic microorganisms such as *Escherichia coli* O157:H7 or *Salmonella* spp. In addition, blood flowing out of the animal also has the potential to become a medium for microbial growth if not handled properly (Habib *et al*., 2021; Schirone and Visciano, 2021). Therefore, the implementation of hygienic slaughter procedures, proper evisceration techniques, and the separation of contaminated carcasses are important steps in controlling hazards at CCPs.

The second stage is cutting and processing. At this stage, equipment such as knives, cutting tables, and conveyor belts serves as direct contact media with meat, posing a high risk of becoming a means of microbial transfer (Ali and Alsayeqh, 2022; Lorenc, 2023). Human factors also play an important role, considering that workers can become vectors of cross-contamination through their hands, gloves, or unsterilized work clothes (Wilson *et al*., 2017). Therefore, the implementation of a consistent equipment sanitation program, worker hygiene training, and monitoring of compliance with standard operating procedures are part of CCP control at this stage.

The next equally important stage is cooling, packaging, and distribution. Cooling at the right temperature (usually below 4°C) is a key CCP because it directly inhibits the growth of pathogenic and spoilage microorganisms (Owusu-Kwarteng *et al*., 2020). Errors in temperature control can lead to significant microbial multiplication even if the initial contamination level is low (Taiwo *et al*., 2024). During the packaging stage, the use of clean packaging materials and hygienic packaging techniques is crucial, especially to prevent cross-contact between raw meat products and ready-to-eat products (Spanova *et al*., 2025). Meanwhile, distribution requires a consistent cold chain. Temperature fluctuations during transportation can reduce the effectiveness of control and increase the risk of product quality and safety damage (Malik *et al*., 2021).

Monitoring, verification, and documentation

Monitoring and verification are important elements in the implementation of HACCP, as both ensure that critical control points (CCPs) are properly managed according to established standards. Without these mechanisms, the HACCP system is only theoretical and cannot guarantee consistent meat product safety (Awuchi, 2023; Motarjemi and Warren, 2023).

Monitoring is carried out continuously to oversee the parameters specified in the CCP (Yang *et al*., 2022). In the meat industry, the most frequently monitored aspects include storage and distribution temperatures, equipment cleanliness, and worker hygiene (Ali and Alsayeqh, 2022; Owusu-Apenten and Vieira, 2022). Monitoring of cooling and transportation temperatures serves to ensure that products are always within a safe range to inhibit the growth of microorganisms (Pajic *et al*., 2024). The cleanliness of equipment, such as cutting tables, knives, and conveyors, must be monitored regularly through visual inspections and organic residue measurements to prevent the accumulation of pathogens (Ali and Alsayeqh, 2022; Lorenc, 2023). Meanwhile, worker hygiene monitoring is carried out through direct observation, compliance checklists, and microbiological tests on hands or gloves to ensure that workers do not become the main vectors of cross-contamination (Armstrong-Novak *et al*., 2023).

Verification is conducted to evaluate the effectiveness of the system as a whole. One commonly used method is microbiological testing of the final product and equipment surfaces, which aims to detect the presence of pathogens such as *Salmonella* or *Listeria monocytogenes* (Awuchi, 2023). In addition, periodic internal audits are another important verification mechanism, as they can assess compliance with standard operating procedures (SOPs) and identify system weaknesses that need improvement (Mohammed, 2023). In some cases, verification is also carried out by external agencies to meet regulatory requirements or international certification standards (Odetunde *et al*., 2021).

Documentation serves as an administrative foundation that supports the monitoring and verification process. All monitoring data, test results, and correction records must be well documented to support the traceability system (Mohammed, 2023). Complete documentation enables the industry to trace the origin of problems in the event of contamination, while also serving as evidence of compliance in regulatory audits or inspections (Farrell *et al*., 2023). Thus, the documentation system not only serves for record-keeping, but also as an instrument of accountability and transparency in food safety management (Mosweu and Ngoepe, 2021). As illustrated in Figure 2, the meat production process includes several stages—slaughter, cutting/processing, cooling, packaging, and distribution—each associated with potential risks of cross-contamination. Critical control points (CCPs) are highlighted at slaughtering, processing, and cooling, where preventive measures such as hygienic slaughtering, sanitation of equipment, worker hygiene, and strict cold-chain maintenance are essential to ensure food safety and minimize microbial hazards.

