ISSN 2449-8955

European Journal of Biological Research

Review Article

DOI: http://dx.doi.org/10.5281/zenodo.10724672

Food safety management: preventive strategies and control of pathogenic microorganisms in food

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Received: 10 October 2023; **Revised submission:** 24 January 2024; **Accepted:** 28 February 2024

https://jbrodka.com/index.php/ejbr

ABSTRACT: Food security is a paramount concern worldwide, as the consumption of food contaminated by pathogenic microorganisms can result in serious risks to human health. The presence of bacteria, fungi, and other potentially harmful microorganisms in food is a reality that demands rigorous preventive and control measures to ensure the quality and safety of food products. In this context, this review addresses food safety management as a preventive and control measure for pathogenic microorganisms in food, aiming to safeguard public health and ensure product quality. The article discusses the importance of strict hygienic practices throughout the food chain, from production to consumption, and analyzes predominant pathogenic microorganisms that can cause foodborne illnesses. The study highlights the relevance of conventional and advanced techniques for microbiological identification as effective tools for accurate and rapid detection of microorganisms in food. Key elements such as temperature, pH, water activity, and additives are emphasized as crucial in inhibiting microbial proliferation. The implementation of quality management systems, notably the Hazard Analysis and Critical Control Points (HACCP) system, and collaboration among various stakeholders are identified as essential to ensuring food safety. The importance of consumer education regarding safe food handling and storage practices is also emphasized. The conclusion emphasizes the central significance of food safety management as a foundation for population health and well-being, reinforcing that synergy and shared responsibility are indispensable pillars to ensure the supply of safe and healthy food for human consumption.

Keywords: Disease prevention; Food chain management; Food security initiatives; Foodborne illnesses; Global food security; Public health concerns.

1. INTRODUCTION

In current times, food security has emerged as one of the major global concerns, driven by the growing awareness of the health risks associated with consuming foods contaminated by pathogenic microorganisms [1]. The presence of these microorganisms in food poses a significant threat to public health, as it can result in foodborne illnesses with serious consequences for individuals and communities [2]. Given this scenario, the implementation of preventive and control strategies becomes vital to ensure the quality and safety of food products, safeguarding the health and well-being of the population.

This review article proposes a comprehensive approach to food safety management, highlighting its significance as a preventive and control strategy against pathogenic microorganisms in food. A profound understanding of these aspects becomes essential, as improper handling, inadequate processing, and incorrect storage of food can facilitate the proliferation of these harmful agents [3,4]. In this context, it is crucial to adopt rigorous measures throughout the entire food chain, from production to consumption, in order to mitigate risks and ensure food safety.

This article examines the key pathogenic microorganisms that can contaminate food, focusing on bacteria, fungi, parasites and virus that are often associated with outbreaks of foodborne diseases [5]. Additionally, it emphasizes the importance of utilizing advanced techniques for microbiological identification, such as Real-Time PCR, Next-Generation Sequencing (NGS), and MALDI-TOF mass spectrometry, to ensure early and accurate detection of these pathogens [6].

The environmental and intrinsic factors affecting microbial growth in food are also explored in this study. Elements such as temperature, pH, water activity, and additives are analyzed in detail, as they play a crucial role in inhibiting the proliferation of these pathogenic microorganisms [7]. Furthermore, the article underscores the importance of applying quality management systems, such as the Hazard Analysis and Critical Control Points (HACCP) system, as an effective approach to identify and control risks throughout the food chain [8].

The collaboration among various stakeholders, including regulatory bodies and international entities, is presented as a fundamental component in promoting global food safety [9,10]. The synergy between different sectors and shared responsibility emerge as indispensable pillars to ensure that the food offered to consumers is safe and healthy [11].

Finally, consumer education is highlighted as a crucial element for the success of food safety strategies. Consumer awareness of safe food handling and storage practices plays a vital role in preventing foodborne illnesses and promoting healthy eating habits [12].

In the current context, where food safety is a complex global issue, this scientific article provides a comprehensive and detailed analysis of food safety management as a preventive and control strategy against pathogenic microorganisms in food. By understanding and applying the measures and knowledge presented in this study, society will be better equipped to address the inherent challenges of food safety, ensuring a continuous supply of safe and high-quality food for human consumption.

2. PATHOGENIC MICROORGANISMS

Pathogenic microorganisms, commonly referred to as pathogens, are microscopic organisms that have the potential to cause disease in humans, animals, and plants. These microorganisms encompass a diverse range of biological entities, including bacteria, fungi, parasites, and viruses (Table 1). When introduced into the body or a host organism, they can disrupt normal physiological functions, leading to a spectrum of illnesses, ranging from mild infections to severe, life-threatening conditions [13,14].

