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The Dynamics of Foodborne Pathogens: Review of their Emergence, Impact on Public Health, and Strategies for Mitigation in the Context of Food Safety Management

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Abstract

Background: Foodborne illnesses pose a significant threat to public health, resulting from the consumption of contaminated food or water. These illnesses are often caused by pathogenic microorganisms, including bacteria, viruses, and parasites, leading to millions of infections and thousands of deaths annually worldwide. Understanding the dynamics of foodborne pathogens is critical for public health security.

Methods: This review examines the emergence and re-emergence of foodborne pathogens, analyzing factors contributing to their proliferation. A comprehensive literature search was conducted across databases, including MEDLINE, Web of Science, and Google Scholar, using keywords related to foodborne pathogens, emerging diseases, and food safety practices. The review synthesizes findings from published studies to provide insights into the pathways through which these pathogens affect health.

Results: The findings indicate a notable increase in foodborne pathogens attributed to technological advancements in food production, changes in agricultural practices, and shifts in consumer behavior. Emerging pathogens such as E. coli O157:H7 and Listeria monocytogenes have been linked to specific food sources, emphasizing the importance of effective food safety management systems. Furthermore,

climate change and environmental factors have exacerbated the challenges in controlling foodborne illnesses.

Conclusion: The ongoing emergence of foodborne pathogens highlights the need for comprehensive public health strategies that include improved surveillance, education, and food safety practices. Collaboration among stakeholders in the food supply chain is essential for mitigating risks and enhancing food security.

Keywords: Foodborne illnesses, public health, emerging pathogens, food safety, health security.

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1. Introduction

Foodborne sickness generally results from the ingestion of food infected with pathogenic microorganisms, including bacteria and their byproducts, viruses, parasites, and other chemicals and agents. A diverse array of microorganisms, including as bacteria, viruses, as well as parasites, may contaminate human food and water, resulting in disease upon ingestion of these organisms or their toxins [1-3].Annually, foodborne illnesses impact millions globally. The federal government in the United States estimates around 48 million annual instances of foodborne disease. This estimate indicates that one in six individuals will suffer illness from contaminated food, leading to 128,000 hospitalizations and 3,000 deaths, thereby imposing a considerable public health obligation and economic strain, despite the food system being one of the safest globally [4]. Central Asian nations and Western nations report around 23 million instances of foodborne illness, leading to 5,000 fatalities annually. Conversely, in Australia, officials predict that there are approximately 5.4 million instances of foodborne infections each year [5-8].

Microbial contamination may arise from several sources, including contact with animal excrement before or after slaughter, inadequate sanitation, food handlers, filthy food processing equipment and instruments, and polluted washing or drinking water [9,10]. Among harmful microbes, viruses such as norovirus as well as hepatitis A are responsible for the highest incidence of foodborne diseases globally. The predominant causes of hospitalizations and deaths are bacterial infections, mostly from species of *Clostridium botulinum*, *Salmonella enterica*, *Campylobacter jejuni*, *Mycobacterium bovis*, *Listeria monocytogenes*, *Shigella* spp., *Vibrio* spp., and *Brucella* spp.*Vibrio vulnificus*, *Yersinia enterocolitica*, *Vibrio cholerae*, *Vibrio parahaemolyticus*, and Shiga toxin-producing *Escherichia coli*. Additionally, animal-derived meals (such as eggs, meat, milk, and seafood), together with leafy green vegetables, as well as fruits, are often associated with microbiological risks [10-12].

The complex framework of the food market is marked by continual changes in manufacturing, shipping, farming methods, and consumer trends. The dynamic adjustments, together with changes in dietary composition, have greatly facilitated the introduction or reappearance of foodborne pathogens [13,14]. Moreover, the exposure of microbes to various environmental conditions while traversing the food chain may affect the formation of antibiotic-resistant diseases. These factors may result in the failure of antibiotic treatment and exacerbate the severity of diseases, hence increasing the frequency and duration of hospitalizations and mortality rates [15-17]. Pathogen resurgence transpires when a previously established pathogen gains enhanced severity and re-emerges as a new hazard, whereas emergence happens when previously undiscovered pathogens are found and associated with cases of foodborne disease [13]. This research aims to examine the impact of technical improvements on the rise of foodborne illnesses and provide effective strategies to guarantee the manufacture of safe food items.

