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REVIEW ARTICLE

Management strategies emphasizing advanced food processing approaches to mitigate food borne zoonotic pathogens in food system

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Abstract

Foodborne zoonoses are the most neglected discipline due to a lack of awareness of potential health hazards, standardized detection methods, and identification of infectious host reservoirs. Food is the major carriage vehicle for the transmission of zoonotic pathogens and many outbreaks globally. Resilient surveillance and holistic intervention of effective mitigation strategies at both preharvest (bacteriophages, probiotics, vaccination, micronutrients, breeding, culling), postharvest (advanced food processing, biofilm removal, and disinfectant), retailer and consumer levels can reduce or prevent pathogens and cross-contamination. Rapid tracking of contamination sources and identification of the route of infection should be implemented using analytical techniques for targeted detection of causative organisms and microbiological risk assessment. An overview elaborating various farm-to-fork pathogenic mitigation strategies at different stages of the food chain is presented. However, special emphasis is placed on the application of advanced novel food processing and preservation techniques, such as high-pressure processing, pulsed light, ultrasound, ultraviolet light, ozone treatment, irradiation and other hurdle technologies for pathogen reduction and food quality assurance. This review will provide an overview of the overall scenario regarding foodborne pathogen–human health interactions and the possible prevention measures that would be helpful for producers, manufacturers, retailers, and consumers for the safer and sustainable development of food products.

KEYWORDS
advanced food processing techniques, foodborne diseases, global pandemic, mitigation strategies, zoonotic pathogens

1 | INTRODUCTION

The recent emerging COVID pandemic reminds us about zoonotic pathogens being catastrophic to the whole world. Many global factors, such as climate change, intensive farming and mechanization, migration, urbanization, human encroachment disrupting nature and increasing the interaction between livestock, wildlife, people, and pathogens, pave the way to pandemics. In recent years, pathogenic diseases have turned out to be the foremost concern to mankind as a global health pandemic. The quick mutation and recombination along with the ecological changes, however, make it difficult to predict and prevent emerging diseases. The current COVID-19 epidemic in China has become a global health hazard and worldwide economic disaster (Vishwakarma et al., 2022), which is an extreme stark reminder of the role of animal reservoirs in public health. This reinforces the urgent need for a one-health approach internationally. Possible mitigation solutions must be addressed through improved management policies, medical surveillance, and clinical diagnosis thereof. Among all, the major primary emphasis should be given to the implementation of novel advanced processing techniques to reduce the chance of catastrophic outbreaks.

1.1 | Zoonotic pathogens and diseases: Human health and emergence of global pandemic

For the last 20 years, the number of pandemics has risen, and USAID has documented nearly 900 strains of infectious disease that soared into pandemics (SARS, HIV/AIDS, Nipah, Hanta, Influenza, Ebola, and COVID-19). Most of these pandemics have emerged from the interaction of human-animal and food systems that eventually put the global economy and food security at risk. Between 58% and 75% of infectious diseases that affect humans originate from microorganisms hosted in animals, suggesting that the majority of human infectious diseases have a zoonotic origin (Ellwanger et al., 2020). According to the World Health Organization (WHO) estimation, infectious communicable diseases account for 20% of global deaths, of which 60% are zoonotic and 75% cause emerging human infectious diseases (Marty & Jones, 2020). Improper and unsanitary handling, storage, and management of animals, livestock products, and wildlife trade have led to mutation, cross-species transmission, and animal–human transmission of zoonotic diseases. Apart from the human–animal–food system interface, which plays a crucial role in pathogenic outbreaks, environmental factors, climate change, animal health, human occupancy of new habitats, and deforestation are also important aspects based on the “one-health” perspective (Ellwanger et al., 2021). Moreover, urbanization, globalization, local urban migration, and transportation have escalated the pandemic (Destoumieux-Garzón et al., 2018). Nevertheless, this review addresses and elaborates the emergence and treatment of foodborne zoonotic diseases only in the context of human–animal–food interactions.

The outbreak and emergence of zoonotic pathogens and diseases have caused a global economic burden and account for more than $220 billion of direct and indirect costs (World Bank, 2010). Grace et al. (2012) reported that the potential economic loss from any pandemic outbreak would cost $3 trillion (5% of global GDP); thus, zoonotic infection could be one of the prime causes of poverty. The financial consequences of these diseases on public health can devastate the economic conditions being already overburdened in developing countries (Shaheen, 2022). Several outbreaks worldwide in the last decade are reported in Table 1. The emergence and re-emergence of infectious diseases is attributed to many inclusive factors, including changes in ecosystems, public health, poverty, and so on. The recent COVID-19 outbreak is an example of a food system-driven emerging disease that has evolved into one of the most disastrous historical moments in humanity. This outbreak, in addition to affecting public health, has a devastating impact on social, economic and natural resources (Topcu & Gulal, 2020). This pandemic has posed a massive impact on almost all economic and financial aspects, for example, education, mental health, labor markets, stock markets, global supply chains, and consumption patterns. affecting the entire global economy (Aucejo et al., 2020). Mounting evidence points to the zoonotic origin of SARS-CoV-2, and some authors have pointed out that emergence due to wildlife consumption or contact/interaction with Chiroptera (being the primary reservoir for its lineage) is likely to be responsible for the emergence of SARS-CoV-2 (Andersen et al., 2020; Everard et al., 2020; Kenyon, 2020). It is highly probable that bushmeat trade might have contributed to the emergence of the recent human COVID-19 pandemic. Bats were the natural hosts of several viruses earlier (SARS-CoV and MERS-CoV) and hence thought to be for SARS-CoV-2, but again, the actual role of this animal species is still under debate and a matter of inspection (Ellwanger et al., 2021). COVID-19 is just one among the number of emerging zoonoses that provides a lesson that numerous infectious zoonotic diseases would arrive in the future unless adequate food value chain monitoring is adopted. It is a call-to-action for addressing various pre- and postharvest management strategies and advanced food processing techniques to mitigate the risk of future viral epidemic outbreaks and their associated challenges.

1.2 | Foodborne pathogens and the food system

The occurrence of pathogens in foodstuffs and new food vehicles for foodborne outbreaks is always a concern to consumers, food microbiologists, and food technologists for investigations (Bolton et al., 2014). Food naturally contains bacteria, viruses, protozoa, and parasites acquired during farm growth to processing to retails and signify contamination throughout the food chain (Callaway et al., 2013). Mixed crop livestock farming is more prone to contamination than conventional farming via the application of raw waste, surface water contamination and direct pathogen transmission from animal to farm (Salaheen et al., 2015).

TABLE 1 Various human outbreaks due to foodborne pathogens

Source	Country	Year	Number of outbreaks	Common pathogen	Illness (fatality)	References
Raw milk consumption	Europe Union	2007–2012	27	*Campylobacter* spp. *Salmonella* spp.	–	EFSA Panel on Biological Hazards (BIOHAZ) (2015)
Raw milk consumption	USA	2007–2012	81	Shiga toxin producing *Escherichia coli*, *Campylobacter* spp., *Salmonella enterica* serotype *Typhimurium*	979	Mungai et al. (2015)
Raw milk products	USA	1998–2011	38	*Salmonella* spp., *Campylobacter*, *Brucella*, STEC	–	Gould et al. (2014)
Fenugreek seed	Germany and France	2011	1	STEC and enteroaggregative *E. coli* (EAggEC)	3911 (47)	Bolton et al. (2014)
Bat (likely to be)	Globally	2019 (continuing)	1	SARS-CoV-2	484,179,897 (6,153,536)	Jalava (2020), World meter
Meat, fish, egg, and their products, buffet meals, bakery products, fruits and vegetables and other foods, fishery products	EU	2017	5079	*Salmonella*, *Listeria*, STEC, *C. botulinum*, Norovirus, *Campylobacter*, Hepatitis A, Norovirus, *Trichinella*, *Vibrio*, *Cryptosporidium*, *Brucella*, Marine biotoxins, Histamine	43,400 (33)	EFSA and ECDC (2018)
RTE foods (meat and fish products, salads, fruits and vegetables, cheese)	EU	2013–2017	52	*Listeria monocytogenes*	447	EFSA and ECDC (2018)
Bovine meat and products, milk, cheese, other dairy products	EU	2013–2017	300	Shiga toxin-producing *E. coli*	3259	EFSA and ECDC (2018)
Yogurt, cheese, pig and sheep meat, mushroom, dressings, cereals, egg	EU	2013–2017	52	Yersinia	466	EFSA and ECDC (2018)

