Review

How Long Do Pathogens Persist in Food? A Systematic Review

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How Long Do Pathogens Persist in Food? A Systematic Review

Eric S. Donkor [1,*], Famous K. Sosah [1], Alex Odoom [1], Bernard T. Odai [2] and Angela Parry-Hanson Kunadu [3]

[1] Department of Medical Microbiology, University of Ghana Medical School, P.O Box KB 4236, Korle Bu, Accra, Ghana
[2] Radiation Technology Centre, Biotechnology and Nuclear Agriculture Research Institute, Ghana Atomic Energy Commission, P.O. Box LG 80, Legon, Accra, Ghana
[3] Department of Nutrition and Food Science, University of Ghana, P.O. Box LG 134, Legon, Accra, Ghana
* Correspondence: esampane-donkor@ug.edu.gh

Abstract: Introduction: The persistence of pathogens in food is a critical aspect of food safety. Understanding the persistence of pathogens in food and the associated environmental factors is essential for implementing effective preventive measures and ensuring the safety of the food supply chain. **Methods**: A comprehensive search was conducted across major databases, including studies published until June 3, 2024. The PRISMA guidelines were followed to ensure a systematic and transparent approach. **Results**: Overall, 75 articles met the inclusion criteria, and these included data on the persistence of a wide range of microbial pathogens in food. *Salmonella* spp. exhibited the longest persistence, surviving on various food samples for up to 36 months at temperatures ranging from -24 ± 1 °C to 80 °C. *E. coli* (including *E. coli* O157:H7) and *Listeria monocytogenes* persisted for extended periods, ranging from 7 days to 12 months, at temperatures between -24 ± 1 °C and 37 °C, whereas the shortest persistence was observed for *Cronobacter* spp., which persisted for 24 hours. Among viruses, the vaccinia virus (VACV) and foot-and-mouth disease virus showed the longest persistence, lasting 60 days, whereas SARS-CoV-2 and MERS-CoV had the shortest persistence at 72 hours. Furthermore, the protozoan parasite *Cryptosporidium parvum* exhibited prolonged persistence for two months. Conclusion: This review provides evidence that major foodborne pathogens, such as *E. coli* O157:H7, *Salmonella* spp., *L. monocytogenes*, and hepatitis A virus, can persist on food for prolonged periods to cause harm. These insights underscore the importance of implementing appropriate control measures to contribute to a safer and more secure food supply chain.

Keywords: persistence; survival; pathogens; environmental factors; food supply chain; food safety; review

1. Introduction

The high and increasing incidence of food-borne illnesses coupled with the emergence and re-emergence of food-borne pathogens have made food safety a very important public health issue. According to estimates of the World Health Organization, there are approximately 600 million food-related illnesses annually, resulting in 420,000 deaths and a loss of 33 million healthy life years (disability-adjusted life years, DALYs) [1]. Food-borne illnesses are also associated with a high economic burden. For example, in the United States, food-borne illnesses cost the economy between US$10 and US$83 billion [2]. In Australia, the cost of food-borne illnesses is estimated at US$1.289 billion per year [3], while in New Zealand, the cost is US$86 million [4]. The common causes of foodborne illnesses include bacteria such as *Listeria monocytogenes*, *Escherichia coli*, and *Salmonella*; fungi such as *Penicillium* and *Aspergillus*, which produce harmful mycotoxins; viruses such as norovirus, hepatitis A and E, and rotavirus; and parasites such as *Trichinella spiralis*, *Toxoplasma gondii*,

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and *Cyclospora* [5,6]. These pathogens can be introduced into food at various stages, including during production, processing, storage, and handling [7]. Several lines of evidence show that some pathogens can survive by entering a dormant or injured state, allowing them to recover or persist [8–10]. Pathogen persistence in food depends on many factors, such as physical and microbial habitats, transmission routes, stress adaptations, and genetic determinants, and can cause repeated food contamination, increasing the risk of food safety violations [11–13]. Gaining insight into the survival durations of different pathogens in various types of food and the influence of environmental factors is essential for developing targeted control strategies. Despite the plethora of primary research data on the subject and its significance, a systematic review that provides comprehensive information to guide preventive, control, and management efforts is yet to be undertaken. This systematic review aims to determine the duration of pathogen survival and persistence in food, as well as the impact of varying external or environmental conditions on pathogen viability.

2. Materials and Methods

2.1. PRISMA Guidelines

To ensure a systematic and transparent approach to the literature search and review, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [14] were followed. The PRISMA guidelines offer a detailed checklist and flow diagram that assist in record identification, screening, and evaluation.