This review was conducted using pertinent studies identified through comprehensive literature searches in electronic databases such as MEDLINE (PubMed), Web of Science, Google Scholar, and accredited scientific websites, employing the terms and keywords "Emerging," "Re-emergence," "Foodborne pathogens," "Evolving," "Food industries," "Processing," "Handling," "Production," "Packaging," "Slaughtering," "Harvesting," and "Food chain." The search approach used these terms as well as keywords in diverse combinations using the Boolean operators "AND" and "OR". Only papers published in

the English language were considered. Abstracts and titles were evaluated, followed by a critical assessment of the complete contents of the chosen research and review publications.

2. The Rise of Foodborne Pathogens

The introduction of novel or unforeseen viruses in food is a critical trend that might affect food safety. Numerous definitions exist for "emerging pathogens." They may encompass a pathogen that has lately been linked to a significant public health emergency involving disease. In other cases, "emerging" has been used to characterize microbial populations that exhibit enhanced stress tolerance and have therefore adapted to novel transmission vectors or habitats. The phrase “emerging foodborne pathogens” denotes microorganisms that have lately been linked to food transmission, despite having been previously recognized as pathogens [18-20].

Numerous novel foodborne diseases have arisen in recent decades [21]. The list comprises bacteria including *Arcobacter butzleri*, *Aeromonas* spp., *Bacillus cereus*, *Burkholderia gladioli* pathovar cocovenenans, *Cronobacter* spp., *Campylobacter* spp., Clostridium difficile, *Clostridium botulinum*, *Clostridium perfringens*, *Helicobacter pullorum*, *Klebsiella pneumoniae*, *Helicobacter canadensis*, *Helicobacter pylori*, *Mycobacterium paratuberculosis*, *Listeria monocytogenes*, and Shiga toxin–producing *Escherichia coli*. *Escherichia coli*, *Salmonella* species, *Shigella* species, *Streptococcus* species, *Staphylococcus aureus*, *Vibrio vulnificus*, *Vibrio cholerae*, *Vibrio parahaemolyticus*, and *Yersinia enterocolitica*; viruses including adenovirus, astrovirus, hepatitis A, hepatitis E, norovirus, rotavirus, and sapovirus; and parasites such as *Cyclospora cayetanensis*, *Cryptosporidium*, *Taenia* species, *Trichinella spiralis*, and *Toxoplasma gondii* [1,14,22-26].

It is evident that, despite significant efforts to eradicate or manage harmful bacteria, new strains persistently develop and manifest in novel vectors. Consequently, the most often reported foodborne diseases have seen substantial alterations over time, particularly when these diseases cannot be attributed to identified microorganisms. Upon the discovery and emergence of a new pathogen, its prevalence often increases or becomes associated with novel food sources due to targeted efforts, frequently accompanied by the development of new detection methodologies, including restricted endonuclease evaluation, pulsed-field electrophoresis gels, multilocus pattern typing, and the polymerase chain reaction (PCR) approach [3,14,22,27,28]. Notable instances include the identification of *E. coli*. In 1996, an epidemic of *E. coli* O157:H7 in Japanese radish sprouts resulted in almost 9,000 illnesses; in 2010, a multi-state incident of *Salmonella enteritidis* linked to table eggs produced 2,752 infections; and in 2014, *Listeria monocytogenes* was identified in caramel-coated apples [29].

Furthermore, people, animals, and the natural environment substantially impact the onset and dissemination of many illnesses. Animals are regarded as the primary source of most infectious illnesses impacting humans, with 61 percent of human illnesses being zoonotic in nature [30]. Consequently, the "zoonotic pool" is considered a substantial and possibly abundant source of new illnesses. The many reports of "new" zoonoses indicate that the zoonotic reservoir remains largely intact, with infections possibly spreading after introduction via additional variables [31-33]. Although a zoonotic agent may not effectively establish and propagate among humans, several variables, including environmental conditions, might promote its dissemination (e.g., nosocomial infections), resulting in food being a medium for pathogen transmission [30,32,34,35]. Consequently, it is anticipated that novel foodborne pathogens will arise in the future, predominantly theorized to be zoonotic pathogens, attributed to various factors such as human-animal interactions, the ingestion of raw and processed animal-derived food products, intensive global animal husbandry, improper waste disposal, environmental alterations, uncontrolled human population growth, and inadequate sanitary conditions [22,25,36].