2.1. Bacteria

The bacteria responsible for foodborne intoxications and infections, for example, are microorganisms that can result in serious health problems when present in foods consumed by humans [15].

Table 1. Pathogenic microorganisms in food: examples and associated illnesses.

Type of contamination	Sources of contamination	Specific species	Associated illnesses
Bacteria	Improper handling, inadequate cooking, contaminated water and surfaces	*Salmonella* sp.	Diarrhea, fever, stomach cramps, nausea, vomiting, chills and headache. Rarely, infection spreads to bloodstream and other organs, posing life-threatening risks without prompt antibiotic treatment.
		Escherichia coli O157:H7	Resemble those of *Salmonella*, including diarrhea, fever, stomach cramps, nausea, and vomiting. However, in some cases, *E. coli* infection can lead to more severe complications such as kidney failure, especially in vulnerable populations
		Listeria monocytogenes	Fever, muscle aches, nausea, and diarrhea are common symptoms of *Listeria* infection. In severe cases, *Listeria* infection can lead to neurological complications, making it a serious health concern, especially for those at higher risk, such as pregnant women, the elderly, and individuals with weakened immune systems.
Fungi	Improper storage, high humidity, inadequate processing	*Aspergillus flavus* and *A. parasiticus*	Production of aflatoxins mycotoxins, associated with a spectrum of illnesses, including acute toxicity manifested through symptoms such as vomiting and liver damage, as well as long-term carcinogenic effects
		Fusarium sp.	Produces mycotoxins that are commonly found in corn and cereals, such as wheat and barley, as well as in cereal-based products. These mycotoxins pose potential health risks to both humans and animals, leading to neurological problems and gastrointestinal issues, and causing reproductive system issues in animals
Parasites	Inadequate cooking, contaminated water and food	*Toxoplasma gondii*	It can lead to flu-like symptoms, including fever, swollen lymph nodes, headache, muscle aches, and skin rash. Poses a particular risk to pregnant women and individuals with weakened immune systems
		Cryptosporidium parvum	Gastrointestinal distress, including symptoms like diarrhea and abdominal cramps, with more severe consequences for individuals with compromised immune systems
		Trichinella spp.	It can include muscle pain, fever, and inflammation, with severe cases potentially leading to complications such as myocarditis and encephalitis
		Taenia solium and *T. saginata*	After ingestion, the larvae develop into adult tapeworms in the human intestines, which can lead to symptoms such as abdominal discomfort, weight loss, and nausea. Infections with *Taenia solium* can indeed result in neurocysticercosis, a severe condition affecting the central nervous system
Viruses	Poor sanitation, contaminated food and water, person-to-person transmission	Norovirus	It can lead to rapid and severe symptoms, including nausea, vomiting, diarrhea, and abdominal pain
		Hepatitis A virus	Infection manifests as acute hepatitis, with symptoms that can include jaundice, fatigue, abdominal discomfort, unusual tiredness and weakness, sudden nausea, vomiting, diarrhea, and in some cases, dark-colored urine. Vulnerable individuals, such as older adults and those with preexisting liver conditions, can experience more severe illnesses, such as liver failure and other liver diseases
		Hepatitis E virus	Infection can lead to acute hepatitis, presenting symptoms similar to other forms of hepatitis, including jaundice and malaise. Chronic infection indeed poses significant risks, particularly for pregnant women
		Rotavirus	Infections can range from mild to severe, with symptoms including severe watery diarrhea, vomiting, fever, and abdominal pain. In vulnerable populations, such as infants, young children, the elderly, and those with weakened immune systems, infections can potentially lead to hospitalization due to the risk of severe dehydration
		Sapovirus	Infections include symptoms such as vomiting, diarrhea, stomach cramps, chills, nausea, headache, and myalgia. They can cause more severe illness in vulnerable individuals, such as those who are immunocompromised

These pathogenic microorganisms can proliferate in food due to improper handling, preparation, storage, and cooking practices. Ingesting food contaminated with these bacteria can lead to gastrointestinal illnesses, ranging in severity from mild symptoms to potentially fatal conditions [16].