2.2. Search Strategy

A comprehensive search was conducted across major databases, including PubMed, Web of Science, and Scopus, using the following search terms: (“persistence” OR “survival”) AND (“pathogen” OR “bacteria” OR “fungi” OR “viruses” OR “parasites”) AND (“food” OR “fruits” OR “vegetables” OR “fresh produce”). Additionally, the reference lists of the identified articles were examined to identify any additional relevant publications. The search spanned studies published until June 3, 2024, with no restrictions on the study period. Only studies published in English were included, and there were no geographical limitations. The primary focus was studies that provided experimental evidence concerning the duration of pathogen persistence in any type of food.

2.3. Study Selection Process

A two-stage screening process was employed to identify relevant studies for inclusion in the review. Initially, the titles and abstracts of the identified studies were reviewed to eliminate duplicates and irrelevant articles. Next, the full texts of the remaining studies were thoroughly examined against predefined inclusion and exclusion criteria to determine their eligibility. Studies providing original data on pathogen persistence or survival on food were included in the review, and the results were extracted. Studies focusing on pathogen survival on food-contact surfaces were excluded because they were outside the scope of this review. Similarly, studies that detected only the presence of pathogens without estimating the duration of persistence were excluded, although they were screened for relevant information. Two reviewers, A.O. and E.S.D., independently conducted the screening process, adhering to predefined criteria, with a third reviewer consulted to resolve any disagreements. Mendeley Desktop version 1.19.8 was utilized to manage the search results and identify duplicate records.

2.4. Data Extraction

The data were independently extracted by the two reviewers via a Microsoft Excel spreadsheet. The information extracted from the eligible articles included the authors, the pathogens studied, the food type or sample, the duration of pathogen survival or persistence, and the external conditions tested.

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2.5. Quality Assessment

The risk of bias in each study was evaluated via the Cochrane ROB2 tool [15], and the results were visually presented via the Robvis tool [16]. This assessment tool examines five key areas of bias, namely, randomization, deviations from planned interventions, missing outcome data, outcome measurement, and selection of reported results. The two reviewers independently assigned a classification of low, high, or some risk of bias to each domain, and any discrepancies were resolved through consultation with a third reviewer. A study was considered to have a low risk of bias if all domains received a low-risk classification, high risk if at least one domain was rated as high risk, and some concerns if there were issues identified in one or more domains.

3. Results

3.1. Search Results

Initially, a total of 1387 records were identified from various databases, including PubMed (834), Scopus (269), Web of Science (224), and from a citation search of relevant articles (60). After removing duplicates (4) and inaccessible records (12), the titles and abstracts of the remaining 1371 records were screened. Among these, 1281 articles were excluded because they did not meet the established inclusion criteria for the review. Subsequently, 90 full-text articles were evaluated for eligibility, resulting in 75 articles [17–91] that met the inclusion criteria for the review, 57 focusing on bacteria [17–73], 17 on viruses [74–90] and 1 on parasites [91] (**Figure 1**).

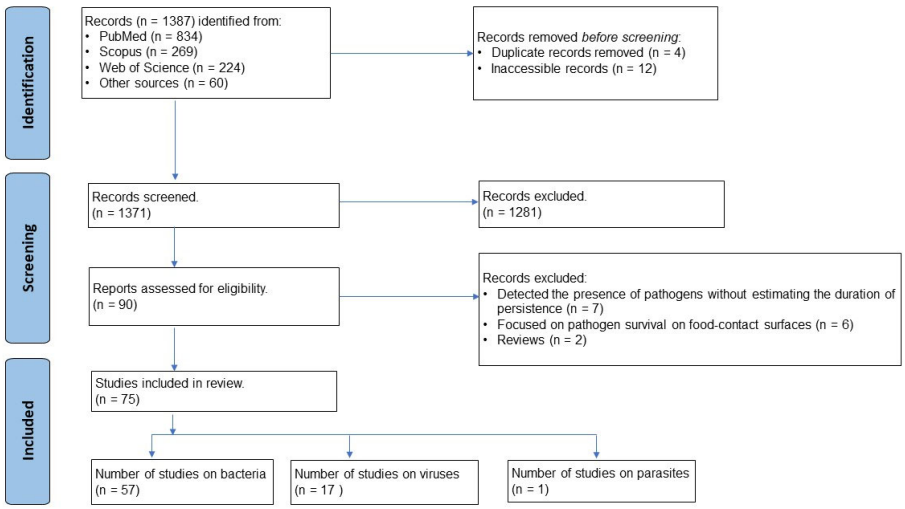

Figure 1. PRISMA flow diagram for the identification, screening, and evaluation of the articles included in the study.

