Herald of Science of S.Seifullin Kazakh Agrotechnical Research University: Veterinary Sciences. – Astana: S. Seifullin Kazakh Agrotechnical Research University, 2024. – № 4 (008). – P. 16-33. - ISSN 2958-5430, ISSN 2958-5449

doi.org/ 10.51452/kazatuvc.2024.4(008).1800
UDC 637.5.05/.07 **Review article**

Meat Quality Control in Beef Production

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Received: 29-10-2024 **Accepted:** 17-12-2024 **Published:** 30-12-2024

Abstract

The hazard analysis and critical control points (HACCP) system is primarily a risk assessment method focused on identifying and controlling the risk factors classified as the critical control points. Pathogenic microorganisms can enter the meat supply chain at various points along their path. Live animals can harbor various pathogens, while unhygienic conditions during slaughter and processing introduce external contamination risks, and cross-contamination can occur during handling and cooking. Traditionally, pathogen control is concentrated in the processing stage. Despite its effectiveness, approaches like HACCP do not fully satisfy the consumer demands for food safety. A more comprehensive approach targeting pathogen control at every stage of the supply chain that is, “from farm-to-table,” offers broader coverage and greater integration.

Meat is one of the most perishable food products, providing an ideal environment for the growth of a wide range of pathogenic bacteria. Foodborne illnesses result from the consumption of bacteria, toxins, or cells produced by microorganisms present in food. Past outbreaks have been linked to various stages of the meat production process; hence, it is logical to develop a risk assessment model encompassing all stages, from raising food animals and processing carcasses to meat preparation and consumption.

The primary task in meat production is the evaluation of the microbiological quality of raw meat and the sanitary conditions at processing facilities based on the presence of indicator microorganisms in the meat, equipment, and processing plants. Accordingly, hygienic measures in meat production, processing, and retail aim to ensure meat safety, prevent rapid spoilage, and preserve its quality. HACCP, which heavily relies on prerequisite programs like good hygienic practice and sanitation standard operating procedures, provides enhanced hygiene standards essential for producing safe meat and meat products throughout the entire meat supply chain.

Keywords: critical control points; food products; HACCP; hygienic methods; microbiological quality; slaughterhouse.

Introduction

The hazard analysis and critical control points (HACCP) system is founded on three core principles: hazard identification, determination of critical control points, and implementation of risk mitigation procedures. Additionally, it involves the development of a monitoring system for evaluating the effectiveness of control measures. A critical control point is a stage in the production process where specific interventions can reduce the risk of adverse outcomes. Ineffective control methods should be revised accordingly [1].

For more than twenty years, food safety professionals have been so vigorously promoting HACCP food safety that they have actually overemphasized the usefulness of the HACCP concept [2]. The global use and success of the HACCP system in the food industry has created false expectations that it can be used successfully at all stages of the food supply chain, from farm to table.

The long global evolution and use of HACCP in food processing facilities has provided a tremendous amount of documentation that the HACCP food safety system is very effective in combating identified foodborne hazards. Its ability to ensure food safety far exceeded that of the quality control system it replaced. The widespread success of HACCP has led regulators, policy makers and consumers to increasingly call for this remarkable tool to be utilized more effectively by applying it throughout the food chain from "farm to table." Simply put, the supply chain consists of seven stages: animal or crop production, slaughter or harvest, raw food production, processed food production, distribution, catering or retail operations, and consumption. The production of processed products is at the center of this supply chain. It is no coincidence that HACCP originated at the food processing stage - from farm to table.

Meat production is increasing worldwide and according to FAO/WHO estimates [3], it will reach 364 million tons by 2023. The growing demand for meat in developing countries is mainly the result of the rapid progress of societies that are becoming increasingly urbanized.

In recent years, there has been growing concern about the presence of pathogenic microorganisms in meat products despite increased hygiene measures for meat and processed meat products [4]. Contamination can occur during processing, through contact with equipment (e.g., grinders, belts, saws), through contact with food handlers (e.g., hands, knives), and through exposure to other environmental sources (e.g., air, water) [5].