One of the most well-known bacteria causing food poisoning is *Salmonella*. It is often associated with animal-derived foods such as raw or undercooked meat, eggs, and unpasteurized dairy products [17]. Salmonella contamination occurs during the production, processing, or inadequate preparation of these foods [18]. When ingested, *Salmonella* can cause symptoms such as diarrhea, nausea, vomiting, abdominal cramps, and fever [19]. In severe cases, Salmonella infection can spread to the bloodstream and lead to more serious complications [20].

Another concerning bacterium is *Escherichia coli*. Some strains of *E. coli*, such as *E. coli* O157:H7, are notorious for causing severe illnesses [21]. This bacterium is often linked to raw or undercooked meat as well as unpasteurized dairy products [22]. *E. coli* infection can result in symptoms similar to those of Salmonella, but in some cases, it can lead to more serious complications like kidney failure [23].

The *Campylobacter* bacterium is another common cause of foodborne infections. It is often found in raw or undercooked poultry, such as chicken [24]. Ingesting food contaminated with *Campylobacter* can lead to gastrointestinal symptoms, including diarrhea, abdominal cramps, and fever [25].

Listeria monocytogenes is a bacterium that can be found in processed foods such as soft cheeses, deli meats, and ready-to-eat vegetables [26]. It is particularly dangerous for vulnerable groups such as pregnant women, the elderly, and people with weakened immune systems [27]. *Listeria* infection can lead to symptoms like fever, muscle aches, nausea, and diarrhea [28]. In severe cases, it can cause neurological complications [29].

Clostridium perfringens is widely found in soil, water, and the intestinal tracts of animals and humans [30]. It is often associated with ready-to-eat foods such as cooked meats, stews, and sauces [31]. Food poisoning caused by *C. perfringens* occurs when prepared foods are kept at room temperature for an extended period, allowing the bacteria to multiply and release toxins into the food [32]. Symptoms include abdominal pain, diarrhea, and nausea [33].

Additionally, *Staphylococcus aureus* is a bacterium that produces toxins that cause food poisoning. Contamination occurs due to improper handling of food, such as leaving it at room temperature for too long [34]. Symptoms include nausea, vomiting, and abdominal cramps [35]. *Vibrio cholerae*, the bacterium responsible for cholera, has also been considered. This infection is primarily transmitted through the consumption of water and food contaminated with infected human feces, posing a common concern in areas with limited access to clean water and basic sanitation [36,37].

2.2. Fungi

In addition to the mentioned bacteria, fungi can also cause foodborne illnesses. Fungi are eukaryotic organisms belonging to the kingdom Fungi. They are distinct from plants, animals, and bacteria, forming a diverse group of living beings [38]. Fungi are characterized by their cells with a defined nucleus, a cell wall primarily composed of chitin, and a lack of chlorophyll, the green pigment responsible for photosynthesis in plants [39].

Fungi play an essential role in nature, acting as decomposers, breaking down dead organic matter and recycling nutrients in the environment [39]. They can also establish symbiotic associations with other life forms, such as mycorrhizae, which benefit both fungi and plants by enhancing nutrient absorption [40].

Although the majority of them are beneficial, some fungi can produce toxic substances known as mycotoxins during their growth and development in food. These mycotoxins can be harmful to human and animal health, causing acute or chronic poisoning and even being carcinogenic [41,42]. Several mycotoxins are of particular interest in food. Among them, aflatoxins, ochratoxin A, fumonisins, deoxynivalenol (DON) or vomitoxin, and zearalenone are notable [43,44].

Aflatoxins are primarily produced by fungi of the genus *Aspergillus*, notably *A. flavus* and *A. parasiticus* [45]. These mycotoxins are often found in agricultural commodities such as peanuts, corn, grains, and seeds, especially under inadequate storage conditions, high humidity, and elevated temperatures [46]. Aflatoxins are highly toxic and carcinogenic, posing a serious risk to human and animal health [47].

Ochratoxin A is another concerning mycotoxin, produced by some species of fungi, including *Aspergillus* and *Penicillium* [48]. It can be found in various foods like grains, coffee, grapes, and meat products [49,50]. Ochratoxin A has the ability to accumulate in the body, primarily in the kidneys, and is known to cause renal damage, besides being classified as potentially carcinogenic [51,52].

Fumonisins, primarily produced by fungi of the genus *Fusarium*, are commonly found in corn and its derivatives [53]. These mycotoxins have been associated with diseases in livestock such as horses and can cause neurological problems and even death in severe cases [54]. Although their effect on humans is not as well established, there are concerns regarding potential health risks [55].