3.2. Persistence of Bacteria

The persistence of bacteria in various food samples was reported in 57 of the studies included in the review. These studies identified 13 different genera of bacteria that survived on food for varying durations (**Table 1**). While *Cronobacter muytjensii* and *Cronobacter sakazakii* persisted for only 24 hours on infant formulas [20], other bacteria demonstrated remarkable resilience. For instance, *Helicobacter suis* survived on retail pork samples for at least 48 hours [41], and El Tor vibrios persisted on vegetables for 24 hours to 3 days [21]. *Campylobacter jejuni* persisted in milk for 4-21 days [17,18]. Several bacteria, including Shiga-toxigenic *Escherichia coli* (STEC) [44,71,72], *Staphylococcus aureus* [30] and Vibrio [44,73], survived on edible seaweeds, oysters, fermented sausages and vegetables for 7 to 28 days at various temperatures. *E. coli* (including *E. coli* O157:H7) persisted on various vegetables, nuts, cheese and meat for longer periods, ranging from 7 days to 12 months, at temperatures between -24 ± 1 °C and 37 °C [23–28,30–40]. *Listeria monocytogenes* persisted on fruits and vegetables for 7 days

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to 12 months at temperatures ranging from -24 ± 1 °C to 37 °C [23,26,30,33–35,42–50]. *Salmonella* spp. demonstrated the longest persistence, surviving in various food samples for up to 36 months at temperatures ranging from -24 ± 1 °C to 80 °C [23,24,26,29,30,32–35,42,44,53–70]. Notably, *Listeria monocytogenes, Salmonella* spp. and *Escherichia coli* O157:H7 persisted at a very low temperature of -24 ± 1 °C [35], and Salmonella Enteritidis PT 30 survived at the highest temperature of 80 °C [66].

3.3. Persistence of Viruses

Seventeen studies examined the persistence of viruses in various food samples (**Table 2**). Nineteen distinct virus species were found to persist in different types of food. Middle East respiratory syndrome coronavirus (MERS-CoV) was observed to persist for only 72 hours on fruits and vegetables stored at 22 °C [83]. In contrast, poliovirus survived on fruits and vegetables for 9 to 15 days, with the virus able to withstand temperatures ranging from -4 °C to 20 °C [86]. Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) persisted on fruits and vegetables for a period of 72 hours to 21 days at 22 °C [83,88,89]. Feline calicivirus (FCV) was found to persist for 4 weeks, surviving at temperatures ranging from 4 °C to room temperature [77,78]. Hepatitis A virus (HAV) persisted for 4 to 50 days, at temperatures ranging from 4 °C to room temperature [74,77,78,81,82]. Human norovirus (NoV) also persisted on food samples for 4 weeks, but only at room temperature [77]. Similarly, murine norovirus (MNV) persisted for 4 weeks at room temperature [74,76,77]. Porcine delta coronavirus (PDCoV) and porcine epidemic diarrhea virus (PEDV) persisted for a long time and survived in food matrices for up to 56 days [87]. Foot-and-mouth disease virus survived on cheese samples and dried casein for 21 to 60 days at a temperature of 2 °C [79,80]. The longest-persistent viruses were Vaccinia virus (VACV) [90] and Foot-and-mouth disease virus [79], both lasting 60 days, while SARS-CoV-2 [83] and MERS-CoV [83] had the shortest persistence at 72 hours. Overall, the virus that was able to withstand the lowest temperature was poliovirus at -20 °C [86], and the viruses that survived the highest temperature were murine norovirus (MNV), hepatitis A virus (HAV), and bacteriophage MS2 at 40 °C [74].

3.4. Protozoa Parasites

Unlike bacteria and viruses, only one of the included studies investigated parasites in food. This study focused on *Cryptosporidium parvum* and reported prolonged persistence on lamb's lettuce for two months [91].

Table 1. Bacterial persistence in various food types.

Bacteria	Sample	Duration	Condition	Reference
Campylobacter jejuni	Unpasteurized milk	21 days	4 °C	Doyle et al. [17]
Campylobacter jejuni ST-883	Raw milk	4-6 days	-	Jaakkonen et al. [18]
Cronobacter	Powdered infant formula (PIF)	3 months	-	Bennour Hennekinne et al. [19]
Cronobacter muytjensii	Infant wheat-based formulas reconstituted with water, milk, grape juice or apple juice	24 h	4, 25 or 37 °C	Osaili et al. [20]
Cronobacter sakazakii	Infant wheat-based formulas reconstituted with water,	24 h	4, 25 or 37 °C	Osaili et al. [20]