3. Factors Leading to the Proliferation of Foodborne Pathogens

Numerous conditions facilitate the growth of infections in food, as seen in Figure 1. Significant factors encompass technological advancements in food production, processing, packaging, and preparation;

changes in agricultural practices, including irrigation techniques; microbial adaptation and the augmentation of virulence genes; shifts in human behavior, particularly regarding food consumption; demographic changes, such as migration and urbanization; shortcomings in public health initiatives; and environmental influences, including climate change, global food trade, travel, and sophisticated detection methods like polymerase chain reaction (PCR) [14,27,35,37-39]. This study will focus only on technological advancements in the food sector that may have facilitated the introduction of novel foodborne diseases.

4. Novel Foodborne Illnesses Associated with Modifications in Industrial Food Technology

Emergent infections involve those that have lately manifested in the population, as well as those that were already established but are currently proliferating in incidence or extending their geographic distribution [32,40,41]. Moreover, a significant proportion of newly diagnosed infections seems to originate from pathogens that were previously existing in the environment but were revealed or acquired a selection advantage owing to changing conditions that facilitated the selection of new host groups. The establishment of a new variation may result in the formation of a distinct disease entity [42,43].

5. Technological Advancements in the Food Supply Chain

The reaction of food processors to consumer as well as market demands for nutritious meals has resulted in a category of minimally prepared foods characterized by reduced levels of sugar, salt, as well as preservatives. Nonetheless, new innovations, including high pressure processing (HPP), may modify the microbial composition of food in ways that are atypical of traditional methods. Nonetheless, the application of HPP in the food sector is constrained by the substantial expenses associated with both technology and maintenance [44,45]. Consequently, other new technologies, such as bio-preservatives and hurdle innovations (mixtures of mild processing procedures), also facilitate the evolution of the food business [46]. Bio-preservatives provide a natural substitute for conventional preservatives and are essential in fulfilling the requirements for clean-label goods [46]. Moreover, hurdle technology, an approach in food preservation that integrates various preservation methods to inhibit microbial growth and prolong food shelf life, poses distinct challenges and opportunities, influencing the microbial composition of food [47]. Nonetheless, it is crucial to acknowledge that these technologies may present significant issues for food safety, since bacteria could react differently to the many stresses imposed by these approaches [35]. Adopting a comprehensive viewpoint that incorporates diverse processing methods enhances the comprehension of the intricate relationship among technology, customer preferences, and food safety [48,49].

The prevalence of swift technological advancements is an inescapable facet of contemporary existence, with the benefits seeming to surpass the drawbacks [50]. Conversely, technology may have facilitated the genesis and rapid proliferation of infectious illnesses by fostering settings conducive to survival of pathogens [50,51]. Technological advancement has impacted the incidence and incidence of infectious illnesses [51,52]. The importance of these discoveries relies on our comprehension of quorum detection, which may determine pathogenic rates and biofilm development, even in food processing conditions [35]. Quorum sensing may affect the capacity of enterohemorrhagic Escherichia coli to colonize the animal gut, a crucial factor in its potential to contaminate food goods and industrial equipment, hence facilitating its development [53].

6. Effects of Contamination Stages in the Food Chain on the Development of Novel Foodborne Diseases

The technology of food production has inadvertently facilitated the genesis of novel foodborne illnesses, since the transformation of basic agricultural resources into finished meals generates several intermediary environmental niches conducive to the development of contamination foci. Every stage of the food chain, including harvesting, slaughtering, manufacturing, processing, preparation, handling, storage, packaging, and transport, must be consistently monitored to reduce the potential for health concerns [12,54]. To effectively mitigate possible issues, measures to detect or prevent contamination in

completed and ready-to-eat food must be implemented [12,54,55]. Deficiencies in sanitary procedures at any stage may substantially impact consumer health.