Regulators require meat processing plants to implement hazard analysis and critical control point (HACCP) systems for meat production processes to reduce pathogens [6]. However, since it is difficult or impossible to completely eliminate pathogens from raw meat, the goal of HACCP for meat focuses on reducing and preventing microbial growth [7]. The HACCP system is now used in many regulated sectors of the food industry.

Monitoring microorganisms in meat products is an important step in HACCP programs [8] and proper storage of meat products is critical to control contamination of meat with spoilage microorganisms [9]. It has been proposed that HACCP systems in meat processing plants should be based on microbiological data, with the assessment of the number of indicator organisms in meat products at different stages of processing [10].

For raw meat products, safety and quality can be assessed using indicator microorganisms, including total aerobic platelet count (APC), coliform count (CC), and Escherichia coli (ECC) [11]. APC provides an estimate of the total bacterial population. Higher APC is generally associated with lower quality and reduced shelf life. The relationship between APC and the concentration of foodborne pathogens in raw meat is unclear. CC and ECC provide an estimate of faecal contamination and poor sanitation during processing. High CC and ECC values generally correlate with higher levels of foodborne pathogens originating from feces [12]. Meat can be further contaminated or cross-contaminated with various pathogenic bacteria after slaughter, such as during chilling, cutting, deboning, and slicing [13].

Thus, all processing conditions are important factors that can affect the microbiological quality. To improve the safety of finished meat products, more information is needed at the stage of contamination of carcasses or meat cuts in meat processing plants [14]. However, data on seasonal variations and meat type in microbiological testing of meat in different meat processing plants are limited. In particular, microbiological assessment of meat in meat processing plants that have implemented the HACCP system has not been carried out.

Quality Control Programs

The most effective strategy for reducing meat contamination and microbial growth is the implementation of quality control programs, such as good manufacturing practice (GMP) and HACCP. These programs involve identifying indicator microorganisms that can predict the presence of pathogenic microorganisms and spoilage-causing bacteria [15]. Notable bacterial foodborne pathogens, including *Salmonella, Campylobacter*, and *verocytotoxigenic Escherichia coli* (VTEC), can accumulate in and be excreted from the gastrointestinal tract of farm animals, including cattle. The typical sequence leading to beef-related foodborne illnesses involves pathogen transmission from cattle to humans through direct or indirect fecal contamination, subsequent cross-contamination, and/or proliferation during the production, processing, and consumption of beef and beef products.

The effective control of beef-borne pathogens necessitates a longitudinal, integrated approach based on the "meat chain" concept. This approach employs the GMP/GHP and HACCP principles, with shared responsibility among all participants in the meat supply chain. It also requires the consideration of resource availability, technical capabilities, consumer attitudes and behavior, and cost-effectiveness [16, 17, 18].

Meat as a Favorable Environment for Microorganism Growth

Meat and meat products provide an exceptionally favorable environment for the growth of pathogenic microorganisms [19]. Its perishable nature and nutrient-rich composition enable meat to support the proliferation of a wide range of pathogenic bacteria [20]. It is vulnerable to contamination at multiple stages, from primary production to the final consumption phase (from farm to fork). Contaminated meat is a major source of foodborne diseases and mortality caused by pathogens entering the body upon ingestion [21]. Foodborne illnesses result from the consumption of bacteria, toxins, or cells produced by microorganisms present in contaminated food [22]. Consequently, retail meat sales are frequently linked to foodborne illnesses if infectious doses are ingested during consumption [23, 24]. Epidemiological and microbiological studies identified cross-contamination during distribution and processing, along with subsequent bacterial growth, as significant contributors to foodborne diseases [25, 26, 27].