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	milk, grape juice or apple juice			
El Tor vibrios	Parsley	24 h	-	Sechter et al. [21]
El Tor vibrios	Tomatoes and carrots	24 to 30 h	-	Sechter et al. [21]
El Tor vibrios	Cucumbers, peppers and okra	24-48 h	-	Sechter et al. [21]
El Tor vibrios	Lettuce	2-3 days	-	Sechter et al. [21]
Enterococcus faecalis	Poultry and cattle feed	7 days	22 °C, relative humidity 65%	Channaiah et al. [22]
Escherichia coli	Raw carrot and cucumber juice	10 days	20 °C	Van Beeck et al. [23]
Escherichia coli O157:H7	Bruised and unbruised tomatoes	7 days	10 and 20 °C	Tokarskyy et al. [24]
Escherichia coli O157:H7	In-shell hazelnuts	12 months	24 ± 1 °C, relative humidity 40% ± 3%	Feng et al. [25]
Escherichia coli O157:H7	Black carrot juice	7 days	4 and 37 °C	Degirmenci et al. [26]
Escherichia coli O157:H7	Rhizosphere and leaf surfaces of lettuce	7-21 days	-	Mark Ibekwe et al. [27]
Escherichia coli O157:H7	Lettuce cultivars	12 days	-	Erickson et al. [29]
Escherichia coli O157:H7	Cabbage cultivars	9 days	-	Erickson et al. [28]
Escherichia coli O157:H7	Vegetables (romaine lettuce, iceberg lettuce, perilla leaves, and sprouts)	7 days	15 °C	Tian et al. [30]
Escherichia coli O157:H7	Grape pulp	30 days	4 °C, pH 2.51-3.26	Marques et al. [31]
Escherichia coli O157:H7	Whole and diced yellow onions (Allium cepa)	6 days	4 °C, relative humidity 30-50%	Lieberman et al. [32]
Escherichia coli O157:H7	Almonds and pistachios	12 months	-19, 4, or 24 °C	Kimber et al. [33]
Escherichia coli O157:H7	Walnut kernels	3 weeks to more than 1 year	23 °C	Blessington et al. [34]
Escherichia coli O157:H7	Raw peanut and pecan kernels	365 days	-24 ± 1, 4 ± 2, and 22 ± 1 °C	Brar et al. [35]
Escherichia coli O157:H7	Cheddar cheese whey	21 days	4, 10 or 15 °C, pH 5.5	Marek et al. [36]
Escherichia coli O157:H7	Lamb meat	12 days	4 and 12 ± 1 °C	Barrera et al. [37]

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Escherichia coli O157:H7	Galotyri cheese	28 days	4 and 12 °C	Lekkas et al. [38]
Escherichia coli O157:H7	Raw goat milk lactic cheeses	42 days	-	Vernozy-Rozand et al. [39]
Escherichia coli O157:H7	Cheese	90 days	-	Maher et al. [40]
Helicobacter suis	Retail pork samples	at least 48 h	-	De Cooman et al. [41]
Listeria monocytogenes	Whole mango	28 days	12 ± 2 °C	Saha et al.[42]
Listeria monocytogenes	Mixed vegetables (containing green beans, corn, and peas)	12 months	-18 or -10 °C	Fay et al. [43]
Listeria monocytogenes	Edible seaweeds	7 days	4, 10, and 22 °C	Akomea-Frempong et al. [44]
Listeria monocytogenes	Raw carrot and cucumber juice	8 days	20 °C	Van Beeck et al. [23]
Listeria monocytogenes	Black carrot juice	7 days	4 and 37 °C	Degirmenci et al. [26]
Listeria monocytogenes	Vegetables (romaine lettuce, iceberg lettuce, perilla leaves, and sprouts)	7 days	15 °C	Tian et al. [30]
Listeria monocytogenes	Almonds and pistachios	12 months	-19, 4, or 24 °C	Kimber et al. [33]
Listeria monocytogenes	Walnut kernels	3 weeks to more than 1 year	23 °C	Blessington et al. [34]
Listeria monocytogenes	Raw peanut and pecan kernels	28 or 365 days	-24 ± 1, 4 ± 2, and 22 ± 1 °C	Brar et al. [35]
Listeria monocytogenes	Chickpeas, sesame seeds, pine nuts, and black pepper kernels	180 days	25 °C, relative humidity 25, 45 and 75%	Salazar et al. [45]
Listeria monocytogenes	Nut, seed, legume, and chocolate-containing butters	6 months	5 or 25 °C	Fay et al. [46]
Listeria monocytogenes	Chocolate liquor, corn flakes, and shelled, dry-roasted pistachios	336 days	4 and 25 °C, relative humidity 35%	Ly et al. [47]
Listeria monocytogenes	Dried apples, raisins and dried strawberries.	336 days	4 and 23 °C	Cuzzi et al. [48]
Listeria monocytogenes	Fresh strawberries	4 weeks	-20+/-2 °C	Flessa et al. [49]