Food production encompasses several operations, including crop cultivation and livestock rearing, where the risk of foodborne pathogens (FBPs) contaminating the food supply is present. It is unsurprising that fresh fruit may get contaminated prior to harvesting during plant production, especially if farms use dirty water for irrigation, encounter environmental extremes, or inappropriately apply fertilizers and pesticides [12]. Failures at any stage of the food chain may lead to catastrophic consequences, allowing opportunistic microorganisms to adapt, proliferate, and create issues in foods that were not previously associated with sickness. An illustration of this is a series of epidemics that occurred in several North American regions in 1996, affecting the District of Columbia, 20 states in the US, and two provinces in Canada. This epidemic resulted in 1,465 cases of sickness, marked by symptoms including diarrhea and significant exhaustion. The primary culprit was fresh raspberries with *Cyclospora cayetanensis*, a harmful parasite not previously linked to food. Unfortunately, research could not identify the exact source of fruit contamination by this disease [3]. Recent reports indicate that *Cyclospora* outbreaks in the US have been associated with fresh produce, including basil, cilantro, lettuce, raspberries, as well as snow peas [56].

It is commonly recognized that animals and livestock farms are often inhabited by harmful bacteria [57]. A novel strain of *Vibrio parahaemolyticus* O3:K6, a marine bacterium present in raw seafood including oysters and mussels, has recently disseminated from Southeast Asia to Japan and the United States. In the early 1990s, a novel *V. parahaemolyticus* serotype appeared in Southeast Asia; subsequently, it precipitated many outbreaks in Japan associated with seafood, and notable outbreaks tied to oysters occurred in the United States in 1997 and 1998 [57]. Oysters were reportedly gathered from maritime areas adjacent to shipping routes when eastern oil tankers released polluted ballast water before to loading gasoline and oil for Japan [3,58]. *Arcobacter*, once categorized as *Campylobacter* and currently more often detected in water, has also been identified in several cattle corpses. It is linked to gastrointestinal diseases in individuals and has been extracted from dietary sources [59,60].

Clostridium difficile, although considered a nosocomial infection, is present in 6–8% of food specimens, with up to 10% of seafood samples testing positive for its spores. It is considered an emerging foodborne disease, with spores in swine or bovine feces potentially contaminating meat products following slaughter [61-63]. Moreover, after slaughter, pathogens may rapidly spread in poultry raising facilities with substantial avian populations. Hot water immersion used for avian slaughter facilitates feather extraction but may disseminate intestinal contents to corpses handled thereafter [64,65]. It is significant that a minimum of 90% of chicken available at retail establishments across various areas is infected with *Campylobacter* spp. This group is believed to account for the highest percentage of bacterial foodborne illnesses in nations that track causative agents, but the illnesses they induce are often mild, self-limiting, and significantly underreported [66]. The main cause of Campylobacter infections in people is chicken. Control efforts for Campylobacter in the United States have concentrated on the chlorination of water baths and chiller tanks, with cleanliness during slaughter [34].

Traditional food processing encompasses many procedures such as milk pasteurization, nut roasting and grinding, cigarette smoking, drying out, and salting [12]. Food product contamination may arise during processing due to improper handling or, more frequently, as a consequence of post-process contamination within the factory surroundings, potentially stemming from workers, floors, walls, equipment, ingredients utilized in processing, or other sources [67].

Arcobacter exemplifies an emerging pathogen. The genus comprises 33 species, including *Arcobacter nitrofigilis*, obtained from plant roots, and *Arcobacter butzleri*, *Arcobacter cryaerophilus*, and *Arcobacter skirrowii*, which have been isolated from animals. These pathogens are part of the *Epsilobacteria*group, which additionally comprises *Helicobacter* spp. and *Campylobacter* species. [59,68]. Arcobacter is often linked to chicken carcasses; however, managing *Arcobacter* on farmlands should mitigate contamination during processing. Nevertheless, several investigations indicate that Arcobacter may exist in processing

conditions and may survive both outside and internally inside carcasses [69]. It was noted that *Arcobacter butzleri*persisted in pen litter for extended durations [68].