Campylobacter spp., *Listeria monocytogenes*, *Salmonella* spp., and *Escherichia coli* O157:H7 are recognized as the major causes of foodborne illnesses (Barba et al., 2017). In fact, *Campylobacter* and *Salmonella* were responsible for approximately 75% of foodborne illnesses in the United States in 2012 (CDC, 2016), and poultry products were the main source of these pathogens. Rupture of the poultry gastrointestinal tract during processing causes contamination (Salaheen et al., 2015). Consumption of unpasteurized milk, dairy-based products, undercooked meat, poultry, sea food, and ground beef are potential sources of foodborne pathogens and risks of zoonosis to consumers. Sources of pathogens and their association with various diseases are listed in Table 2 (Chuang et al., 2020; Dos Anjos et al., 2020). Dairy-based pathogens causing foodborne outbreaks in Europe were *Salmonella* spp., followed by *Campylobacter* spp. and staphylococcal enterotoxin (SET), where cheese and milk were the main sources contributing *Campylobacter* spp. (56%), flavivirus (11%), *Staphylococcus aureus* (10%), STEC and *Salmonella* spp. (both 7%) in milk, whereas *Staphylococcus aureus* (30%) and *Salmonella* spp. (52%) were observed in cheese (Elmi et al., 2020).

1.3 | Routes and causes of pathogen contamination

Foodborne zoonotic pathogens enter, transmit, and may cross contaminate at any stage of the food chain. Several sources of contamination are observed at the farm or harvesting, processing, packaging, storage, transportation, retail, and consumer levels, as illustrated in Figure 1. Irrigation water, feed, manure, rodents, birds, livestock animals, wild animals, insects and pests, harvesting equipment, soil, crops, and agricultural fields are the major sources of contamination (Salaheen et al., 2015). Water is a major source of infection in the food supply chain by transporting transmissible parasites into crop irrigation water, recreational sites (fresh and marine waters), and public water supplies (food and agro industry use, food preparation or processing; Broglia & Kapel, 2011).

TABLE 2 List of major pathogens causing diseases and potential food sources

Pathogen	Disease	Available in food animal/products
Salmonella	Vomiting, watery diarrhea, fever, gastroenteritis, abdominal pain	Shellfish, pigs, cattle, poultry
Shigella	Hemolytic uremic syndrome (HUS), abdominal pain, gastroenteritis, bloody diarrhea, malaise, fever	Beef, chicken, beef, and other animal meats
Campylobacter	Diarrhea, gastroenteritis, nausea vomiting, abdominal cramps	Cattle, poultry, pigs, lamb
Escherichia coli	Nausea, gastroenteritis, fever, abdominal cramps vomiting, hemorrhagic colitis, HUS, thrombocytopenia purpura, mucoid, dysentery, chills, mucus, and blood in stools	Beef and its products, poultry, pork, shellfish, cattle, cheese, uncooked milk
Yersinia enterocolitica	Mesenteric lymphadenitis, septicemia terminal ileitis, meningitis, gastroenteritis	Sheep, poultry, pork, and meat products
Listeria monocytogenes	Diarrhea, abdominal pain, gastroenteritis, miscarriage, fever	Pigs, cattle, goats, sheep, and meat-based foodstuffs
Clostridium botulinum	Paralysis, botulism	Fish, chicken, mutton
Staphylococcus aureus	Urinary tract infections, toxic shock syndrome, food poisoning, tissue infections	Milk, cattle, pigs, pork, and its products
Streptococcus	Rheumatic fever, sore throat, kidney inflammation,	Eggs and raw milk
Vibrio	Wound infections, acute gastroenteritis, septicemia	Shellfish, undercooked, or raw seafood
Hepatitis E	Nausea, jaundice, hepatitis (during pregnancy), and fever	Deer, swine, meat, raw/undercooked liver, shellfish, sausage
Hepatitis A	Nausea, fatigue, joint pain, vomiting, jaundice, fever	Raw shellfish
Noroviruses	Stomach pain, nausea, body ache, vomiting, dehydration, diarrhea, headache, fever	Infected foods, molluskes
Astroviruses, Sapoviruses	Diarrhea, vomiting, gastroenteritis	Shellfish, cattle, swine, poultry, and lambs
Rotaviruses	Gastroenteritis, vomiting, abdominal cramp, diarrhea	Cattle, pigs, shellfish, and animal products
Entamoeba histolytica	Fatigue, dysentery, liver abscess, diarrhea, abdominal pain	Moist foods
Toxoplasamagondi	Muscle aches, flu, lymph nodes, blindness, encephalitis, miscarriage, and stillbirth	Unprocessed/underdone meat (sheep, poultry, cattle, and pigs)
Cryptosporidium	Pain, vomiting, nausea, stomach cramps, diarrhea, fever, dehydration	Shellfish, uncooked beef, pork, and chicken
Taenia	Neurological complications (influence on eyes, heart, brain, muscles), malaise, abdominal pain	Cattle, swine, and meat products

Source: Louge et al. (2017).