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Listeria monocytogenes	Bell peppers	14 days	4 °C	Moreira et al. [50]
Listeria monocytogenes	Cantaloupe rinds	7 days	24 °C	Moreira et al. [50]
Listeria monocytogenes	Kale, cauliflower, and broccoli	6 days	13 °C	Moreira et al. [50]
Mycobacterium avium subsp. paratuberculosis (Map)	Ultrafiltered white cheese	60 days	-	Hanifian [51]
Mycobacterium paratuberculosis	Cheddar cheese	27 weeks	-	Donaghy et al. [52]
Salmonella	Whole mango	28 days	12 ± 2 °C	Saha et al. [42]
Salmonella	bruised and unbruised tomatoes	7 days	10 and 20 °C	Tokarskyy et al. [24]
Salmonella	Peanut oil	96 ± 8 days	-	Fong et al. [53]
Salmonella	Chia seeds	94 ± 46 days	-	Fong et al. [53]
Salmonella	Peanut shell	42 ± 49 h	-	Fong et al. [53]
Salmonella	Edible seaweeds	7 days	4, 10, and 22 °C	Akomea-Frempong et al. [44]
Salmonella	Lettuce cultivars	12 days	-	Erickson et al. [29]
Salmonella	Cabbage cultivars	9 days	-	Erickson et al. [28]
Salmonella	Dry- and wet-inoculated sucrose	52 weeks	5 and 25 °C	Beuchat et al. [54]
Salmonella	Boil-in-bag eggs	36 months	40 °C	Flock et al. [55]
Salmonella	Chocolate protein drink, peanut butter	12 months	40 °C	Flock et al. [55]
Salmonella	Whole and diced yellow onions (Allium cepa)	6 days	4 °C, relative humidity 30-50%	Lieberman et al. [32]
Salmonella	Almonds and pistachios	12 months	-19, 4, or 24 °C	Kimber et al. [33]
Salmonella	Walnut kernels	3 weeks to more than 1 year	23 °C	Blessington et al. [34]
Salmonella	Raw peanut and pecan kernels	28 or 365 days	-24 ± 1, 4 ± 2, and 22 ± 1 °C	Brar et al. [35]
Salmonella	Dehydrated garlic flakes	88 days	25 °C, ambient relative humidity	Zhang et al. [56]

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Salmonella	Ground black pepper (Piper nigrum)	45 or 100 days	25 or 35 °C, high relative humidity	Keller et al. [57]
Salmonella	Ground ginger	170 or 365 days	25 and 37 °C, relative humidity 33% (low) and 97% (high)	Gradl et al. [58]
Salmonella	Whole almond kernels	28 days	35, 22, 4, or -18 °C	Xu et al. [59]
Salmonella	Strawberries, cranberries, date paste, and raisins	182 - 242 days	4 and 25 °C	Beuchat et al. [60]
Salmonella	Ground black pepper (Piper nigrum)	8 months	25 and 35 °C, ambient humidity	Keller et al. [57]
Salmonella dublin	Beef-pork pepperoni	42-43 days	-	Smith et al. [61]
Salmonella enterica	Tomato	14 days	-16.7 °C	Zhou et al. [62]
Salmonella enterica	Raw carrot and cucumber juice	10 days	20 °C	Van Beeck et al. [23]
Salmonella enterica	Whey protein powder	6 months	36 °C	Farakos et al. [63]
Salmonella enterica	Catfish mucus	63 days	10- 22 °C	Dhowlaghar et al. [64]
Salmonella enterica serovar Enteritidis ATCC 13076	Colonial cheese	28 days	-	Degenhardt et al. [65]
Salmonella enterica serovar Typhimurium	Vegetables (romaine lettuce, iceberg lettuce, perilla leaves, and sprouts)	7 days	15 °C	Tian et al. [30]
Salmonella Enteritidis PT 30	Almond kernels	68 weeks	80 °C	Limcharoenchat et al. [66]
Salmonella Enteritidis PT 30	Whole Nonpareil variety almonds	48 weeks	4 or 23 °C	Abd et al. [67]
Salmonella Tennessee	Peanut butter	14 days	-	Matak et al. [68]
Salmonella Typhimurium	Peanut butter	14 days	-	Matak et al. [68]
Salmonella Typhimurium	Black carrot juice	7 days	4 and 37 °C	Degirmenci et al. [26]
Salmonella Typhimurium	Pacific oyster	30 days	-	Chakroun et al. [69]
Salmonella typhimurium	Cheddar, swiss, and mozzarella cheeses	2 months	5 °C, pH 5.8	Leyer et al. [70]

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Shiga toxin-producing *Escherichia coli* (STEC)	Fermented sausages	28 days	-	Böhnlein et al. [71]
Shiga toxin-producing *Escherichia coli* O157:H7. STEC O157	Korean style kimchi	8 weeks	4 °C	Gill et al. [72]
Shigatoxigenic *Escherichia coli* (STEC)	Edible seaweeds	7 days	4, 10, and 22 °C	Akomea-Frempong et al. [44]
Staphylococcus aureus	Vegetables (romaine lettuce, iceberg lettuce, perilla leaves, and sprouts)	7 days	15 °C	Tian et al. [30]
Vibrio	Edible seaweeds	7 days	4, 10, and 22 °C	Akomea-Frempong et al. [44]
Vibrio vulnificus	Oysters	2 weeks	Refrigeration conditions	Wood et al. [73]

Table 2. Persistence of viruses on various food types.