Bovine spongiform encephalopathy (BSE), which originated in Britain, is a recent example of a disease that has surfaced. BSE likely originated from the interspecies transmission of scrapie from sheep to cattle, facilitated by alterations in rendering procedures that allowed the survival of the scrapie agent in sheep byproducts, which were then given to calves [70,71]. In 1985, a malfunction in the processing of milk at a milk production facility resulted in approximately 150,000 illnesses with Salmonella enterica. Moreover, substantial cholera outbreaks have been linked to municipal water systems in poor nations, often resulting from insufficient sewage treatment, the contamination of drinking water with sewage due to unintentional plumbing cross-connections, or faulty operation of equipment [72]. Contaminated water caused an incident with canned mangoes, where Salmonella enterica infection occurred due to the entry of contaminated cooling and sanitation water via minute cracks in the can walls [35].

Food preparation often transpires at restaurants, residences, or food processing facilities, and may only include cooking, heating, and plating meals. Contamination may arise from food workers who are ill, fail to adhere to established sanitary practices on proper handwashing, or engage in cross-contamination [12]. For example, the illness caused by *E. coli* O157:H7 was first recognized in 1982 after two outbreaks in the United States associated with the consumption of uncooked hamburgers from a fast-food chain. This disease has since emerged as a significant source of bloody diarrhea epidemics, with recorded instances in Japan, Canada, the UK, and the US [40,73]. Furthermore, owing to insufficient sanitation and hygiene, Aeromonas spp. Among many diseases, they may reside in food-processing equipment, potentially serving as a cause of food cross-contamination [14].

Recently, many plant-based and dehydrated food components have been shown to have *Cronobacter*spp., including *C. sakazakii* may be inherently present in the production process due to lapses in appropriate hygiene measures. Contamination can happen externally during the manufacture of powdered baby formula in hospital neonatal departments or at home. This may happen after the water retention of baby formula before use, if stored improperly or for an extended duration, facilitating bacterial proliferation and development [35,74,75]. A significant discovery, particularly in Southeast Asia, was the association of Streptococcus suis with the handling or consumption of undercooked or raw pork and the killing of pigs [76-79]. An epidemic of gastroenteritis in North America was associated with St. suis infection of cantaloupe on the farm due to inadequate cleaning or washing of melons prior to cutting.

The maintenance of appropriate storage circumstances is a critical element affecting the efficacy of food safety measures and the optimization of its shelf life. In several countries, adherence to appropriate storage conditions is obligatory at the manufacturing level and extensively advocated for domestic usage. Guidelines delineate permissible limits of duration and temperature for refrigerated and frozen preservation, as well as ambient factors such as moisture, gaseous ambiance, and flow rates [54]. Moreover, food storage techniques have resulted in the proliferation of some foodborne viruses, especially in undercooked animal products, cheeses, and vegetables that were either cooked or maintained at inappropriate temperatures for prolonged durations, even inside a refrigerator [80,81]. Meningitis outbreaks attributed to *Listeria monocytogenes* were associated with tainted food, since this psychrotroph can proliferate at 0 °C. *Hydrophila* has lately garnered increasing public health attention as a possible etiological agent of both gastrointestinal and extra-intestinal infections, especially in immunocompromised individuals, with many circumstances contributing to severe health problems [14,82]. A key aspect affecting the public health implications of Aeromonas in food is their capacity to proliferate at temperatures ranging from 4 °C to 51 °C. Consuming polluted water or food cooked with contaminated water significantly increases the hazards associated with Aeromonas [14,83].

Food packaging offers advantages such as advertising and branding, safeguarding against physical damage or environmental factors, aiding in food preservation, and enhancing shelf life [54]. Additives such as antioxidants, stabilizers, and plasticizers are often used into monomer components during the manufacturing of packaging materials to improve film characteristics. Migration of chemicals from

packaging to food has been documented under certain situations [55]. packing has been deemed a potential contributor to the formation of pathogenic organisms; nevertheless, no outbreaks directly linked to packing materials have been observed [54,84].

The shipment and delivery of food from farms, suppliers, or manufacturing facilities to wholesalers, merchants, food service businesses, or consumers at home constitute critical phases for perishable foodstuffs. The significance of this issue stems from the potential for numerous adverse events during this phase, including physical harm, temperature assault, and exposure to inadequate sanitation, such as the use of unclean vehicles and negligent handling, which can elevate the risk of bacterial, chemical, or physical hazards leading to food contamination [1,12]. For example, in 1994, there was an epidemic of foodborne disease caused by *S. enteritidis* was verified in 80 individuals who consumed ice cream disseminated nationwide after the transportation of a pre-mix in an unsanitary tanker truck [51].