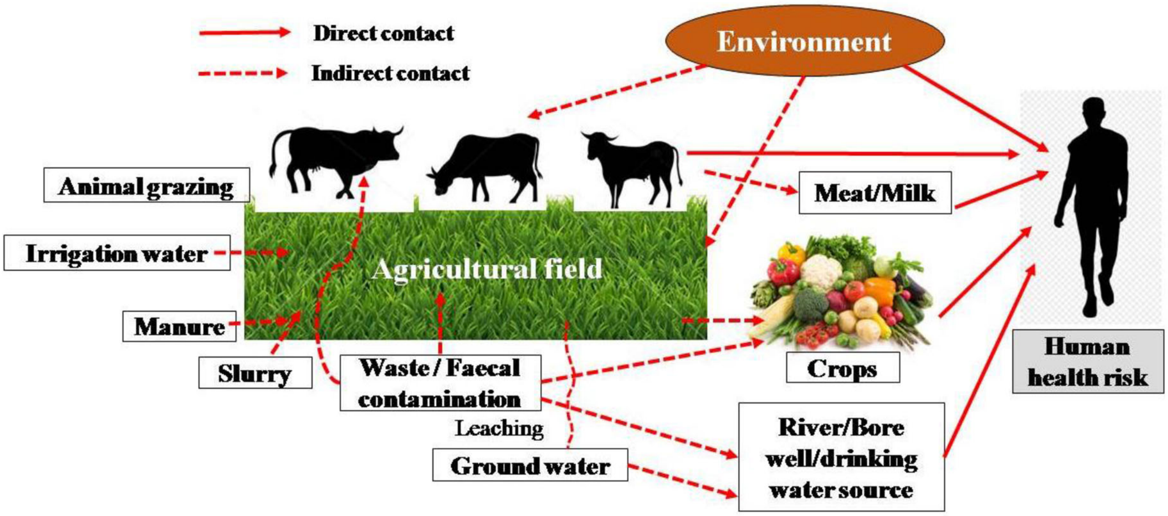

FIGURE 1 Routes of pathogen infection

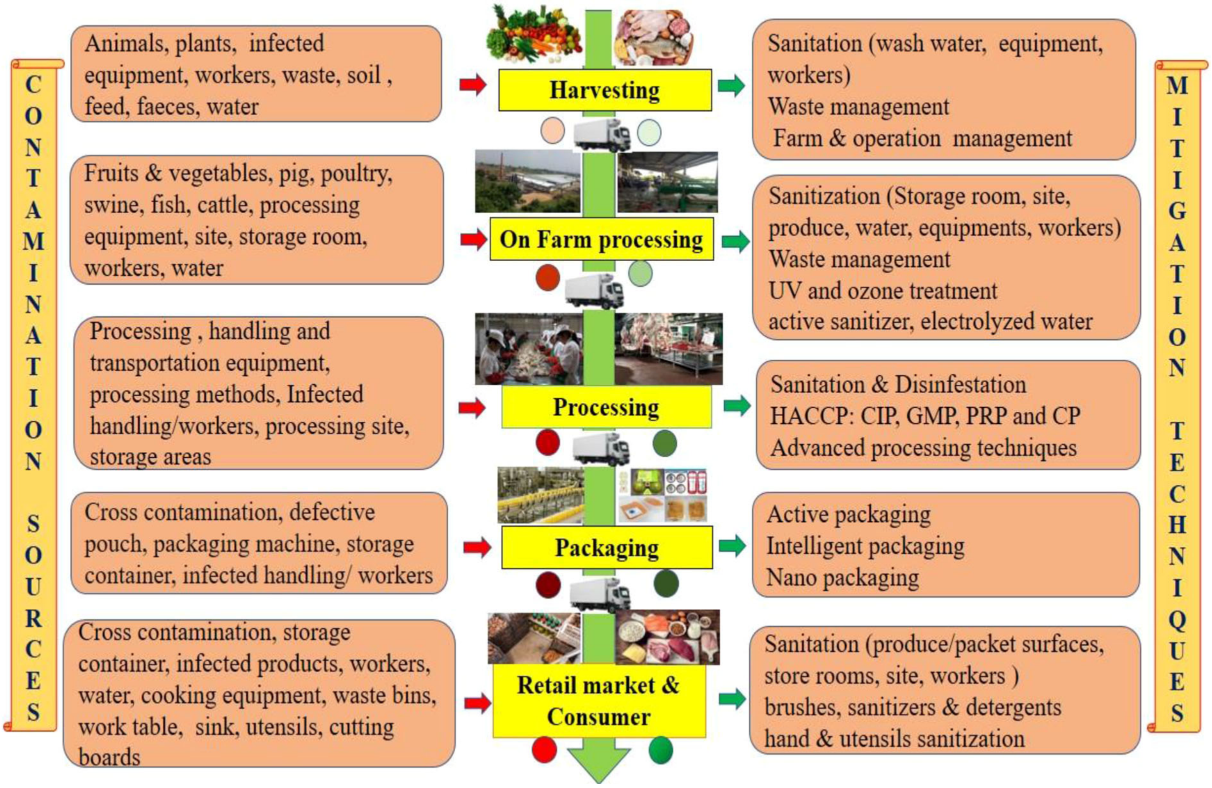

FIGURE 2 Various sources of contamination and mitigation techniques at different steps of the food chain. *Source*: Pérez-Rodríguez & Mercanoglu Taban (2019) and Al-Tayyar et al. (2020)

Processing of sick animals and diseased or defective plants contaminates fresh products. Scalding, picking, and evisceration increase the possibility of contamination in poultry processing (Salaheen et al., 2015). Industrial production of animal nutrition and pet food has been a channel for pathogen transmission and large-scale human illness outbreaks. Dry dog food and beef patty dog food production have sickened and hospitalized many people in US states, Texas, Canada (CDC, 2012; Lambertini et al., 2016).

2 | EFFECTIVE MITIGATION STRATEGIES FOR FOOD BORNE PATHOGENS

The purpose of modern food production is to reduce human illness by controlling pathogens. Figure 2 summarizes contamination sources and mitigation techniques from harvesting to consumption. Several intervention and mitigation strategies have been carried out in recent years at both preharvest or postharvest levels. These would be advantageous and an impactful approach from the perspective of outbreak prevention, as illustrated in Figure 3. Precise management, rapid identification of infections, tracking of origin, and quick removal of contamination at the farm level will reduce the subsequent risk from open grazing animals, the environment, and agricultural products entering the food processing chain (Bolton et al., 2014; Villa et al., 2016).

Interdisciplinary and multilevel intersectoral approaches and preventive control programs led by professional and institutional bodies are required to prevent any pandemic or global health emergency (Häsler et al., 2012). Sustainable hygienic practices and awareness in agriculture and food, application of bioprotective cultures and antimicrobial agents in animal husbandry, and processing of food could prevent pathogenic transmission and disease risks. Moreover, implementing good hygienic and manufacturing practices and safety management during processing, production and within industrial workers could prevent contamination (Pérez-Rodríguez & Mercanoglu Taban, 2019). The development of antimicrobial food packaging material for the packaging of frozen food, livestock products, sea food, perishable fruits and vegetables, dairy products, and high moisture food could reduce postprocessing pathogenic contamination (Al-Tayyar et al., 2020).

Antimicrobial drugs that include antibiotics, antifungals, antivirals and antiparasitic agents are being extensively used to treat numerous infections and have benefitted humanity by the dramatic reduction in morbidity and mortality from diseases. However, the indiscriminate utilization of these drugs for nonspecific purposes and inappropriate disposal of antimicrobials in the ecosystem has resulted in the antimicrobial resistance of microorganisms, which is a major constraint (Ellwanger et al., 2021). Therefore, it can either be effective or deleterious depending on its use, and the drug resource should be applied with extreme caution. This incites an urgent requirement of enabling drug repurposing strategies and developing medicines suiting multiresistant microbial strains as well as targeting new infectious agents.

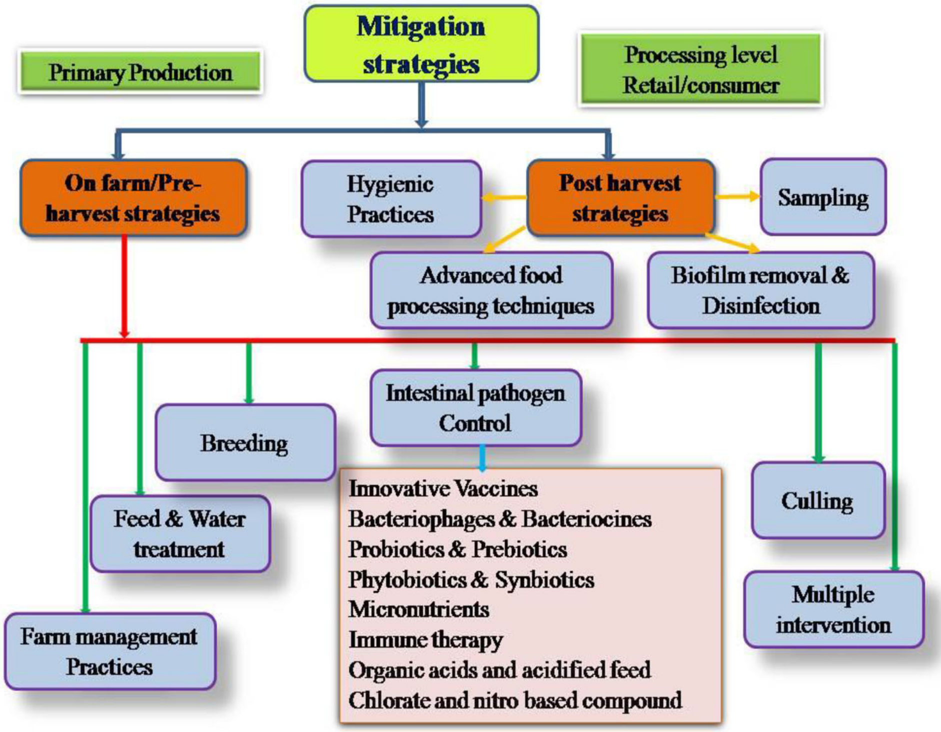

FIGURE 3 Different mitigation strategies at pre- and postharvest levels. *Source*: Doyle and Erickson (2012), Lambertini et al. (2016), and Mendonca et al. (2020)

2.1 | Preharvest or on-farm mitigation strategies

Agriculture, animal, and aquaculture products are susceptible to pathogens at the preharvest stage (Iwu & Okoh, 2019) sourcing from soil, water, air, feed, manure, animal and human waste, workers, on-farm harvesting, handling, and transportation equipment (Biswas et al., 2019; Devane et al., 2018). Preharvest/on-farm mitigation is crucial for the management of agricultural structures, farm, water, and waste operations as a major food safety measure at the farm level (Hoagland et al., 2018). Good agricultural practices (GAPs) and preharvest interventions, such as the application of biocontrol microbes and health monitoring of aqua species, could minimize pathogen introduction (Broglia & Kapel, 2011). There is significant genetic disturbance in economically important traits, as most farmed aquatic species are still wild. The substantial opportunity for genetic improvement of disease resistance and other performance traits as well as success of in vivo genome-editing trials opens exciting new avenues to improve aquaculture production and sustainability. Genome editing using CRISPR/Cas9 (purpose of editing entire broodstock populations to carry the desirable alleles in the germplasm) seems to be a potent technique to accelerate sustainable genetic improvement in aquaculture. Immunity and disease resistance are key target aquaculture traits that have already been investigated using genome editing in Rohu carp and Grass carp, respectively (Gratacap et al., 2019).