Meat and meat products are commonly implicated in food poisoning outbreaks. During production, processing, and storage, these products can become contaminated with pathogenic bacteria, such as *Listeria monocytogenes* [28, 29]. Hygiene and quality during meat handling and processing must be continuously monitored to ensure that meat products adhere to international quality and safety standards [30]. Given its rich nutrient profile, meat is a prime environment for the growth of pathogenic bacteria. The microbiological contamination of carcasses predominantly occurs during handling processes, including skinning, evisceration, processing, storage, and distribution in slaughterhouses and retail outlets [31].

In India, dietary habits have significantly shifted because of rapid urbanization and Westernization, leading to increased consumption of non-vegetarian foods. This shift has resulted in a rising meat demand. Concurrently, consumers have become more vigilant regarding meat quality, freshness, and health aspects [32]. The microbiological quality of meat and meat products is critical for public health. Numerous reports have documented foodborne disease outbreaks linked to meat consumption [33, 34, 35]. Fecal contamination, either through direct deposition or indirect contact via contaminated equipment, workers, facilities, and air, is a primary source of contamination [36]. Pathogens can contaminate meat at various stages of the slaughtering process [37, 38], necessitating appropriate control measures for eliminating or preventing microbial contamination. Among the pathogenic bacteria that can contaminate beef, *Salmonella spp., Listeria monocytogenes,* and *E. coli O157* are frequently associated with foodborne illnesses [39, 40]. It is now widely acknowledged that traditional meat inspection procedures cannot fully ensure that consumers are not exposed to infectious doses of meat-borne pathogens [41]. Therefore, meat inspection authorities worldwide are promoting or mandating the implementation of HACCP systems for meat production processes. While comprehensive HACCP systems should address physical, chemical, and microbiological hazards, the latter remains as a primary concern in meat production [42].

Critical Control Points

In the pre-harvest stage (on the farm), the global recycling of microbial pathogens can be mitigated through the strategic management of agricultural lands and livestock by-products. The fecal shedding of pathogens by farm animals is reduced by employing antimicrobial feed treatments, sourcing new animals from controlled environments, implementing biosecurity measures, optimizing animal welfare (including stress management), maintaining hygienic housing conditions, and utilizing prebiotics, probiotics, competitive exclusion strategies, and vaccination programs.

During the harvest stage (at the slaughterhouse), minimizing transportation time and ensuring optimal pre-slaughter conditions for animals can help reduce cross-contamination via transport vehicles or holding pens. The key measures include maintaining hygienic practices during slaughter and carcass processing, implementing effective sanitation procedures, and potentially applying treatments to hides and/or carcasses to prevent contamination.

In the post-harvest stage (processing, storage, distribution, and consumption), pathogen control in meat products often relies on bactericidal steps, such as cooking, or, where such steps are not employed, on the "multiple hurdles" concept of microbial control. Additional post-harvest risk reduction measures include effective cleaning and sanitation of all facilities involved in meat-processing, maintaining the cold chain, preventing cross-contamination during further processing or cooking, and educating consumers on food hygiene. The effectiveness of control measures varies depending on the pathogen and the stage of the meat supply chain. For instance, some pathogens in beef (e.g., *VTEC, Salmonella*) are most effectively controlled through primary production measures combined with enhanced slaughter hygiene. In contrast, other pathogens (e.g., *L. monocytogenes*) are best controlled during the processing and storage stages [43].

Quality monitoring systems are commonly implemented in the food industry to systematically assess indicators at specific points along the technological line and during meat handling [44]. In these systems, operations that significantly affect the microbiological quality of the product must be identified as critical control points (CCPs) and/or quality control points and managed to minimize contamination by pathogenic or spoilage bacteria [45]. Cleaning and disinfection are essential components of biosecurity on livestock farms, reducing animal exposure to foodborne pathogens [46, 47].

Management practices in feedlots can affect animal health, carcass quality, and, potentially, food safety. Feedlots, where cattle from various sources are mixed and housed at high densities, can be sources of contamination by *EHEC O157* (*enterohemorrhagic E. coli O157*) and *Salmonella* spp. Advanced enrichment and isolation techniques demonstrated that the EHEC O157 prevalence among cattle is significantly higher than that previously estimated, reaching 5.8% [48, 49]. Microbiological testing provides a means of assessing how effectively operators control slaughtering, processing, and production processes to minimize and control contamination [50]. The effectiveness of these systems has been demonstrated. Based on these indicators, corrective actions can also be taken to prevent or reduce potential contamination.