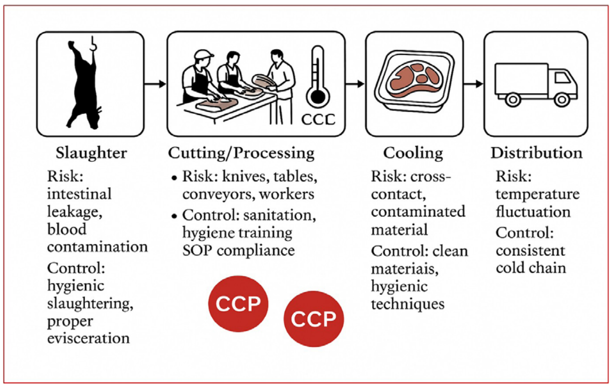

Figure 2. Critical Control Points (CCPs) in the meat production chain.

Case studies and implementation of haccp in the meat industry

The application of HACCP in the meat industry is not only theoretical, but has also been widely implemented in various commodities such as beef, poultry, and pork with varying results. Case studies from various countries show that the effectiveness of this system is greatly influenced by the prevailing social, economic, and regulatory contexts. Comparisons between developed and developing countries reveal differences in the levels of success and challenges faced. In addition, supporting factors such as the quality of regulations, worker competence through training, and the adequacy of production facilities have been shown to play an important role in determining the success of HACCP implementation in the meat sector.

Examples of HACCP implementation in the beef, poultry, and pork industries

The application of HACCP in various types of meat industries shows variations in control strategies tailored to the biological and technical characteristics of each commodity. Table 3 shows the differences in the focus of HACCP application in the beef, poultry, and pork industries. These differences are mainly based on the dominant pathogen types and critical control points that are prioritized for control.

In the beef industry, the main critical control points are usually located at the slaughter and evisceration stages, where the risk of cross-contamination by pathogenic microorganisms is very high (Han *et al.*, 2023). The pathogens of most concern are *Escherichia coli* O157:H7 and *Salmonella* spp. Control measures are implemented through hygienic evisceration procedures, carcass washing with hot water or antimicrobial solutions, and rapid cooling to prevent microbial growth (Habib *et al.*, 2021; Schirone and Visciano, 2021). In addition, temperature monitoring in storage and transportation rooms is an important component in preventing the multiplication of microorganisms after slaughter (Pajic *et al.*, 2024).

In the poultry industry, the risk of cross-contamination is generally higher due to production processes that involve large volumes with relatively short processing times (Bolohan *et al.*, 2025). The dominant pathogens commonly found are *Campylobacter* spp. and *Salmonella* spp.. The most crucial CCPs in the poultry industry are the scalding, plucking, and carcass washing stages, where water serves as a potential medium for the spread of microbes between carcasses (Morshdy *et al.*, 2025). Therefore, control is carried out through routine water replacement, the application of a counter-current flow system in the washing process, and the use of air cooling or air-liquid mixture techniques to suppress microbial growth (Kumar *et al.*, 2022).

Meanwhile, in the pork industry, the dangers that are often of concern come not only from bacteria such as *Salmonella*, but also parasites such as *Trichinella* spiralis (Gabriël *et al.*, 2022). CCPs in pork processing include ante-mortem and post-mortem inspections, which serve to de-

Table 3. Examples of HACCP implementation in the beef, poultry, and pork industries.