Deoxynivalenol (DON), also known as vomitoxin, is another mycotoxin produced by *Fusarium* fungi, such as *F. graminearum* and *F. culmorum* [56]. This mycotoxin is often found in cereals, especially wheat, barley, and corn [57]. Exposure to DON can cause gastrointestinal problems like nausea, vomiting, and diarrhea, in both humans and animals [58].

Zearalenone is another mycotoxin produced by *Fusarium* fungi. It can be found in cereals and cereal-based products [59]. Zearalenone is known for its ability to mimic the estrogen hormone and can cause reproductive system issues in animals, negatively affecting production and reproductive health [60,61].

The consequences of mycotoxin contamination in food are severe. They can cause organ damage, such as to the liver and kidneys, and negatively impact the nervous and immune systems [62,63]. Some mycotoxins also exhibit estrogenic effects, affecting the reproductive system of animals and potentially causing hormonal imbalances in humans [61,64].

2.3. Parasites

Parasites present yet another class of microorganisms that demand attention. Parasites are organisms that rely on other living hosts to sustain themselves, often at the expense of the host's well-being. In the context of foodborne illnesses, the ingestion of contaminated food can introduce parasites into the human body, leading to a range of health complications [65].

Parasites encompass a diverse range of organisms, including protozoa and helminths, more commonly known as worms. These organisms find their way into the food chain through various avenues, such as mishandling, improper cooking, or even contaminated water sources [66]. Once ingested, parasites can establish themselves within the host's gastrointestinal tract or other organs, potentially triggering gastrointestinal, hepatic, and even neurological disorders [67]. Several parasites stand out due to their impact on food safety and public health.

Toxoplasma gondii, a protozoan parasite, can be transmitted through the consumption of undercooked or raw meat from infected animals, particularly pork, lamb, and game meats. It can also spread through contact with contaminated soil, water, and vegetables [68]. *Toxoplasma* infection can lead to flu-like symptoms, posing a particular risk to pregnant women and those with weakened immune systems [69].

Cryptosporidium parvum and *Giardia duodenalis*, both protozoan parasites, often find their way into the human body via contaminated water sources. However, they can also hitch a ride through contaminated food, such as fresh produce irrigated or washed with tainted water [70]. Ingesting food or water housing these parasites can lead to gastrointestinal distress, including diarrhea and abdominal cramps, with more severe consequences for those with compromised immune systems [71].

Trichinella spp., parasitic worms, can lurk in undercooked or raw meat from infected animals, particularly pork and game meats. Infection occurs through the consumption of larvae, which then mature in the host's muscles [72]. The result can be muscle pain, fever, and inflammation, with severe cases potentially causing myocarditis and encephalitis [73].

Tapeworms, such as *Taenia solium* and *T. saginata*, are also consired significant. These parasites are contracted through the consumption of undercooked or raw beef or pork, respectively. After ingestion, the larvae develop into adult tapeworms in the human intestines, leading to symptoms like abdominal discomfort, weight loss, and nausea [74]. *T. solium* infection can even result in neurocysticercosis, a severe condition affecting the central nervous system [75].

2.4. Viruses

Distinct from other microorganisms, viruses consist of genetic material enclosed within a protein coat. Lacking the cellular structure of living organisms, viruses rely on host cells for replication and survival [76]. Viral contamination of food can occur through various routes, including poor sanitation practices, improper handling, and contact with infected food handlers [77]. Several prominent foodborne viruses merit close attention due to their potential impact on public health:

Norovirus stands as a leading culprit behind foodborne illnesses. Often associated with contaminated food, water, and person-to-person transmission, norovirus ingestion can trigger rapid and severe symptoms, including nausea, vomiting, diarrhea, and abdominal pain [78]. Notably, outbreaks of norovirus can escalate quickly in crowded environments such as cruise ships and institutional settings [79].

The hepatitis A virus (HAV) primarily gains entry through the consumption of contaminated water and food, particularly shellfish and produce. HAV infection manifests as acute hepatitis, marked by symptoms such as jaundice, fatigue, and abdominal discomfort [80]. Although most individuals recover fully, certain populations, such as older adults and those with preexisting liver conditions, can experience more severe illness [81].

Rotavirus is a leading cause of severe diarrhea and dehydration in infants and young children. While most infections are associated with person-to-person transmission, contaminated food can also contribute to the spread of this virus [82]. Rotavirus symptoms can range from mild to severe, potentially leading to hospitalization in vulnerable populations [83].