7. Conclusions

Microbial risks may impact the food chain at several stages, including manufacturing, assembly, planning, transportation, storage, and handling. Changes in the processing and storage of food procedures from farm to plate may greatly contribute to the establishment of foodborne pathogens. Emerging infections may become linked to certain sectors of the food chain. The concurrent worldwide revolution and changes in food processing, packaging, storage, and distribution over the 20th century have led to the emergence of novel foodborne pathogens and modifications in the epidemiology of foodborne illnesses.

Climate change and harsh weather may significantly influence the evolution patterns of novel pathogens. These characteristics highlight the need of diligent, ongoing monitoring and efficient treatment of outbreaks stemming from new diseases or atypical dietary sources. Understanding the principles and processes of contemporary technology used in the food business to manage food-borne pathogens and their potential contributions to the development and re-emergence of these diseases is vital. Moreover, it is essential to adopt effective agricultural, manufacturing, and sanitary practices, alongside the implementation of the Food Safety Management System (FSMS) grounded in the concepts of hazards assessment and Critical Control Point (HACCP) and quality control (QC) as a proactive strategy for identifying, preventing, and mitigating foodborne pathogens to guarantee the microbial safety of food products.

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ديناميكيات مسببات الأمراض المنقولة بالغذاء: مراجعة لنشأتها وتأثيرها على الصحة العامة واستراتيجيات التخفيف في سياق إدارة سلامة الأغذية

الملخص

الخلفية:تشكل الأمراض المنقولة بالغذاء تهديدًا كبيرًا للصحة العامة، نتيجة لاستهلاك الطعام أو الماء الملوث. غالبًا ما تُسبب هذه الأمراض الكائنات الدقيقة الممرضة، بما في ذلك البكتيريا والفيروسات والطفيليات، مما يؤدي إلى ملايين الإصابات وآلاف الوفيات سنويًا على مستوى العالم. يُعد فهم ديناميكيات مسببات الأمراض المنقولة بالغذاء أمرًا بالغ الأهمية لأمن الصحة العامة.

المنهجية:تستعرض هذه المراجعة ظهور وإعادة ظهور مسببات الأمراض المنقولة بالغذاء، مع تحليل العوامل المساهمة في انتشارها. تم إجراء بحث شامل في قواعد بيانات مثل MEDLINE و Web of Scienceو Google Scholarباستخدام كلمات مفتاحية متعلقة بمسببات الأمراض المنقولة بالغذاء، الأمراض الناشئة، وممارسات سلامة الأغذية. تُركّز المراجعة على تجميع نتائج الدراسات المنشورة لتوفير رؤى حول المسارات التي تؤثر بها هذه المسببات على الصحة.

النتائج:تشير النتائج إلى زيادة ملحوظة في مسببات الأمراض المنقولة بالغذاء تُعزى إلى التطورات التكنولوجية في إنتاج الغذاء، والتغيرات في الممارسات الزراعية، والتحولات في سلوك المستهلكين. تم ربط مسببات الأمراض الناشئة مثل *E. coli* *O157:H7*و*Listeria monocytogenes*بمصادر غذائية محددة، مما يبرز أهمية أنظمة إدارة سلامة الأغذية الفعالة. علاوة على ذلك، أدت التغيرات المناخية والعوامل البيئية إلى تفاقم التحديات المرتبطة بالسيطرة على الأمراض المنقولة بالغذاء.

الخلاصة:يؤكد ظهور مسببات الأمراض المنقولة بالغذاء على الحاجة إلى استراتيجيات شاملة للصحة العامة تشمل تحسين أنظمة المراقبة، وزيادة الوعي، وتطبيق ممارسات سلامة الأغذية. يعد التعاون بين الجهات الفاعلة في سلسلة الإمداد الغذائي أمرًا ضروريًا لتقليل المخاطر وتعزيز أمن الأغذية.

الكلمات المفتاحية:الأمراض المنقولة بالغذاء، الصحة العامة، مسببات الأمراض الناشئة، سلامة الأغذية، أمن الصحة.