2.1.1 | Farm management practices

Preharvest/on farm mitigation techniques include sanitization and disinfection of animal structures with ozone, formaldehyde, glutaraldehyde, quaternary ammonium compounds, chlorine, and acetic acid to eliminate *Salmonella* species (Gosling et al., 2017), *Escherichia*, *Shigella*, *Bacillus*, and *Pseudomonas* (Jiang et al., 2018). Polyhexa methylene biguanide hydrochloride, biguanide, hydrogen peroxide, and quaternary ammonium compounds were applied to disinfect the hatching egg surface, making it 80-100% free from *Salmonella* (Buhr et al., 2013; Cox et al., 2007). Sodium hypochlorite, peroxyacetic acid, lactic and citric acid blend, and lactic acid to poultry carcass for 30 s decreased *Camp jejuni* by 1.2–2.0 log CFU/ml (Li et al., 2017). Spraying of levulinic sodium dodecyl in poultry transport cages reduces pathogens (Zhou et al., 2019). Peracetic acid solution spray reduced Campylobacter and Enterobacteriaceae by 3.6 and 3.8 log CFU/crate base, respectively (Atterbury et al., 2020).

2.1.2 | Water treatment

Contaminated water sources are a major risk factor for pathogen carriage in animals and aquaculture. Chemicals, such as chlorine, chlorine dioxide, organic acid, pectic acid, hydrogen peroxide, lactic acid, caprylic acid, and acidic calcium sulfate, were used to decontaminate

E. coli in the water sources (Zhao et al., 2006). Electrochemical disinfection, electrolyzed oxidizing water and hydrodynamic cavitation were identified as emerging disinfection strategies (Dandie et al., 2020). Chemical-free advanced electric field treatment for water disinfection in pipes caused >6-log inactivation of bacteria with 1 V (Zhou et al., 2020). Side-emitting optical fibers behaving as ultraviolet (UVC) light-emitting diode (LED) light reduced 2.9 log of *E. coli* at a dose of 15 mJ/cm^2 (Lanzarini-Lopes et al., 2019).

2.1.3 | Feed and micronutrient diet formulation

Feed supplements show promising results in pathogen reduction. Decontamination of feed through formaldehyde and propionic acid reduced the *Salmonella* species in feed storage and mills (Ricke et al., 2019). Basal diets supplemented with ferric tyrosine reduced *C. jejuni* counts by 2 $\log_{10}$ in bird caeca (Skoufos et al., 2019). Additionally, ZnO nanoparticles exhibited notable antibacterial activity against *S. aureus*, *E. coli*, *Pseudomonas aeruginosa*, and *Klebsiella pneumonia* bacterial strains in weaned piglets (Wang, Li et al., 2020). Zeolite supplementation of chickens reduced poultry pathogens without disturbing beneficial bacteria (Prasai et al., 2017). Similarly, biochar 2% w/w feed supplements reduced poultry pathogens such as *Campylobacter hepaticus* and *Gallibacteriumanatis* (Willson et al., 2019). Bilberry and walnut leaf additives in feed decreased *Enterobacteriaceae* in laying hens (Popescu et al., 2020).

2.1.4 | Organic acids and acidified feed

Organic acids such as short- and medium-chain fatty acids and monoglycerides have emerged as pathogen deactivators and health improvers in pig production (Jackman et al., 2020). Similarly, the reduction in *Salmonella* spp. and *Campylobacter* against increases in the absorption of essential nutrients in broilers were found using organic acids and acidified feeds (Abdollahi et al., 2020; Nguyen & Kim, 2020). Organic acids showed an enhanced immune system and reduction in pathogens in paglet (Yang et al., 2019).

2.1.5 | Bacteriophages and bacteriocins

Bacteriophages are nonpathogenic viruses that target and infect specific bacteria. They replicate within the host (bacteria) through a lytic, replicative cycle. Bacteriophages appear to be a promising new food safety tool in the poultry industry. This can be applied to both food and the environment. At the preharvest stage, bacteriophages are used as phase therapies, such as antibacterial agents and feed additives, used prior to slaughter for the prevention, treatment and control of bacterial infections. Similarly, at the postharvest stage, it has two applications, that is, food biocontrol (food biopreservatives, food decontamination/safety, direct-on food application, food packaging, etc.), and disinfection (processing aid and decontamination of food contact surfaces, equipment, skin of poultry carcasses, etc.). Bacteriophages act as an alternative to traditional disinfectants for surface sanitization in livestock facilities or slaughterhouses. The application of bacteriophages onto the surface of poultry meat can reduce the contamination of the final product. It has been used for the biocontrol of pathogens in broiler meat (Nafarrate et al., 2020). Most of the studies have used bacteriophage cocktails to reduce pathogen viability by incubating the samples onto the phage solution. The commercial bacteriophage Salmonelex was successfully used to control *Salmonella* in chicken meat (Moon et al., 2020). Similarly, lytic bacteriophages against *Salmonella* spp. (Kim, Kim et al., 2020), MHH6 and PR2 against *E. coli* infection (Ngu et al., 2020), and *Campylobacter*-specific bacteriophages against *Campylobacter* (Chinivasagam et al., 2020) were reported.

Bacteria producing proteinaceous toxins called “bacteriocins” inhibit the growth of some other strains through membrane depolarization. Lactic acid bacteria act as potential probiotics for improving nutrient intake, pathogen reduction and animal immune system stimulation (Vieco-Saiz et al., 2019). Therapeutic use of Colicin/Microcin and Salmocins producing probiotic bacteria against animal pathogens was successfully utilized (Mushtaq, 2020).

2.1.6 | Prebiotics, probiotics, synbiotics, and phytobiotics

Prebiotics reduced *Salmonella* and *Clostridium perfringens* populations in broilers and colitis type symptoms in swine (Khalique et al., 2020). Probiotics such as fructooligosaccharides, isomaltooligosaccharides, lactose, and lactulose act as nondigestible feed, benefiting pathogen reduction in animals. *Saccharomyces*-derived prebiotic refined functional carbohydrates with yeast culture reduced *Campylobacter* in chickens (Froebel et al., 2019). *Lactobacillus casei* and *Lactobacillus plantarum* suppress the activity of *Bacillus cereus*, *Cronobacter sakazakii* and *Alkaliphilus oremlandi* pathogens in cows (Xu et al., 2017). Similarly, *Lactobacillus plantarum 15-1* and fructooligosaccharides reduced *E. coli* and *Salmonella enteritidis* in broilers and laying hens (Adhikari et al., 2019; Ding et al., 2019). *Lactobacillus rhamnosus GG* and *Lactobacillus johnsonii L531* reduced *Salmonella typhimurium* and *Salmonella enterica* in pigs (He et al., 2019; Splichalova et al., 2019). Similar to *Enterococcus faecium*, *Lactobacillus reuteri*, *Bifidobacterium animalis*, *Pediococcus acidilactici*, and fructooligosaccharide, synbiotics reduce the colonization of *Salmonella* and *Clostridium* populations in the carcass and intestine of broiler chickens (Shanmugasundaram et al., 2019; Villagrán-de la Mora et al., 2019).

Phytobiotics are nonnutritive constituents with several biological activities, such as antimicrobial, anti-inflammatory, and transcription-modulating effects. Micciche et al. (2019) reviewed the role of plant-derived essential oils, particularly carvacrol, thymol, and cinnamaldehyde, as phytobiotics that act as effective antimicrobials against *Campylobacter* in the poultry production chain at both the pre- and postharvest levels. Washing broiler chicken skin with a 2% carvacrol suspension reduced *C. jejuni* counts by 2.4–4 log, and this essential oil was suggested as an antimicrobial wash treatment in postharvest poultry (Shrestha et al., 2019). In another study, a commercial mixture of natural antimicrobials comprising lactic acid, citric acid, and citrus extract was effective against *E. coli O157* in vitro and in a model rumen system, and this mixture could be potentially used to control this pathogen in the animal gut (Stratakos et al., 2019).