Hepatitis E virus (HEV) is transmitted primarily through the consumption of contaminated water and undercooked meat, particularly pork and game meats. HEV infection can lead to acute hepatitis, causing symptoms similar to other forms of hepatitis, such as jaundice and malaise [84]. In certain regions, chronic HEV infection can pose significant risks, especially for pregnant women [85].

Sapovirus, like norovirus, is associated with gastroenteritis and often spreads through contaminated food and water. Symptoms of sapovirus infection include vomiting, diarrhea, and stomach cramps. While sapovirus infections are generally self-limiting, they can cause more severe illness in vulnerable individuals [86].

3. FOOD SAFETY MANAGEMENT

Food contamination arises from a multitude of sources, resulting in the introduction of harmful substances or pathogens that undermine the safety and quality of food products [87-89]. A comprehensive understanding of these sources is essential for the implementation of effective food safety measures. Pathogenic microorganisms, encompassing bacteria, fungi, parasites, and viruses, can infiltrate food during various stages of production, processing, handling, and storage (Table 2). For this reason, efficient food safety management is a shared responsibility among producers, industry, distributors, retailers, and regulatory authorities.

Table 2. Sources of foodborne pathogenic contamination and descriptions.

Contamination Source	Description
Raw Ingredients	Contamination can originate from raw materials used in food production, such as contaminated soil or water for crops and livestock.
Cross-Contamination	Transfer of pathogens from one food to another, usually through shared utensils, cutting boards, or hands during food preparation.
Improper Handling	Poor hygiene practices by food handlers, such as inadequate handwashing, can introduce pathogens into the food.
Inadequate Cooking	Insufficient cooking temperatures or inadequate cooking times may leave harmful microorganisms alive in the food.
Contaminated Equipment	Equipment used in food processing, packaging, or storage can harbor pathogens if not cleaned and sanitized properly.
Water and Ice	Contaminated water used for washing produce, diluting beverages, or making ice can introduce pathogens to the food.
Poor Storage Conditions	Inadequate temperature control during storage can lead to the growth of harmful microorganisms.
Pests	Insects, rodents, and other pests can carry and transmit pathogens to food products.
Environmental Factors	Airborne contamination, dust, and pollution can introduce pathogens into food during processing or handling.
Unsanitary Facilities	Contaminated food preparation surfaces, storage areas, and facilities can contribute to microbial growth.
Inadequate Packaging	Improperly sealed or damaged packaging can allow contaminants to enter the food.
Improper Transportation	During transportation, food can be exposed to unsanitary conditions, leading to contamination.
Improper Thawing	Thawing food at room temperature can allow bacteria to multiply, leading to contamination.
Inadequate Supplier Verification	Contaminated ingredients from suppliers can introduce pathogens to the final product.

One of the key aspects to be considered is hygiene in production. In the field, it's essential to adopt good agricultural practices that minimize the presence of contaminants in food [90]. This includes the responsible use of pesticides, proper pest and disease control, ensuring the personal hygiene of workers involved in production, and protecting planting areas against potential external contaminations [91-93].

In food processing industries, it's crucial to follow good manufacturing practices (GMP). These guidelines encompass various aspects, such as strict equipment and facility hygiene, precise control of temperature and processing time, proper training of employees for safe food handling, and product traceability, which enables the identification of the origin and destination of each batch, facilitating corrective actions in case of issues [94,95].

Another crucial point is quality control carried out throughout the entire food chain [96]. It's important to also verify the presence of pesticide residues and other chemicals that could be harmful to health [97]. Additionally, microbiological testing and laboratory analyses are essential to monitor the presence of pathogens and other contaminants in food [98].

4. MICROBIOLOGICAL IDENTIFICATION TECHNIQUES

4.1. Collection and Sampling

The first step in this process, in this context, is the careful collection of representative samples of the food in question. These samples can be obtained from different batches, production areas, or storage locations to ensure that the analysis is comprehensive and reflects the potential diversity of microorganisms present [99,100]. Accuracy at this stage is crucial as the quality of the result depends on the sample's representativeness. Once the samples are collected, they need to be prepared for analysis. This may involve homogenizing the food and breaking up any clumps to achieve a uniform mixture [101]. Additionally, in some cases, the samples may need to be diluted in sterile solutions to allow for a manageable number of microorganisms on culture plates, ensuring reliable results [102].

4.2. Conventional Identification Methods

The subsequent step, isolation and enrichment, is crucial to promote the growth of the target microorganisms. For this purpose, samples are incubated on specific culture media that provide optimal conditions for the growth of particular groups of microorganisms [103,104]. Upon the growth of microorganisms on the culture plates, the preliminary identification stage begins. At this stage, it is observed morphological characteristics, Gram staining, and biochemical tests to differentiate the microorganisms present [105]. These initial tests help identify general groups of microorganisms.