The safety and quality of meat products can be evaluated using various microbial indicators, such as the aerobic mesophilic count and coliforms [51]. The aerobic mesophilic count assesses the general microbial population in the environment and processing equipment, where high contamination levels indicate poor hygienic conditions [52]. Coliforms serve as indicators of inadequate sanitary conditions during food processing, production, and storage, with *E. coli* being a classic indicator of the potential presence of intestinal pathogens and a good measure of the sanitary quality of processed foods [53].

The Salmonella spp. transmission from animals to food is a significant concern for human health. It can only be controlled through rigorous cleanliness and adherence to hygienic procedures during slaughter and processing [54]. As natural reservoirs of pathogenic strains, cattle often contaminate ground beef with *EHEC O157* isolated from live animals, carcasses, and retail meat [55]. One study found that cattle housed in feedlots for less than 20 days were 3.4 times more likely to test positive for *EHEC O157* compared to those housed for longer periods [56]. Although *E. coli* is a common and usually harmless inhabitant of the gastrointestinal tract, some strains produce verotoxin that causes severe illness, including diarrhea, hemorrhagic colitis, and potentially fatal kidney failure [57, 58]. Stress responses in cattle, which are potentially linked to feed withdrawal and transportation, may exacerbate these issues. Additionally, *EHEC O157* has been detected in water bodies on many farms, suggesting that water sources may act as long-term reservoirs for this pathogen [59].

"Farm-to-Table" Concept

Meat is susceptible to contamination from both internal and external sources to the animal during slaughter and sale. Live animals can harbor a range of microorganisms on the surfaces that come into contact with their environment. The major contamination sources include animal hides and feces. Additional contamination sources can be the slaughter area, slaughterhouse environment, retail floors, air, and vehicles used for transporting meat from the slaughterhouse [60, 61]. Retail points also contribute to meat contamination [62]. In retail environments, tools like knives, wooden boards, and scales are common sources of bacterial contamination, particularly from *Staphylococcus aureus* and *Shigella species* [63]. Cross-contamination during transport not only affects cattle, but is also a significant source of pathogen transmission in poultry. Despite cleaning and sanitizing efforts, the crates and containers used for poultry transport often remain contaminated with *Salmonella* [64].

Considering that past disease outbreaks are linked to multiple production stages, it is advisable to create a thorough risk assessment model that addresses every stage, from animal rearing and carcass processing to meat preparation and consumption. In pork production, the supply chain encompasses the following stages: pre-harvest (on the farm, during transport, and storage), slaughter (skinning, evisceration, chilling, and production), processing (grinding, treatment, transport, storage, and distribution), consumption (cooking and eating), dose–response (exposure assessment, dose–response function, morbidity, and mortality), and human disease costs [65, 66].

The primary sources of the microbiological contamination of beef carcasses during slaughter include the leakage of intestinal contents and the cross-contamination from hides of slaughtered animals [67, 68]. Fecal contamination is a significant source of microorganisms [69]. The microbiological testing of carcasses is routinely used to verify the HACCP compliance in slaughterhouses. In the European Union (EU), this involves measuring aerobic colony counts and *Enterobacteriaceae* counts known as hygiene indicator organisms to ensure they are within established permissible limits [70].

Cutting and boning operations at meat-processing facilities involve extensive handling, which increases microbial risk due to the following reasons: (a) cross-contamination from hands and tools (e.g., knives, saws, and conveyors); and (b) the transfer of bacteria from the meat surface to its internal parts [71]. However, satisfactory results from slaughter line testing do not guarantee the meat product safety. Additionally, microbial contamination on surfaces in contact with food can sometimes exceed that on carcasses, leading to the accumulation of contamination during the cutting and processing stages [72, 73].