2.1.7 | Immunotherapy and innovative vaccines

Passive immune protection to animals using antibodies as therapeutic agents manufactured in biological units to avert colonization of specific pathogens (Doyle & Erickson, 2012). Animal vaccination is another measure to manufacture or recover antibodies and prevent pathogens as well as moderate the immune system. Vaccines were developed and tested against *Salmonella* spp. responsible for animal diseases in pig and dairy cattle (Gil et al., 2020) and to decrease *E. coli O157:H7* shedding in cattle (Mir et al., 2019). Recent advances in vaccine development, such as the Live wine against erysipelothrix rhusiopathiae in chickens (Crespo et al., 2019), flagellin-NG34/CS17 against heterologous IV infections in chickens (Sisteré-Oró et al., 2020), and the H5N8 e strain against a clade 2·3·4·4c H5N6 HPAIV in chickens (An et al., 2019), successfully controlled the outbreak.

2.2 | Postharvest management strategies

Hygienic measures, processing, disinfection of food containing pathogens, biofilm removal and sterilization of food equipment, packages are the major postharvest control strategies. Moreover, consumer awareness is crucial throughout the food value chain, for example, at the processing, distribution, sale, retail and consumption levels.

2.2.1 | Hygienic measures

The handling and consumption of meat, blood, and offal from wild animals (bushmeat/wildmeat) are very common. This practice has facilitated the introduction of different pathogens in the human population (Ellwanger et al., 2021). The way to reduce these epidemic events is to limit the interaction of humans with wild animals, mainly with mammals and birds (known to be the critical causes). Risk mitigation at the household level is the foremost important strategy to prevent pathogen contamination or any cross-contamination by practicing hand washing, disinfecting surfaces, cooking foods, sanitizing pet areas, preventing pet contact, practicing safe pet feeding practices, keeping pet food in dry and isolated areas, and keeping children (less than 5 years) away from pet food, feeding areas, and supervision during interactions (Lambertini et al., 2016). Hand hygiene and sanitation must be practiced at agricultural and animal fairs at exiting barns as well as at each step of the food chain to prevent foodborne zoonosis (Lauterbach et al., 2020). In this context, the requirement to comply with strict sanitary rules for meat trading also needs to be extended to all meat trading locations. The probable link between the emergence of SARS-CoV-2 and a wet market in Wuhan city (Hubei Province, central China; Whitworth, 2020) clearly demonstrates the need for the actions mentioned above.

2.2.2 | Advanced food processing techniques

The safekeeping of consumers over the transmission of zoonotic foodborne infectious disease from diseased animal consumption, unhygienic slaughter houses and unscientific processing means has been a deep concern for centuries. The occurrence of foodborne illness outbreaks requires the intervention of advanced novel processing and preservation techniques to mitigate pathogens and fulfill HACCP requirements (Mendonca et al., 2020; Ortiz-Solá et al., 2020). Different techniques for the treatment of pathogens in various food products are reported in Table 3. Advanced disinfection methods include the use of high-pressure processing (HPP), pulsed electric field, ozone, cold plasma (CP), ultrasound (US), UV light, pulsed light, irradiation, supercritical carbon dioxide, organic acids, and nanopackaging to inactivate pathogens (Porto-Fett et al., 2020; Sasikumar et al., 2019). The nonthermal processing technologies escalated their demands in the near past for their promising deliverables of high-quality, convenient foods with natural taste and flavor that are free of chemical additions and preservatives. Physical techniques, such as lasers, radiation, photodynamic therapy, and nonthermal atmospheric plasma, have also been used for disinfection in industrial environments.

High-pressure processing

HPP is one of the most accepted nonthermal technologies and has been successfully implemented in commercial and industrial applications in recent years. A pressure level of 300–600 MPa with a treatment time of 3–10 min at room or chilled temperature can provide a 2–5 log reduction of pathogenic and spoilage microbes in meat and fish products (Boziaris et al., 2021; Chuang et al., 2020). HPP is more suitable for processed meat and fish products than for raw meat and fish (Bolumar et al., 2021). Zagorska et al. (2021) found *S. aureus* (maximum 7 log reduction at 600 MPa/30 min) to be more pressure resistant than *E. coli* and *L. monocytogenes* (maximum inactivation was reached at 550 MPa/15 min) in milk samples. In fruit juice and beverages, HPP is considered the best alternative to traditional thermal processing for extending shelf-life and conserving sensory and nutritional quality (Petrus et al., 2019). Pokhrel et al. (2022) studied the effect of HPP on carrot juice and found that HPP treatment reduced the *L. innocua* pathogen up to a 6 log reduction. In addition to pathogen reduction, carrot blends showed good color with stability up to a 28-day storage period. In commercial fruit juice treatment, pressure up to 600 MPa for 3 min was used to reduce the operating and maintenance costs. Pressure change technology (PCT) and ultrashear technology are new advancements under HPP for the inactivation and stabilization of liquid foods. In PCT, 50 MPa pressure with inert gases is dissolved and diffused in the liquid medium to destroy the cell structure (Vignali et al., 2022). Ultrashear technology is a continuous flow process and can be

TABLE 3 Different advanced processing techniques for the treatment of pathogens in food products

Product	Treatment	Dosage	Pathogen	Log reduction	References
Meat and fish products					
Frozen fish fillets	HPP	250 MPa, 10 min at -32°C	*Listeria monocytogenes* and *Salmonella enterica*	3.5 log CFU/g	Boziaris et al. (2021)
BHI broth, raw and smoked trout	HPP	200 MPa for 15 min, liquid smoke (0.50%, v/v) and freezing (-80°C)	*Listeria monocytogenes*	5 log CFU/g	Ekonomou et al. (2020)
Deboned dry-cured hams	HPP	600 MPa, 5 min	*L. monocytogenes*	2 log (on the surface) and 3 log (interior of hams)	Pérez-Baltar et al. (2020)
Ground chicken meat	HPP	600 MPa for 3 min	*Escherichia coli*	$>6\ \log_{10}$	Xu et al. (2020)
Meatballs	HPP	400 or 600 MPa for up to 18 min	*Escherichia coli*	0.9–3.0 log CFU/g	Porto-Fett et al. (2020)
Frozen chicken breast fillets	HHP	500 MPa, 1 min	*Salmonella* spp.	2	Cap et al. (2020)
Beef	Ozone	218–283 mg O_3/m^3	*L. monocytogenes*	<2 log CFU/g	Giménez et al. (2021)
Turkey breast meat	Ozone	1×10^{-2} kg/m^3 Exposure time: 2–8 h	Mesophilic bacteria	Upto 3 log reductions	Ayranci et al. (2020)
Meat	Gamma irradiation	6 kGy and 8 kGy	*Shigella* spp., *Staphylococcus* spp., *Salmonella* spp., *Vibrio* spp., *Pseudomonas* spp., and *Listeria* spp.	4 (6 kGy), and 6 (8 kGy)	Mrityunjoy et al. (2019)
Ground chicken meat	Gamma irradiation	0.061 kGy/min	*E. coli*	D_{10}- 0.18–0.61 kGy	Xu et al. (2019)
RTE sliced ham	X-ray irradiation	0.2–0.8 kGy	*S.* Typhimurium, *L. monocytogenes*, and *E. coli* O157:H7	5.7, 6.9, and 7.2	Cho and Ha (2019)
Beef	Ultrasound	40 kHz, 11 W/cm^2	*Mesophilic, psychrophilic, Staphylococcus* spp., *and Coliform bacteria*	0.04–0.35 log CFU/ml	Valenzuela et al. (2021)
Chicken meat	Ultrasound	20 kHz and 27.6 W/cm^2; 40 kHz and 10.3 W/cm^2; 850 kHz and 24.1 W/cm^2	Mesophilic, lactic acid bacteria	3.7 (20 kHz) and 2 (40 kHz)	Pinon et al. (2019)
Chicken skin	Ultrasound	(37 kHz, 380 W) and ethanol (0%, 30%, 50%, or 70%)	*S.* Typhimurium	>1 (37 kHz, 30%)	Seo et al. (2019)
Chicken fillet	UV (UVC-254 nm) and pulsed UV light	0.05–3.0 J/cm^2 (10 mW/cm^2, 5–300 s)	*S.* Enteritidis, *L. monocytogenes*, *S. aureus*, enterohemorrhagic *E. coli*, *Pseudomonas* spp., *Brochothrix thermospacta*, *Carnobacterium divergens*, and *E. coli* producing β-lactamase	UV 1.1–2.8 and PUV 0.9–3.0 CFU/cm^2	McLeod et al. (2018)
Caiman meat	UVC	0.005–0.199 J/cm^2	*Salmonella* spp.	Inoculated agar plates (6.72–7.13) and caiman meat (2.47–2.88)	Canto et al. (2019)