Commodity	Dominant pathogen	Critical Control Point (CCP)	Primary control strategy	Source
Beef	*E. coli* O157:H7, *Salmonella spp.*	Slaughter, evisceration, cooling	Hygienic evisceration, carcass washing with hot water/antimicrobial agents, rapid cooling, monitoring of storage and distribution temperatures	(Habib *et al.*, 2021; Shavisi, 2023)
Poultry meat	*Campylobacter spp.*, *Salmonella spp.*	Scalding, dehairing, carcass washing, cooling	Regular water replacement, counter-current flow system, air cooling, or air-liquid combination	(Ahmed *et al.*, 2021)
Pork	*Salmonella spp.*, *Trichinella spiralis*	Ante- and post-mortem examinations, cooking, preservation	Inspection of slaughtered animals, cooking at adequate temperatures, preservation through fermentation and salting to suppress microbes	(Akaike *et al.*, 2024)

Table 4. Comparison of HACCP implementation in developed and developing countries.

Aspect	Developed country	Developing country	Source
Regulation and supervision	Strict regulations, mandatory HACCP in the food industry, regular monitoring, and strict audits	Regulations exist but implementation is weak; limited inspection personnel	(Owusu-Apenten and Vieira, 2023)
Infrastructure	Modern facilities, maintained cold chain, hygienic production system	Limited infrastructure, especially in small-to-medium-sized units; inconsistent cold chain	(Radu *et al.*, 2023)
Technology	High-tech support (automatic temperature monitoring, PCR, digital traceability)	Limited technology, relying more on conventional methods	(Fernando *et al.*, 2024)
Human resources	Trained workers, ongoing training programs, and high awareness	Low worker competency, limited training, minimal awareness	(Allam *et al.*, 2023)
Economic support	Supported by substantial capital, investment in food security is easily accessible.	Financial constraints; HACCP investment is considered an additional burden	(Liu *et al.*, 2021)
Consumer awareness	High, encouraging the industry to maintain its reputation and safety standards	Still low; price is more dominant than food safety aspects	(Okpala *et al.*, 2023)
The main challenge	The complexity of global supply chains, international certification requirements	Limited resources, weak enforcement of regulations, disparities between large and small businesses	(Tenorio *et al.*, 2021)
Opportunities for improvement	Technological innovation, digital integration, improvement of international standards	Support from international institutions (FAO, WHO), capacity building, export orientation	(Radu *et al.*, 2023)

tect animals at risk of carrying pathogens (Andoni *et al*., 2023). In addition, the cooking and preservation stages are critical control points, as adequate heating has been proven effective in inactivating *Trichinella* and other pathogenic bacteria (Franssen *et al*., 2021). In processed pork products such as sausages and ham, fermentation control and salt content also play an important role in creating conditions that are not conducive to microbial growth (Barcenilla *et al*., 2022).

Successes and challenges in implementing HACCP in developed countries vs. developing countries

The implementation of HACCP in the meat industry shows significant differences between developed and developing countries, both in terms of success rates and challenges faced. These differences are generally influenced by regulatory factors, human resource capacity, infrastructure, and available technological support (Radu *et al*., 2023). Table 4 shows the fundamental differences in HACCP implementation between developed and developing countries.

In developed countries, HACCP implementation is relatively more successful because it is supported by strict regulations and a structured food surveillance system (Radu *et al*., 2023). Countries such as the United States, Canada, and members of the European Union have mandated the implementation of HACCP in the food industry, including meat, as a legal requirement. Strong regulatory oversight, accompanied by a routine audit system, ensures industry compliance with food safety standards (Okpala and Korzeniowsk, 2023). In addition, the availability of modern technologies such as automatic temperature monitoring systems, PCR-based microbiological detection, and digital traceability systems further strengthens the effectiveness of HACCP. Another contributing factor is high consumer awareness of food safety, which encourages the industry to maintain quality and market confidence (Fernando *et al*., 2024).