Slaughterhouses are a critical sector in the food industry in terms of potential foodborne illnesses and health hazards, particularly if the food hygiene principles are not strictly followed [74]. The hygiene practices of slaughterhouse workers play a crucial role in contamination. Dirty hands, clothing, and equipment used in carcass handling are contamination sources [75]. A study indicated that 48.4% of slaughterhouse workers did not cover their hair; 29% did not use aprons; and 64.5% wore jewelry (e.g., rings, bracelets, and watches) while working. These findings are consistent with data showing that 61.6% of workers did not cover their hair, and jewelry usage was not regulated [76].

The contamination in slaughterhouses and retail meat shops arises from the use of contaminated water, unhygienic practices (e.g., improper handling), and the use of contaminated surfaces and tools during meat-cutting operations [77].

Transportation can be a stressor for farm animals associated with the shedding of pathogenic bacteria like *EHEC O157* and *Salmonella* spp. in feces, leading to a contamination of trailer floors and bedding [78]. If trailers and bedding are not cleaned and disinfected between trips, they can spread contamination to other farms, the slaughterhouse environment, and other animals [79]. Hygiene rules apply not only during animal housing, but also during transportation. Cattle transported over long distances (more than 160.9 km) are twice as likely to test positive for *E. coli O157* at slaughter compared to those transported at shorter distances [80]. Ineffective vehicle cleaning and sanitizing contributed to contamination in 84% of cattle hides with *E. coli O157*, which had not been detected in any animal at the farm of origin [81].

Hygienic Methods and Quality Control of Meat and Meat Products

As widely recognized, the most significant threats to fresh meat products come from pathogenic bacteria capable of causing illness in humans, including *Salmonella, S. aureus, L. monocytogenes, Campylobacter,* and *E. coli O157*. Particularly, *E. coli O157* can cause food poisoning with only a small number of cells. The primary contamination sources are the slaughter animals themselves, workers, and the working environment. Air contamination through aerosols and water used in carcass processing plays a relatively minor role [82, 83]. Contaminants largely originate from an animal's skin and include microorganisms from the stomach and the intestines, which are released with feces [84]. Foodborne pathogens are a significant public health and economic concern in developed countries [85, 86].

A contamination level of up to 10^5 CFU/cm² indicates good hygienic conditions during slaughter, while higher levels suggest unsatisfactory conditions. Meat contaminated at 10^6 CFU/cm² indicates spoilage, characterized by unpleasant odor and reduced shelf life, while contamination reaching 10^7 CFU/cm² is associated with a noticeable slime formation [30]. Mold counts are used as the indicators of sanitary quality in food production facilities because molds can rapidly proliferate on food residues adhering to surfaces, consequently posing a potential contamination risk. Some molds produce toxic metabolites known as mycotoxins, which can pose health risks to humans and animals [87].

Hygienic methods and quality control measures for meat and meat products are recommended in many countries, particularly in the food service sector [88]. Without proper hygiene control, slaughterhouse and meat-processing environments can become significant sources of bacterial contamination [89].

The primary objective in meat production is the assessment of the microbiological quality of raw meat and the sanitary conditions at processing facilities based on the presence of indicator microorganisms in the meat, equipment, and processing plants. Identifying the key contamination points and introducing microorganisms into meat allow specialists responsible for production hygiene to implement proper manufacturing practices at meat-processing facilities, thereby improving a product's microbiological quality [90]. Microbiological carcass testing is commonly used to verify the HACCP compliance in slaughterhouses. In the EU, this involves measuring the aerobic colony and *Enterobacteriaceae* counts, known as hygiene indicator organisms, to ensure they are within specified permissible limits [91].

Hygienic measures in meat production, processing, and retail aim to ensure meat safety, prevent rapid spoilage, and maintain quality. HACCP, which heavily relies on prerequisite programs, such as GHP and sanitation standard operating procedures, ensures improved production hygiene conditions necessary for safe meat and meat products throughout the meat supply chain. By the end of the 20th century, HACCP had been mandated, implemented, and continuously used by every meat company involved in international trade [92].