Virus	Sample	Duration	Condition	Reference
Bacteriophage MS2	Oysters, fresh peppers	2 weeks	4, 15, 25, and 40 °C, relative humidity 50% and 70%	Lee et al. [74]
Bacteriophage MS2	Eastern oysters (Crassostrea virginica)	6 weeks	7, 15, or 24 °C	Kingsley et al. [84]
Bacteriophage phi 6	Meat, fish products	30 days	refrigerated and frozen temperatures	Bailey et al. [75]
Calicivirus (FCV)	Lettuce leaves	7-14 days	4 °C	Esseili et al. [76]
Feline calicivirus (FCV)	Cereal, chocolate pistachios	4 weeks	room temperature	Nasheri et al. [77]
Feline calicivirus (FCV)	Marinated mussels	4 weeks	4 °C	Hewitt et al. [78]
Foot-and-mouth disease virus	Camembert cheese	21 days	2 °C, pH 5	Blackwell [79]
Foot-and-mouth disease virus	Cheese	60 days	-	Blackwell [79]

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Foot-and-mouth disease virus	Cheddar cheese	30 days	-	Blackwell [79]
Foot-and-Mouth Disease Virus	Dried casein	42 days	25 °C	Cunliffe et al. [80]
Hepatitis A virus	Alfalfa seeds	50 days	22 °C	Wang et al. [81]
Hepatitis A virus (HAV)	Cereal, chocolate pistachios	4 weeks	room temperature	Nasheri et al. [77]
Hepatitis A virus (HAV)	Marinated mussels	4 weeks	4 °C, pH 3.75	Hewitt et al. [78]
Hepatitis A virus (HAV)	Oysters or the surface of fresh peppers	2 weeks	4, 15, 25, and 40 °C, relative humidity (RH) (50% and 70%)	Lee et al. [74]
Hepatitis A virus (HAV)	Lettuce	9 days	4 °C	Croci et al. [82]
Hepatitis A virus (HAV)	Carrot	4 days	4 °C	Croci et al. [82]
Hepatitis A virus (HAV)	Fennel	7 days	4 °C	Croci et al. [82]
Human norovirus (NoV)	Cereal, chocolate pistachios	4 weeks	room temperature	Nasheri et al. [77]
Middle East Respiratory Syndrome (MERS-CoV)	Apples, tomatoes cucumbers	72 hrs	22 °C relative humidity 30%–40%	Blondin-Brosseau et al. [83]
Murine hepatitis virus (MHV)	Meat and fish products	30 days	refrigerated and frozen temperatures	Bailey et al. [75]
Murine norovirus (MNV)	Alfalfa seeds	50 days	22 °C	Wang et al. [81]
Murine norovirus (MNV)	Cereal, chocolate pistachios	4 weeks	room temperature	Nasheri et al. [77]
Murine norovirus (MNV)	Lettuce leaves	7-14 days	4 °C	Esseili et al. [76]
Murine norovirus (MNV)	Oysters or the surface of fresh peppers	2 weeks	4, 15, 25, and 40 °C, relative humidity 50% and 70%	Lee et al. [74]
Noroviruses (NoV)	Lettuce and turkey	at least 10 days	7 °C	Lamhoujeb et al. [85]
Noroviruses (NoV)	marinated mussels	4 weeks	4 °C	Hewitt et al. [78]

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Poliovirus	Lettuce, green onion white cabbage	15 days	4 °C	Kurdziel et al. [86]
Poliovirus	Strawberries	15 days	-20 °C	Kurdziel et al. [86]
Poliovirus	Raspberries	9 days	4 °C	Kurdziel et al. [86]
Porcine Delta Corona Virus (PDCoV)	Feed ingredient matrices	56 days	-	Trudeau et al. [87]
Porcine Epidemic Diarrhea Virus (PEDV)	Feed ingredient matrices	56 days	-	Trudeau et al. [87]
Porcine sapovirus (SaV)	Lettuce leaves	7-14 days	4 °C	Esseili et al. [76]
Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)	Ready-to-eat deli items, fresh produce, and meats (including seafood)	21 days	-	Jia et al. [88]
Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)	Apples, tomatoes cucumbers	72 hrs	22 °C, relative humidity 30–40%	Blondin-Brosseau et al. [83]
Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)	Tew-cut beef and ground beef	2 days	-	Featherstone et al. [89]
Transmissible Gastroenteritis Virus (TGEV)	Feed ingredient matrices	56 days	-	Trudeau et al. [87]
Transmissible gastroenteritis virus (TGEV)	Meat and fish products	30 days	refrigerated and frozen temperatures	Bailey et al. [75]
Tulane virus	Alfalfa seeds	50 days	22 °C	Wang et al. [81]
Tulane virus (TV)	Lettuce leaves	7-14 days	4 °C	Esseili et al. [76]
Vaccinia virus (VACV)	Cheese	60 days	25 °C	Rehfeld et al. [90]

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3.5. Risk of Bias

The risk of bias for the 75 studies included in this systematic review was assessed using the Robvis tool, as shown in **Figure 2.** The tool categorizes bias into three levels: low risk (green), some concern (yellow), and high risk (red). The overall low risk of bias across all domains suggested that the studies were methodologically sound and reliable.