Conversely, in developing countries, the implementation of HACCP still faces many obstacles. One of the main obstacles is limited financial resources and infrastructure (Madilo *et al*., 2024). Many small and medium-sized meat processing units are not yet able to meet the facility standards required to support the implementation of CCP, such as the availability of refrigerated space, hygienic packaging systems, or cold chains (Dima *et al*., 2024). In addition, workers' level of understanding and competence regarding HACCP principles is still low due to limited training programs. Regulatory aspects are also often not optimal; although several countries have adopted HACCP standards, their implementation and supervision are often hampered by weak law enforcement and limited inspection personnel (Almutairi *et al*., 2025; Subedi *et al*., 2025).

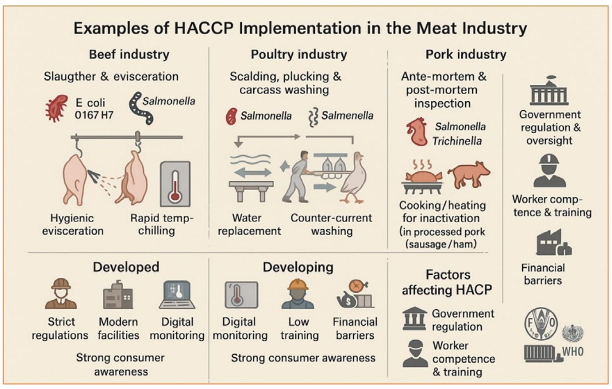

Figure 3. HACCP implementation in the meat industry.

Nevertheless, a number of initiatives in developing countries show progress. Support from international organizations such as the FAO and WHO in the form of training programs, technology transfer, and technical assistance has helped strengthen local capacity (Gennari *et al*., 2021). Several large export-oriented industries have also successfully adopted HACCP in full due to global market demands. However, the gap between large companies and small and medium-sized enterprises is still quite large, so the success of HACCP implementation in developing countries has not been evenly distributed (Liu *et al*., 2021; Lee *et al*., 2023). Figure 3 shows the implementation of HACCP in the meat industry, highlighting critical control points in beef, poultry, and pork processing, as well as differences in application between developed and developing countries.

Factors affecting the effectiveness of HACCP

The effectiveness of HACCP implementation in the meat industry is largely determined by a number of interrelated supporting factors, including regulations, worker competence through training, and the availability of adequate production facilities. These three aspects serve as the main foundation that determines whether the HACCP system can be implemented consistently and sustainably (Ahmed *et al*., 2023).

Government regulation and oversight are important elements in ensuring consistent implementation of HACCP. Countries with strong regulatory frameworks are generally able to require the food industry, including the meat sector, to adopt HACCP as a legal standard (Okpala *et al*., 2023). In addition to regulation, effective oversight through regular inspections and audits ensures industry compliance with established procedures (Bolanle *et al*., 2024). Without clear regulations and strict oversight mechanisms, HACCP implementation risks becoming an administrative formality without real implementation in the field (Awuchi, 2023).

In addition to regulations, worker competence is a crucial factor, given that humans play a direct role in every stage of meat production (Romanov *et al*., 2022). HACCP can only be implemented effectively if workers understand the basic principles of this system and the importance of maintaining personal and environmental hygiene (Owusu-Apenten and Vieira, 2022). Regular training is necessary to improve workers' skills in monitoring CCPs, recognizing potential deviations, and implementing appropriate corrective actions (Mosso *et al*., 2025). Low levels of worker knowledge and awareness have been shown to be one of the main barriers to HACCP implementation, especially in small-scale processing units (Madilo *et al*., 2024).

Another factor that is no less important is production facilities. The implementation of HACCP requires infrastructure that meets standards, such as hygienic slaughter rooms, stable cooling systems, stainless steel cutting equipment, and hygienic packaging systems (Ahmed and Al-Mahmood, 2023). The availability of a consistent cold chain from processing to distribution is also a key requirement in controlling microbial growth (Pedro *et al*., 2023). Without adequate facilities, monitoring, and controlling CCPs is difficult to do effectively, thereby defeating the main purpose of HACCP, which is to prevent cross-contamination (Awuchi, 2023).