Furthermore, microscopy is a fundamental tool in this process. It enables direct visualization of the microorganisms present in the samples, which can provide important clues about their identity. By observing characteristics such as shape, size, and cellular arrangement, technicians can gather valuable information to aid in microorganism identification. Quantification is also important to determine the quantity of microorganisms present in the samples. This can be done through colony counting on Petri dishes or more modern techniques like flow cytometry, which allows rapid and accurate assessment of microorganism quantities in a sample [106,107].

For more precise identification, however, more specific tests are conducted. This can include more detailed biochemical tests, serological tests to detect the presence of specific antigens, metabolism tests to analyze the production of characteristic chemicals, and even antibiotic susceptibility tests to determine the microorganism's response to different treatments [104,108,109]. An example is the Enzyme-Linked Immunosorbent Assay (ELISA), which is used to detect specific pathogens like Salmonella and Listeria [110,111].

To ensure the accuracy and reliability of results, the confirmation step is crucial. This may involve advanced molecular techniques, such as genetic sequencing, which provides detailed information about the microorganism's DNA and allows highly specific identification.

4.3. Advanced Identification Methods

The research and identification of relevant microorganisms in food have significantly evolved in recent years, thanks to the development of alternative methods that provide greater efficiency, speed, and accuracy compared to traditional techniques. These advancements are crucial to ensuring food safety and the quality of consumed products, as well as monitoring and controlling outbreaks of foodborne diseases.

Polymerase Chain Reaction (PCR), for example, is a powerful molecular technique that selectively amplifies specific DNA sequences present in a sample, making it one of the most widely used methods in microbiology and molecular biology for the identification of microorganisms in food [112]. The principle of PCR is based on the use of heat-stable enzymes, such as Taq DNA polymerase, to repeatedly amplify a specific DNA sequence in a chain reaction. The reaction involves successive cycles of heating (DNA denaturation), cooling (primer hybridization), and extension (new DNA chain synthesis) [113].

Another widely employed modern approach is Real-Time PCR (qPCR). This revolutionary technique enables the amplification of target DNA from specific microorganisms present in food, such as pathogenic bacteria [114]. Providing results within hours, qPCR is essential for the rapid detection of pathogens like *Salmonella*, *Escherichia coli*, and *Listeria*, allowing immediate actions to contain potential risks to public health [115,116].

Furthermore, Next-Generation Sequencing (NGS) has played a transformative role in food microorganism research. With its ability to simultaneously sequence multiple genomes, NGS offers a comprehensive view of the microbial composition of a food sample [117]. This approach not only identifies pathogenic microorganisms but also contributes to the study of normal microbiota, enabling a deeper understanding of microbial interactions in food products [118].

Another promising technique is Matrix-Assisted Laser Desorption/Ionization Time-of-Flight Mass Spectrometry (MALDI-TOF MS). This approach analyzes protein or peptide patterns present in microorganisms and compares these patterns to a database for identification [119]. MALDI-TOF mass spectrometry offers an efficient and accurate way to identify microorganisms in food, becoming a valuable tool for food analysis laboratories [120,121].

Biosensors have emerged as innovative devices for the detection of microorganisms in food. These sensors use biological components to interact with target microorganisms, generating detectable signals, such as color changes [122]. This approach is especially useful for portable and field applications, enabling rapid and convenient identification of microorganisms [123].

Metagenomics, in turn, has revolutionized our understanding of microbial diversity in food. This approach directly analyzes the genetic material extracted from a sample, allowing the identification of microorganisms without the need for prior isolation or cultivation [124]. Metagenomics is particularly valuable for studying complex microbial ecosystems in food, highlighting the interconnection between different microorganisms [124].

Nanotechnology has also been explored to develop sensitive and specific detection methods for microorganisms in food. In this technology, functionalized nanoparticles interact with target microorganisms and generate detectable signals, providing an innovative and highly sensitive approach for the identification of pathogens and contaminants [125,126].

Furthermore, the use of automation and artificial intelligence has enabled the development of automated microorganism detection systems in food. These systems, so called Automated Detection Systems, are capable of analyzing large volumes of data and providing accurate, real-time results, making the identification process more efficient [127-129].