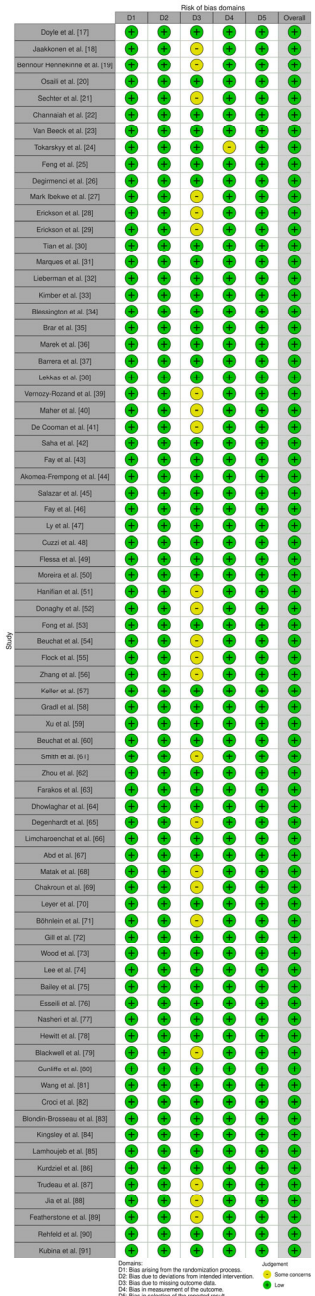

Figure 2. Assessment of bias of the included studies using the Cochrane risk-of-bias [17–91].

4. Discussion

The persistence of pathogens in food poses a serious threat to food safety and public health. In this review, our aim was to provide valuable information regarding the duration for which pathogens can remain viable on different food items. Many studies have focused on the persistence of bacterial pathogens compared with that of viruses. This may be due to difficulties in the detection and quantification of the viral genome [92]. Moreover, only a single study reported the persistence of a protozoan parasite, *Cryptosporidium parvum*, on fresh produce, despite its global association with

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foodborne illnesses, which account for more than 8 million cases annually [93]. Similarly, no studies have reported the persistence of fungi in food, despite their ability to produce mycotoxins, which can withstand heat and processing, thereby posing a risk in both raw and processed foods [94]. The persistence of bacterial species in food samples was greater than that of viral species. Generally, bacteria persist for longer durations on food, up to 36 months, than do viruses, which persist for up to 60 days. However, the shortest survival duration was greater for viruses at 72 hours than for bacteria at 24 hours. *Salmonella* is a major concern among pathogens because of its ability to persist for extended periods, making it one of the most prevalent zoonotic foodborne pathogens and a significant threat to global public health. It causes both typhoid fever and gastroenteritis, with nontyphoidal *Salmonella* (NTS) serovars being associated with the latter [95]. According to the World Health Organization's estimation in 2010, there were approximately 153 million NTS infections worldwide, leading to 56,969 fatalities, with almost half of these cases resulting from foodborne transmission [95]. Additionally, in 2018, *Salmonella* was responsible for more than half of the reported foodborne illness outbreaks in the European Union [96]. *Salmonella* is transmitted to humans throughout the entire food production process, from farm to fork, primarily through the consumption of contaminated animal- and plant-based foods [97].

One of the key factors influencing pathogen persistence is the surrounding environment. Most studies examined the influence of temperature on the persistence of foodborne pathogens. Temperature can affect the growth, reproduction, and overall survival of these microorganisms [98]. Pathogens are typically sensitive to high temperatures; however, higher temperatures within their optimal growth range facilitate faster replication and increase contamination risk [99]. Both bacteria and viruses were found to survive at relatively high temperatures, with bacteria surviving up to 80 °C. *Salmonella*, hepatitis A virus and murine norovirus presented increased heat resistance. On the other hand, viruses such as poliovirus were able to survive at temperatures as low as -20 °C, whereas bacteria such as *E. coli, Listeria monocytogenes* and *Salmonella* survived at -24 °C. Refrigeration at approximately 4 °C is generally effective in slowing the growth of most pathogens and prolonging the shelf-life of food products. However, *E. coli* O157:H7 is an exception because of its ability to survive and withstand refrigeration conditions compared with storage conditions at room temperature [100]. This particular strain of *E.* coli is strongly associated with foodborne disease outbreaks, especially those that are linked to the consumption of contaminated leafy green vegetables [101]. Moreover, factors such as humidity and air quality affect the growth and persistence of pathogens [102,103]. Few studies examined the influence of relative humidity on pathogen survival in (or in) food. Typically, elevated humidity provides an ideal setting for the growth and survival of pathogens, especially in foods with a high moisture content [104]. Conversely, low humidity may facilitate the persistence of viruses [105,106].