Challenges and prospects

Although the implementation of HACCP has proven effective in reducing the risk of cross-contamination in the meat industry, its implementation in the field still faces a number of challenges as well as development opportunities (Rebezov *et al*., 2024). Barriers such as limited resources, costs, and hygiene awareness are issues that need to be addressed, while technological advances, integration with other food safety systems, and the move towards a digitalized meat processing industry open up new prospects for improving product safety and quality (Madilo *et al*., 2024).

Main obstacles

Although the HACCP system has been widely recognized as an effective approach to controlling hazards in the food industry, its implementation in the meat sector still faces various obstacles. One of the biggest obstacles is the cost of implementation (Radu *et al*., 2023; Dima *et al*., 2024). The HACCP implementation process requires a significant investment, both in terms of supporting infrastructure, such as hygienic processing rooms and a stable cold chain, and in terms of sustainable monitoring and documentation technology (Awuchi, 2023). For large-scale businesses, these costs can be covered as part of a long-term strategy, but for small and medium-sized units, they are often considered an additional burden that is difficult to meet (Radu *et al*., 2023).

In addition to cost factors, limited human resources (HR) are also a significant obstacle. HACCP implementation requires workers who understand the basic principles of this system, are able to identify critical control points, and are skilled in taking corrective action when deviations occur (Motarjemi and Warren, 2023; Uzoigwe and Kongolo, 2024). In practice, many meat processing units in developing countries still rely on minimally trained workers, making it impossible to implement HACCP consistently (Dima *et al*., 2024). The lack of training and coaching programs also exacerbates this situation, preventing workers from developing their competencies in line with the complexity of the system that must be implemented (Awuchi, 2023).

The next obstacle is low awareness of the importance of hygiene. In most meat processing units, especially small-scale ones, hygiene is often seen as secondary to productivity (Nyokabi *et al*., 2023). This means that workers' personal hygiene and environmental sanitation are not prioritized. Lack of hygiene awareness not only increases the risk of cross-contamination but also has the potential to reduce the overall effectiveness of the HACCP system, because the basic principles of hazard prevention cannot be properly implemented without hygienic behavior from all parties involved in the production chain (Awuchi, 2023; Rebezov *et al*., 2024).

Advances in supporting technology

Technological advances have contributed significantly to improving the effectiveness of HACCP implementation in the meat industry (Rebezov *et al*., 2024). One rapidly developing innovation is the use of Internet of Things (IoT)-based sensors that enable real-time monitoring of temperature, humidity, and environmental conditions throughout the production and distribution chain (Sallam *et al*., 2023). The application of these sensors not only improves the accuracy of critical control point (CCP) monitoring but also enables early detection of deviations that could potentially reduce product quality and safety (Mattarozzi *et al*., 2023).

In addition to IoT, rapid pathogen detection technologies based on molecular biology, such as real-time PCR and biosensors, are increasingly being integrated into food safety systems (Sobhan *et al*., 2025). These methods enable the identification of pathogenic microorganisms such as *Salmonella* spp., *E. coli* O157:H7, or *Listeria monocytogenes* in a much shorter time compared to conventional culture methods (Habib *et al*., 2021; Schirone and Visciano, 2021). The application of rapid detection not only speeds up the decision-making process but also strengthens cross-contamination prevention efforts by minimizing delays in hazard identification (Rebezov *et al*., 2024).

Furthermore, the concept of blockchain for traceability has begun to be applied in the meat industry supply chain. This technology enables transparent, integrated, and tamper-proof data recording from the animal husbandry stage, slaughtering, processing, to final distribution (Patel *et al*., 2023; Nasir *et al*., 2024). With blockchain, each stage of production can be accurately traced, thereby increasing consumer confidence while supporting the HACCP audit process (Ellahi *et al*., 2025). This transparency also adds value to the meat industry in meeting international standards, especially in export markets that emphasize product safety and traceability (Hallak and Tacsir, 2022).