5. PREVENTION AND CONTROL OF MICROBIAL PROLIFERATION

Microbial proliferation is influenced by optimal growth conditions, such as temperature, humidity, pH, and nutrient availability in food. Contamination occurs during various stages of the production process, including cultivation, harvesting, processing, improper storage, and handling [130]. Cross-contamination is another common source of microorganism spread, where bacteria or other pathogens are transferred from one food to another [131,132].

Prevention and control of microbial spoilage are essential to ensure food safety. Measures of personal hygiene and sanitation are crucial to prevent food contamination by unwanted microorganisms. This includes practices such as frequent handwashing, wearing clean and appropriate attire, as well as maintaining facilities and equipment properly sanitized [133].

The personal hygiene of food handlers is one of the primary pillars in contamination prevention. Regular and proper handwashing, the use of clean clothing, and being mindful of coughing and sneezing near food are critical practices to avoid the transmission of unwanted microorganisms [134,135]. Correct sanitation of facilities, equipment, and utensils is also paramount. Regular cleaning and proper sanitization ensure the elimination of potential sources of cross-contamination, minimizing the proliferation of microorganisms in food [136,137].

Proper storage is another critical factor in preventing microbial spoilage. Keeping raw and processed foods at appropriate temperatures, such as refrigeration and freezing, slows down the growth of microorganisms, preventing them from reaching dangerous levels [3]. Additionally, controlling humidity and using suitable packaging helps prevent the entry of microorganisms [138].

Thermal treatment, such as cooking, pasteurization, and sterilization, is one of the key measures to eliminate pathogenic microorganisms and reduce microbial load in processed foods, making them safer for consumption [139]. pH and water activity control are also important to prevent the growth of unwanted microorganisms. Adjusting these parameters creates a less favorable environment for the development of bacteria and fungi, extending the shelf life of foods [140]. Adding additives, such as preservatives and natural or artificial antioxidants, is a common strategy to inhibit microbial growth and ensure the preservation of processed foods for a longer period [130,141].

Regularly monitoring and analyzing the presence of pathogenic microorganisms and indicators of spoilage are essential to identify potential issues before they become a threat to food safety [13]. Traceability, in this context, is also an important tool in preventing food safety-related issues. The ability to trace the origin of foods facilitates the rapid identification and resolution of potential contamination cases [142]. Furthermore, education and training of staff on good practices for food handling and storage are crucial for the correct adoption of these preventive measures [135].

It is important to emphasize that, during food transportation, it is essential to ensure proper conditions to preserve their safety. Temperature and hygiene during this stage must be rigorously controlled to prevent the growth of microorganisms and product deterioration [3]. Adequate packaging and protection against contamination are essential to maintain the integrity of food throughout its journey to the consumer [143].

In addition to ensuring food safety at all stages of the supply chain, it is necessary to inform consumers about the necessary precautions to maintain food safety in their homes. This includes guidance on proper food hygiene before consumption, appropriate storage and handling to avoid cross-contamination, and recognizing signs that the product may be compromised [144].

6. EFFICIENT FOOD SAFETY MANAGEMENT

To enable efficient food safety management, solid cooperation among the various stakeholders is essential. The implementation of quality management systems, such as the Hazard Analysis and Critical Control Points (HACCP) system, is an effective approach to identify critical control points along the chain and systematically take preventive and corrective actions [8]. The HACCP is a systematic approach to food safety management that aims to prevent, eliminate, or reduce potential hazards that could pose risks to food safety (Figure 1).

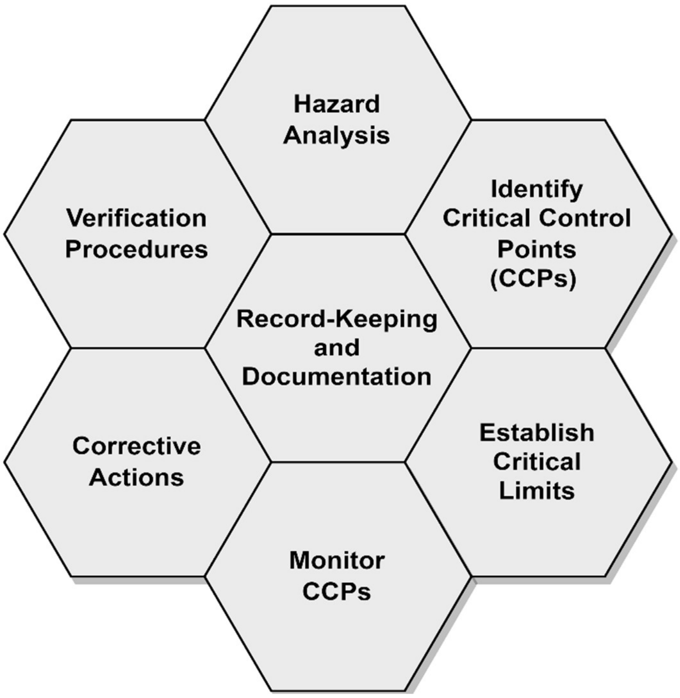

Figure 1. Principles of Hazard Analysis and Critical Control Points (HACCP).