In addition to being impacted by the surrounding environment, certain foods possess natural antimicrobial properties that can hinder the growth of pathogens. For example, spices and herbs such as onion, parsley, lemongrass, garlic, and cinnamon possess antimicrobial properties that help reduce the survival and growth of pathogens when incorporated into food [107]. As observed in this review, bacteria can survive for only a few weeks on foods with these antimicrobial properties. Similarly, the pH of food can affect pathogen survival; however, only few studies explored this phenomenon. Foods that possess a low pH (high acidity), such as citrus fruits and vinegar, can impede the growth of most pathogens. However, *E. coli* O157:H7 has the unique ability to tolerate and adapt to acidic environments, enabling it to thrive better in acidic foods and beverages [108]. On the other hand, foods with relatively high pH values (low acidity), including meats and dairy products, may create an environment where most pathogens can survive and multiply. Similarly, the composition of nutrients in food also affects the survival of pathogens. Foods rich in protein, such as meats, boiled-in-bag eggs, chocolate protein drinks, whey protein powder, poultry, food and feed ingredients, and seafood, provide an abundant source of nutrients for pathogens to grow and multiply, thereby increasing their survival period and the risk of contamination. Water activity, which refers to the available water content in food, also plays a role in pathogen survival [109]. Foods with a water activity greater than 0.95 provide a supportive environment for the growth of pathogens [110]. Foods

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with high water activity include raw meats, fresh produce, fruits, and vegetables. However, foods with low water activity, such as hazelnuts, chia seeds, green beans, corn, peanut butter, whey protein powder, nuts, and dehydrated products, were found to have increased survival rates of *Salmonella*, *Escherichia coli* O157:H7, and *Listeria monocytogenes* compared with foods with high water activity. Low-moisture foods (LMFs) are often associated with outbreaks caused by norovirus and hepatitis A virus. Examples include a norovirus outbreak in 2008 in Korea, where dry radish was identified as the source of 117 symptomatic infections [111]; a norovirus outbreak in 2017 in Japan, involving 2094 cases linked to dry seaweed [112]; and a hepatitis outbreak in Australia, where sun-dried tomatoes were identified as vehicles [113].

Pathogens have the potential to spread from one food to another through cross-contamination. The cross-contamination of ready-to-eat foods, such as salads or fruits, with raw meat can lead to the survival of pathogens, posing a significant risk to human health [96]. Throughout the entire food production process, from primary production to secondary processing, the risk of contamination by persistent foodborne pathogens remains a concern. To prevent this, it is crucial to maintain strict separation between raw and cooked foods, utilize separate cutting boards and utensils, practice good hygiene, and good agricultural practices that reduce contamination and cross-contamination of both crop and animal products. Proper food handling, storage, adherence to recommended temperatures, good manufacturing practices and hazard analysis and maintaining cleanliness throughout the food preparation process are all important steps to ensure food safety [114,115]. In addition, specific food processing methods, including cooking, pasteurization, and canning, are effective in eliminating or reducing the presence of pathogens. Cooking food at appropriate temperatures can effectively kill most pathogens, rendering the food safe for consumption. For example, cooking meat to an internal temperature of 165 °F (74 °C) helps eliminate pathogens such as *Salmonella* and *Escherichia coli* [116,117]. Pasteurization, a heat treatment process commonly used for liquids such as milk and juice, also aids in destroying pathogens while preserving the quality of the product [118]. Importantly, these measures are crucial for minimizing the risk of foodborne illnesses, regardless of the specific type or persistence duration of the pathogens involved. Therefore, regular monitoring, testing, use of validated process controls, and continuous education and training of food handlers are crucial to ensure the implementation of proper food safety protocols and prevent the persistence of pathogens on food.

This review followed the PRISMA guidelines for a thorough search and included data from multiple studies encompassing a wide range of pathogens, including bacteria, viruses, and protozoan parasites. Furthermore, this review considered the influence of environmental factors, particularly temperature, on pathogen persistence. This valuable information can be utilized to shape food safety protocols and guidelines, leading to more effective measures for control and prevention. Overall, this review provides a comprehensive understanding of the potential risks associated with various types of pathogens found in food. However, this review has several limitations. There was a greater focus on bacterial isolates, potentially resulting in an underrepresentation of other pathogens' persistence data. Another limitation is the possibility of publication bias, where studies demonstrating longer pathogen persistence may have been more likely to be published, whereas those showing shorter persistence or nonsignificant results may have been overlooked or unpublished. Similarly, reporting bias may exist, as studies selectively report certain aspects of pathogen persistence, possibly omitting negative or inconclusive results. These biases could impact the overall conclusions drawn from the review.

5. Conclusions

This review offers important insights into the survival durations of pathogens in food, including bacteria, viruses, and protozoan parasites. The findings emphasize the varying survival times of different pathogens on various food types and the influence of temperature on their persistence. The use of this knowledge to establish appropriate control measures can contribute to a safer and more secure food supply chain.

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