Synergy between HACCP and other food safety systems

The implementation of HACCP in the meat industry cannot be viewed as a stand-alone system, but rather needs to be integrated with various other food safety standards and practices in order to optimize its effectiveness (Overbosch and Blanchard, 2023). This synergy is crucial because each system has complementary focuses and strengths, thereby forming a more comprehensive framework for preventing cross-contamination and ensuring product safety. One of the most obvious forms of integration is with Good Manufacturing Practices (GMP) (Bonciolini *et al*., 2025; Chandimali *et al*., 2025). GMP serves as a basic prerequisite that ensures the production environment, equipment, and work practices meet minimum hygiene standards before HACCP is implemented (Owusu-Apenten and Vieira, 2022). Without good GMP, the implementation of HACCP risks being ineffective because critical control points will be difficult to maintain in facilities that do not meet hygiene requirements (Hasnan *et al*., 2022).

In addition to GMP, Sanitation Standard Operating Procedures (SSOP) also play an important role in supporting the effectiveness of HACCP (Owusu-Apenten and Vieira, 2022). SSOP regulates routine sanitation measures that must be carried out, both on equipment and in the work environment, so as to reduce the risk of contamination before the production process takes place (de Oliveira *et al*., 2016). The integration of SSOP with HACCP ensures that hazard control is carried out in layers, starting from initial prevention to monitoring at critical points of production (Singapurwa *et al*., 2022).

Furthermore, the implementation of ISO 22000 provides a broader food safety management framework because it combines HACCP principles with a quality management system approach (Chen *et al*., 2021). ISO 22000 emphasizes documentation, communication within the supply chain, and continuous improvement, thereby providing added value in terms of transparency and consistency of implementation (Glykas, 2024). By integrating ISO 22000, the meat industry is not only able to control biological, chemical, and physical risks but also strengthen consumer confidence through internationally recognized standards (Okpala and Korzeniowsk, 2023).

Prospects for a digitalization-based smart meat processing industry

The global food industry is currently transforming through digitalization, including in the meat processing sector (Radu *et al*., 2023). The concept of a smart meat processing industry integrates digital technology with food safety principles, including HACCP, to create a more adaptive, efficient, and transparent production system (Rebezov *et al*., 2024). Digitalization enables rapid and accurate monitoring, data analysis, and decision-making, thereby minimizing the potential for cross-contamination early on (Donaghy *et al*., 2021).

One of the key elements in digitization is the implementation of an Internet of Things (IoT)-based automatic monitoring system (Sobhan *et al*., 2025). Smart sensors can be installed at critical points in production to record temperature, humidity, air flow, and water quality in real time (Narayana *et al*., 2024). The collected data not only helps in early detection of deviations from standards, but also enables the implementation of predictive maintenance to prevent equipment damage that could trigger contamination risks (Molęda *et al*., 2023).

In addition, the application of big data and artificial intelligence (AI) opens up opportunities for more comprehensive analysis of production data. AI can be used to predict contamination trends, evaluate the effectiveness of sanitation strategies, and optimize critical control points based on historical patterns (Naseem and Rizwan, 2025). This provides added value for the meat industry in developing a more proactive rather than reactive HACCP system (Chhetri, 2024).

Furthermore, blockchain technology plays an important role in ensuring the traceability of meat products. With a transparent and decentralized recording system, every stage in the supply chain, from farm to distribution, can be accurately traced (Bosona and Gebresenbet, 2023; Patel *et al*., 2023). This transparency not only strengthens consumer confidence but is also a key requirement for meeting international export standards.

Conclusion

Cross-contamination is one of the main threats in the meat industry and has a significant impact on food safety. The implementation of HACCP has proven to be an effective strategy for controlling these hazards through a systematic, prevention-based approach. The success of implementation is largely determined by management commitment, worker training, and strong regulatory support. Going forward, the integration of HACCP with digital technology and sustainable industrial practices will be key to strengthening food safety while enhancing the competitiveness of meat products in the global market.

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Conflict of interest

The authors have declared no conflict of interest.

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