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TABLE 3 (Continued)

Product	Treatment	Dosage	Pathogen	Log reduction	References
Goat meat	UVC	100 and 200 μW cm^2, 2–12 min lemongrass oil 0.25%–1% (1%, 200 μW/cm^2, 2)	*E. coli* O157:H7	6.66 CFU/ml	Degala et al. (2018)
Sliced deli meat	UVC LED irradiation	280 nm, 34 s	*E. coli* O157:H7, *S. typhimurium*, and *L. monocytogenes*	1.5–3	Kim and Kang (2020)
Goat meat and beef surfaces	Pulsed UV light	1.27 J/cm^2, 4.47 cm distance, 60 s	*E. coli* K12	1.66 and 1.74 CFU/ml	Bryant et al. (2021)
Dry-cured ham	Pulsed light	8.4 J/cm^2	*Listeria innocua*	1–2 CFU/cm^2	Fernández et al. (2020)
Chicken breast	Cold plasma (atmospheric dielectric barrier discharge)	39 kV and 3.5 min	*Salmonella*, *L. monocytogenes*, *E. coli* O157:H7 and Tulane virus	3.7, 3.5, 3.9, and 2.2	Roh et al. (2020)
Asian sea blass slices	Cold atmospheric plasma (high voltage) and chitooligosaccharide (COS) from squid pen	HVA (90% Ar/10% O_2), 5 min, COS conc. (0.05, 0.1 and 0.2) g/100 g fish slices	*Clostridium perfringens*, psychrophilic bacteria	Not detected	Singh and Benjakul (2020)
			Lactic acid bacteria	3.77–4.37	
			Enterobacteriaceae	4.03–4.50	
			Pseudomonas	6.62–6.82	
			Hydrogen sulfide producing bacteria	5.05	
Chicken breast	HPP and antibacterial	450 MPa (10 min, 4°C) and papaya extract (0.3%, w/w), 3/5 h	*Salmonella*	6 log CFU/g	Chen et al. (2022)
Raw ground chicken meat	HPP and antimicrobial	350 MPa for 4–12 min and allyl isothiocyanate 0.05%–0.075% AITC (w/w) and 0.1% acetic acid (w/w)	*Salmonella*	5–7 log	Chai and Sheen (2021)
Beef patties	HPP and *Lactobacillus acidophilus*	500 MPa for 5 min	Aerobic count	3.35 log CFU/g	Lee et al. (2021)
Chicken meat	HPP and essential oil	350 MPa for 10 min with 0.60% carvacrol	*Salmonella* and *Listeria monocytogenes*	>5 log	Chuang et al. (2020)
Tilapia fillets	HPP and UV radiation	0.103 J/cm^2, and 220 MPa, 10, 25°C 4-day storage	Total aerobic psychrotropic count (TAPC), total aerobic mesophilic count (TAMC), *Enterobacteriaceae* count	3–5 CFU/g	Monteiro et al. (2018)
Chicken breast	Supercritical CO_2 and high-power ultrasounds		Mesophilic bacteria and yeasts and molds	6	Morbiato et al. (2019)
Tilapia fillets	MAP and UV radiation	50% CO_2 and 50% N_2, UV (0.30 J/cm^2)	*E. coli* O157:H7, *S. typhimurium*	UV (1.13 and 0.70) MAP and UV (0.50)	Lázaro et al. (2020)
Chicken meat and skin	Ultrasound and plasma-activated water	800 ms•OH (309 nm), Hα (656 nm), O777 (777 nm), and O (844 nm), 40°C 60 min	*S. aureus* and *E. coli* K12	0.83 and 1.33	Royintarat et al. (2020)
Goat meat	Ozonated and electrolyzed water	0.045% NaCl and tap water, 30 min	*E. coli* K12	1.03	Degala et al. (2020)

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TABLE 3 (Continued)

Product	Treatment	Dosage	Pathogen	Log reduction	References
Beef meat	Aqueous ozone and UVC	Each cycle having a dose of 69 mJ/cm^2 of light and 30 s of ozone spray (concentration of 0.9 ppm), the time between each cycle was 1 h and repeated 10 times	*E. coli*	1.7	Perez et al. (2022)
Poultry meat surface	Organic acid in combination with atmospheric cold plasma (ACP)	Acid concentration: 50 mM ACP: 30 s	*S. Typhimurium*	>2.5	Yadav & Roopesh (2022)
Liquid whole egg (LWE)	Ultrasound and lysozyme	35–45°C, 605–968 W/cm^2, 5–35 min, and with HT 58–64°C, 3–4 min	*Salmonella typhimurium*	4.26 (968 W/cm^2, 35°C, 20 min) and 4.75 (64°C, 3 min)	Bi et al., 2020
Beef, chicken, and pork meat	Antimicrobial photodynamic treatment	Curcumin (40 μM) LED: 450 nm, 55 mW/cm^2 Fluence: 15 J/cm^2	*S. aureus*	Beef: 1.5; Chicken: 1.4; Pork: 0.6	Corrêa et al. (2020)
Dairy products					
Milk	HPP	400–600 MPa for 15–30 min	*L. monocytogenes*, *S. aureus*, and *E. coli*	1.48–7.0	Zagorska et al. (2021)
Milk and whey concentrates	Ozone	3.5 g/L and time 0–60 min	Coliforms, *Enterobacteriacaea*, *Staphylococi*, yeast, and mold	0.6–1 log CFU/ml	Sert and Mercan (2021a)
Skim milk powder	Ozone	3.5 g ozone/h and time 0–120 min	*Staphylococci*, *Enterobacteriaceae*, Coliform, *Clostridium* spp., Yeasts, molds, *Salmonella* spp., *Bacillus* spp., and TAMB	For 120 min. Not detected	Sert and Mercan (2021b)
Bovine milk	UVC	253.7 nm and 18 W	Total mesophilic aerobic bacteria, yeast–mold, *S. typhimurium*, *L. monocytogenes*, *S. aureus*, *E. coli*	2–4 log CFU/ml	Atik and Gumus (2021)
Milk	Blue light	413 nm, 720 J/cm^2, 2 h	*S. aureus*, *E. coli*, *Pseudomonas aeruginosa*, *S. Typhimurium*, and *Mycobacterium fortuitum*	5	Dos Anjos et al. (2020)
Sliced cheese	X-ray irradiation	0.2, 0.4, 0.6, and 0.8 kGy	*E. coli* O157:H7, *S. enterica*, *Salmonella Typhimurium*, and *L. monocytogenes*	5 (0.6 kGy)	Park and Ha (2019b)
Whey dairy beverage	Ohmic heating	3 V/cm, 57.5–60°C for 3.8-4 min	*L. monocytogenes*	2.10	Pereira et al. (2020)
Fruits and vegetables					
Apple	Ozone	51–87 μg/L ozone gas for up to 36 weeks	*Listeria innocua*	5.7 $\log_{10}$ CFU/apple	Sheng et al. (2022)
Fresh-cut durian	Ozone	0–1000 mg/L for 3 and 5 min	Coliform	1.93 log CFU/g	Sripong et al. (2022)

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TABLE 3 (Continued)