Conduct a Hazard Analysis: Identify potential biological, chemical, and physical hazards that may occur in the production process; Identify Critical Control Points (CCPs): Determine the points in the process where hazards can be controlled or eliminated; Establish Critical Limits: Set specific criteria for each CCP to ensure that hazards are effectively controlled; Monitor CCPs: Regularly monitor and measure the CCPs to ensure they are within the established critical limits; Establish Corrective Actions: Define steps to be taken if a deviation from critical limits occurs, including identifying the cause and taking appropriate actions; Establish Verification Procedures: Regularly review and verify the effectiveness of the HACCP system and its control measures; Establish Record-Keeping and Documentation: Maintain thorough records of the HACCP plan, monitoring activities, corrective actions, and verification procedures.

Governmental agencies play a central role in regulating and overseeing food safety. Establishing norms and quality standards, as well as conducting regular inspections of facilities and products, are essential to ensure compliance with requirements and safeguard public health [145].

For instance, the World Health Organization (WHO) assumes a pivotal role in setting global guidelines that direct safe practices in hygiene, quality, and microbiological food safety on an international level [16]. Its recommendations are crucial for shaping food policies and regulations in many countries around the world.

Furthermore, the Codex Alimentarius, a joint program of the WHO and the Food and Agriculture Organization of the United Nations (FAO), plays a crucial role in setting international standards and guidelines for food safety [146]. The Codex works to harmonize regulations and ensure uniformity of food standards across different countries, thus promoting safe and equitable international trade of food.

At the national level, regulatory agencies play a vital role in implementing and enforcing food regulations. In the United States, the Food and Drug Administration (FDA) is a reference point, establishing stringent regulations that cover everything from production to the marketing of food [147]. The FDA is known for its detailed guidelines, rigorous testing, and risk assessments aimed at safeguarding public health and maintaining food quality standards.

In this complex network of global and national organizations, it's important to carefully balance the established international rules with the need to adapt them to different situations in order to ensure food safety. Collaborating effectively among countries is crucial to align how we handle food safety, while also considering the impact of unique cultural and local factors on how we put these rules into action [148].

As technology keeps advancing and smart strategies driven by data become more common, these new ideas offer a big potential to greatly improve how we manage food safety across borders. Innovations like Internet of Things (IoT), and artificial intelligence (AI) are increasingly being used to strengthen our ability to track where food comes from, monitor it in real-time, and quickly catch any safety issues [127,149,150]. Looking ahead at what might happen, like changes in the environment due to climate change or shifts in what consumers want, highlights even more why it's crucial to be proactive and flexible in how we make sure our food is safe to eat.

7. CONCLUSION

The significance of food safety management, as demonstrated in this article, is paramount in the prevention and control of pathogenic microorganisms within the food supply chain, thereby ensuring public health. Research highlights several key aspects contributing to a more resilient food chain:

• Food safety management is crucial for preventing and controlling pathogenic microorganisms in food.

• Collaboration across the food chain, from production to consumption, is essential for effective management strategies.

• Factors like temperature, pH, and water activity, alongside advanced identification techniques, play key roles in microbial control.

• Consumer education is essential in promoting safe food handling practices, thereby reducing foodborne illnesses and reinforcing confidence in the food system.

In conclusion, the continuous evolution of practices, technologies, and regulations in this field drives the provision of safe, healthy, and high-quality food products, thus fulfilling the crucial mission of food safety management in contemporary society.

Author Contributions: PHM conceived, drafted, and wrote the manuscript. EDB supervised and revised the manuscript. Both authors read and approved the final version of the manuscript.

Conflict of Interest: The authors declare no potential conflict of interest.

Acknowledgment: This work was conducted with the support of the National Council for Scientific and Technological Development (CNPq). The authors thank CNPq for the financial assistance and UNESP University for the support. The author P.H.M. thanks C.M., J.F.M., G.M. and C.T.M. for their unconditional collaboration and support.

Source of Funding: National Council for Scientific and Technological Development (CNPq).

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