Under EU legislation that is, regulation EC nos. 852/2004, 853/2004, and 854/2004, food business operators at all stages of the production chain bear the primary legal responsibility for ensuring the safety of the food they produce. While HACCP-based procedures are not required at the primary production stage (on the farm), farmers are expected to produce food with hygiene considerations in mind using an approach similar to HACCP. Although the classic HACCP approach is not fully applicable to food safety control on meat farms, the HACCP principles can still be applied to identify hazards and potential corrective actions. Food safety systems for beef should include at least: (1) full animal traceability; (2) provision of clean, uncontaminated feed; (3) provision of clean, uncontaminated water; (4) hygienic animal housing/living conditions; (5) clean livestock; (6) animal health, welfare, and disease prevention; (7) proper waste disposal; (8) hygienic transport and handling; and (9) biosecurity [93, 94].

Foodborne diseases are more common in developing countries because of the widespread improper food handling and sanitation practices, inadequate food safety laws, weak regulatory systems, lack of financial resources for safer equipment, and insufficient education for food industry workers [95].

The bacterial composition of meat serves as an acceptable indicator of its hygienic quality. The poor infrastructure at slaughterhouses, unsanitary animal handling, and improper carcass handling contribute to high bacterial loads in meat. Therefore, evaluating bacterial counts can indicate potential threats to human health [96].

Conclusion

A higher meat contamination level by these microorganisms reflects the poor hygiene and sanitation practices applied at the slaughterhouse during transportation to meat-processing plants and during processing at meat plants [97].

However, the lack of specific critical control points that can eliminate or control the identified hazards hinders the effective use of HACCP throughout the supply chain. Food safety measures can be used at every stage of the supply chain, but most of these measures will be pre-programs rather than critical control points from the HACCP system [98]. The most pressing food safety issues in the food industry today are caused by the presence of Escherichia coli O157:H7 and Salmonella in raw meat and poultry products and in processed foods. Attempts to control these pathogens either at the "farm" or "table" level of the supply chain have failed due to the lack of effective control measures at these stages available at the food processing stage.

Cross-contamination and other poor food handling practices can also lead to foodborne illness. Thus, the idea that HACCP can be effectively applied from farm to fork has been reconsidered.

The microbiological quality of beef and meat products is highly dependent on the hygienic conditions prevailing during their production and processing. Without proper hygienic control, the environment in slaughterhouses and butcher shops can be an important source of microbiological contamination.

The impact of HACCP on process hygiene performance in slaughterhouses has been previously studied [99, 100]

Specific studies were conducted to determine whether mandatory implementation of HACCP systems in meat processing and retail establishments has any significant impact on their microbiological indicators of process hygiene [101]. The reduction in bacterial counts on food contact surfaces, butchers' hands and refrigeration units was found to provide strong evidence of improved process hygiene performance and justifies the adoption of GHP and SSOP in meat plants. This relatively large-scale study showed that the implementation of HACCP was associated with improved process hygiene in meat plants. However, this finding is necessarily limited in scope as it is not possible at this time to determine whether such improvements would have a similar positive effect on the incidence of meat borne diseases. Further research is clearly needed to establish this.

This information on the key microbiological contamination points in the beef processing chain will assist hygiene professionals in such establishments in developing appropriate hygiene procedures to prevent or reduce microbiological contamination of beef and meat products.

Authors' Contributions

GI: Conceptualized and designed the study, analyzed the data, and drafted the manuscript. SS: Conducted an extensive literature review and analyzed the data. Both authors reviewed and approved the final manuscript.

Acknowledgments

These studies were conducted on the initiative topic registered in the National Center of State Scientific and Technical Expertise of the Republic of Kazakhstan "Determination of CCPs in beef production in the conditions of the south and southeast of the Republic of Kazakhstan" (state registration number 0124RKI0140).

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