Product	Treatment	Dosage	Pathogen	Log reduction	References
Fresh parsley leaves	Ozone and chlorine	12.0 mg/L and 100 mg/L for 5 min at 5°C	*E. coli*	3.2 (chlorine) and 2.2 (ozone)	Karaca and Velioglu (2020)
Spinach leaves	X-rays	0.3 kGy	*E. coli 0157:H7 and L. monocytogenes*	2.83 and 1.32 log CFU/ml	Lim and Ha (2021b)
Blueberries and tomatoes	UV	23–28 mW/cm^2, 254 nm	*Salmonella*	(1.8–2.0) and (2.4–2.9)	Huang and Chen (2020)
Blueberries, grape tomatoes, and iceberg lettuce shreds	Pulsed light (PL) and ultraviolet	0.15 and 0.3 J/cm^2 per pulse; 3 pulses/s), and 13 and 28 mW/cm^2; 1, 2 min	*Salmonella*	4.5–5.7 (blueberries), 4.4–5.4, (grape tomatoes), and 1.9–3.1 (iceberg lettuce)	Huang and Chen (2019)
Apple, tomato, and cantaloupe	Hydrogen peroxide aerosol (cold-plasma activated)	17.62 ml/m^3	*S. typhimurium* and *L. innocua*	3 (cantaloupe) and 1 (tomato)	Song et al. (2020)
Cherry tomatoes	Acidified sodium benzoate	NaB (3000 ppm, pH 2.0) and free chlorine (200 ppm, pH 6.5, 4°C and 21°C)	*E. coli* O157:H7, *S enterica*	4–5 log CFU/g	Chen, Zhang et al. (2019)
			L. monocytogenes	NaB (5.49 log CFU/g) and chlorine (4.98 log CFU/g)	
Blueberry	Chlorine, lactic acid, and chlorine dioxide	100–200 ppm, 2%, 15 ppm	*L. monocytogenes* and *S. Typhimurium*	6.6–7.2	Tadepalli et al. (2019)
Mango	Chlorine dioxide and sodium hypochlorite	(3 and 5 ppm) and (100 and 200 ppm)	*Salmonella*	2.13 (10 min, 5 ppm)	Contreras-Soto et al.
Bell peppers	Chlorine dioxide and sodium hypochlorite	pH 6 and 8	*E. coli* O157:H7	6.58 (ClO_2)	López-Cuevas et al. (2019)
Spinach leaves	Chlorine (100 ppm), lactic acid (0.5%), and acetic acid (0.5%)	4°C, treatment time: 15 min	*E. coli* O157: H7 and *L. monocytogenes*	2.64 and 3.15 (chlorine, 48 h) 3.07 (24 h) and 1.40 (lactic acid)	Chhetri et al. (2019)
Apple	Peroxyacetic acid	80 ppm PAA treatment, 2 min	*L. monocytogenes*	1.7 and 2.6 (46°C)	Shen et al. (2019)
Apple and bell pepper	Spindle and nanometer Krypton–Chlorine Excimer Lamp	222 nm, 5 and 7 min	*E. coli* O157:H7, *S. enterica and S. typhimurium,*	2.0	Kang and Kang (2019)
			L. monocytogenes	4.26 (apple) and 5.48 (bell) after 7 min	
Grape	Plasma-activated water (PAW) and mild heat	55°C, 30 min	*S. cerevisiae*	5.85	Xiang et al. (2020a)
Berry Fruits	Chlorine dioxide (ClO_2)	0.63–4.40 ppm-h/g	Tulane virus	4 (1.25 ppm-h/g)	Kingsley and Annous (2019)
Apple, mandarin, and tomato	Acidic electrolyzed water (mixed with fumaric acid and CaO)		*E. coli* O157:H7 and *L. monocytogenes*	2.85–5.35	Chen, Tango et al. (2019)

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TABLE 3 (Continued)

Product	Treatment	Dosage	Pathogen	Log reduction	References
Carrots	Chlorine dioxide gas (ClO_2) or ozone (O_3)	0.03, 0.06, and 0.12 mg ClO_2/g for 2.5 22 h exposure and 0.04, 0.07, and 0.15 mg ClO_2/g for 5.0 h and 0.86 or 1.71 μg O_3/g for 2 kg sample for 2.5 and 5.0 h	*E. coli* (STEC), *Salmonella enterica*, and *L. monocytogenes*	>7	Bridges et al. (2018)
Fruit juices and beverages					
Concord grape juice	HPP	400 MPa and 2 min	*S. enterica* and *E. coli* O157:H7	5	Petrus et al. (2019)
Coconut water	HPP	593 MPa for 3 min at 4°C	*Salmonella* spp., *E. coli* O157:H7, and *L. monocytogenes*	<1	Raghubeer et al. (2020)
Apple juice	HPP	139 and 561 MPa and from 39 to 181 s	*E. coli* O157:H7, *L. monocytogenes, S. enterica*	>5 (490 MPa)	Petrus et al. (2020)
Carrot juice	HPP	200–400 MPa and 1–5 min.	*L. innocua* (ATCC 51742)	5	Pokhrel et al. (2022)
Apple juice	Gamma irradiation	200, 400, 600, and 800 Gy	*E. coli* O157: H7	>3 (>600 Gy)	Fernandes and Prakash (2020)
Apple juice	X-rays	1 kGy	*E. coli 0157: H7*	5.48–8.02 log CFU/ml	Lim and Ha (2021a)
Cantaloupe melon juice	UVC	13.44 W/m^2	*L. innocua* and *Alicyclobacillus*	3.7 (4032 J/m^2) and 4.7 (16,128 J/m^2)	Fundo et al. (2019)
Coconut water	UV	1142 μE/m^2 and 1919 μE/m^2	*B. cereus* and *Clostridium sporogenes*	5.5	Pendyala et al. (2019)
Coconut water	UVC	40 mJ/cm^2	*E. coli, S.* Typhimurium*, L. monocytogenes*	>5	Bhullar et al. (2019)
Orange juice	UVC	16.8 kJ/m^2, 20 min	*Alicyclobacillus* spp.	>4 CFU/ml	do Prado et al. (2019)
Tangerine–orange juice blend	Ultraviolet (UVC)	1720 mJ/cm^2, 20°C, and 15 min	Combination of *S. cerevisiae*, cocktails of yeasts, and *E. coli*	3.9–4.3	Fenoglio et al. (2019)
Grape juice	Shortwave ultraviolet (UVC)	UVC lamp 254 nm, length 30 or 80 cm, 5.2, 17.1, or 31 ml/s)	*S. cerevisiae*	5–6 (45 min, 17.1, or 31 ml/s)	Antonio-Gutiérrez et al. (2019)
Carrot juice	UV radiation and mild heat	60°C, 3.92 J/ml, 3.6 min	Bacteria, spoilage yeasts, and bacterial spores	5	Gouma et al. (2020)
Coconut water, orange and pineapple juice	Pulsed light	0.18, 2, and 5.6 W/cm^2) and (0–15 s)	*E. coli* (MTCC 433)	4.0, 4.5, and 5.33 (95.2 J/cm^2)	Preetha et al. (2020)
Blueberry juice	Cold plasma	11 kV and 1000 Hz, ionized gas (0%, 0.5%, and 1% O_2 conc.) 2, 4, and 6 min	*Bacillus* sp.	7.2	Hou et al. (2019)
Apple juice	Electrical discharge plasma	21 kV, 30 min	*Zygosaccharomyces rouxii*	5.6	Wang, Wang et al. (2020b)
Orange juice	Thermosonication	47°C, 30 min, and 20 kHz	*Alicyclobacillus acidoterrestris*	1	Wahia et al. (2019)
Khoonphal (*H. ematocarpusvalidus*) juice	Thermosonication	700 W, 20 kHz 31, 26, 21, 16, and 9 min 40, 45, 50, 55, and 60°C	*E. coli* and *S. cerevisiae*	5 (50°C for 21 min)	Sasikumar et al. (2019)
Cashew apple juice	Ultrasound (US) and ozone	373 W/cm^2; 10 min; 40°C and (0.24 mg O_3/ml	Total mesophilic aerobic bacteria, yeasts, and molds	3.3 and 1.2 CFU/ml	Fonteles et al. (2021)

(Continues)

TABLE 3 (Continued)

Product	Treatment	Dosage	Pathogen	Log reduction	References
Orange juice	Ultrasound, photosensitizer, blue light	462 nm	*E. coli* and *Staphylococcus aureus*	4.26 and 2.35	Bhavya and Hebbar (2019)
Apple juice	Gas phase surface discharge plasma with a spray reactor	12, 36, and 60° Brix, 30 min	*Zygosaccharomyces rouxii* LB	3.05–5.60	Wang et al. (2019)
	Krypton--chlorine excilamp and ohmic heating	222 nm, 20 W, 33 V_{rms}/cm (0.3 duty ratio, 500 Hz) 65.9°C 70 s	*E. coli* O157:H7	4.6	Kim, Park et al. (2020)
	Combined HPP and dimethyl dicarbonate	100–600 MPa, 26–194 s, and DMDC (116–250 mg/L	*E. coli* O157:H7, *S. enterica*, and *L. monocytogenes*	5	Petrus, Churey, Humiston et al. (2020b)
	Ultraviolet-A light and fumaric acid	200–400 nm, 0.03 mW/cm^2, 0.1% FA, 30 min	*E. coli* O157:H7, *Salmonella enterica serovar Typhimurium*, and *L. monocytogenes*	6.65, 6.27, and 6.49	Jeon and Ha (2020)
	Ultrasound treatment mixed with fumaric acid	40 kHz, 0.15%, 5 min	*E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes*	5.67, 6.35, and 3.47	Park and Ha (2019a)
	Shear stress and moderate electric field	2879/s^1; 120 V/cm, 50 °C, 7.5 min	*E. coli* K12	5.62	Mok et al. (2019)
	Hyperbaric storage	50 MPa in 30 days, and 100 MPa in 2 days	*Alicyclobacillus acidoterrestris* spores	~5 CFU/ml	Pinto et al. (2019)
	UVC-LEDs irradiation	800 and 1200 mJ/cm^2	*Zygosaccharomyces rouxii*	4.86 and 5.46	Xiang et al. (2020b)
Tomato juice	Photodynamic therapy (erythrosine B, red mediated)	100 W and 0.4 mW/cm^2, 200–1500 nm, 5, 10, and 15 min xenon light (E + L+) and erythrosine photosensitization	*E. coli* O157:H7, *S. typhimurium*, and *L. monocytogenes*	6.77, 2.74, and 6.43 (E + L+, 15 min)	Cho and Ha (2020)
Apple cider	Naringenin (NG) and mega-resveratrol (RV)	RV 8.7 mM and 13.0 mM or NG 7.3 mM and 11.0 mM, 4°C, 14 days	*E. coli* O157:H7	NG (4.5) RV (2.5)	Nair et al. (2020)
Orange, pineapple, watermelon, and a mix	Chitosan powder	1000, 1500, and 2000 μg/ml	*S. typhimurium*, *E. coli* 0157:H7, *L. monocytogenes*, and *S. aureus*	≥5	Omogbai and Ikenebomeh (2019)
Cajá, guava, and mango juices	Mild heat treatment	0.30–0.32 μl/ml, 54°C	*E. coli* O157:H7 and *S. enteritidis* PT 4	≥5	de Carvalho et al. (2019)

operated at high pressures ranging from 20,000–60,000 psi for liquid beverages, sauces, and nanoemulsions. During ultrashear processing, disruption of particles occurs due to shear generated by high pressure, which inactivates microbes and enhances the shelf-life, texture, and organoleptic properties of the processed product (Janahar et al., 2021).

Ozone treatment

Ozone is a form of triatomic oxygen and has been used for several years in water treatment plants. Recently, ozone has gained more focus in the food industry due to its cost-effective, eco-friendly nature, oxidizing power, and antimicrobial activity (Giménez et al., 2021). Pathogen inactivation is caused by highly reactive superoxide and hydroperoxide radicals. Ozone affects the cell wall and membrane with progressive degradation to cellular integrity. Several studies have focused on the utilization of this technique in the meat industry (Khanashyam et al., 2022). Exposure of ozone on beef products shows a 1–3 log reduction against *L. monocytogenes*, *mesophilic bacteria* and *E. coli* K12 (Ayranci et al., 2020, Degala et al., 2020, Giménez et al., 2021). While targeting microbial disinfection, some negative effects, such as discoloration and lipid oxidation, in the meat product were observed (Khanashyam et al., 2022). Therefore, parameter optimization, such as concentration, exposure period and temperature, should be maintained to maintain the overall quality of products. The combination of ozone with freeze-drying and CO treatments has successfully been applied (Cantalejo et al., 2016; Lyu et al., 2016). A study conducted by Sert and Mercan (2021a) reported a reduction in the microbial count in skim milk powder: *Staphylococci* (2.51–1.89 log CFU/g for 60 min), *Enterobacteriaceae* (2.36–1.72 for 30 min), coliform (2.70–1.66 for 90 min), *Clostridium* spp. (not detected—30 min), yeasts and molds (3.09–1.47 for 60 min), *Salmonella* spp. (2.09–1.30 for 30 min), *Bacillus* spp. (1.94–1.12 for 30 min), and TAMB (3.14–1.90 log CFU/g for 60 min). The mentioned microbes were not detected in samples after treatment with ozone for 120 min. Sert and Mercan (2021b) showed effective microbial reduction on milk and whey concentrates with 18.9% and 9.9% decreases in aflatoxin content, respectively. In fruits and vegetables, ozone application is mainly focused on preservation with microbial safety. Sripong et al. (2022) studied the impact of gaseous ozone on the inactivation of microbial contamination of fresh-cut durian fruit and found that coliform and total bacterial counts were reduced by 1.93 and 2.72 CFU/g, respectively, at 900 mg/L ozone for 3 min. In addition, it maintained and enhanced the firmness, color, sensory quality, and antioxidant activity of durian fruit. However, a smaller concentration of ozone (51–87 μg/L) with a longer exposure period (36 weeks) in a controlled atmospheric storage structure with 1-MCP pretreatment reduced *L. innocua* by 5.7 $\log_{10}$ CFU/apple, delaying ripening (Sheng et al., 2022). Ozone gas with a flow rate of 5.6 L/min at a concentration of 7.2 ppm exposed to sugarcane juice for 20 min caused a 3.72 log reduction of aerobic mesophiles and a 2.43 log yeast–mold reduction (Panigrahi et al., 2020).

Cold plasma

Cold plasma (CP) is another new intervention technology being extensively used to achieve desirable inactivation of different microbial species without compromising food product quality. Recently, the role of reactive oxygen species (ROS) in microbial decontamination has been critically inspected as a major focus in the control of infectious diseases. ROS can either eradicate pathogens directly by causing oxidative stress or remove them indirectly via a variety of nonoxidative mechanisms, including T-cell responses, autophagy, and pattern identification receptor signaling. Severe bombardment by CP reactive species provokes surface lesions of the living cells of the microorganism. Its usefulness has applications in raw meat handling/delivery processes and decontamination of food surfaces/packaging materials. The sequential combination of organic acids (i.e., lactic acid or gallic acid) and CP treatment synergistically reduced the *S. typhimurium* cell metabolic activity (Yadav & Roopesh, 2022). The acid treatment alone enhanced the cell permeability (10%–15%), and the subsequent exposure of these permeabilized cells to CP discharge likely augmented the accessibility of plasma reactive species to the cellular membrane. Kaushik et al. (2022) highlighted the potential of CP as a control method against outbreaks of airborne viral infections, such as COVID-19. Plasma technology has been applied to reduce or decimate viral loads in the oral cavity of ventilated patients. The use of plasma-induced oxidation of cysteine is also advocated for modifying SARS-CoV-2 pathogenicity, and it might be administered even via anesthetic masks, feasibly during surgery.

US processing

US is a mechanical sound wave within the range of 20 kHz–100 MHz that propagates in a medium by generating expansions and compressions. This is classified into power (20–100 kHz), high-frequency (100 kHz–l MHz), and diagnostic US (1–10 MHz). Ultrasonic waves produce bubbles or cavities in the given medium, and continuous higher acoustic energy absorption induces the implosion of bubbles releasing higher energy, leading to higher mass transfer, also called the cavitation effect (Pinon et al., 2019). This cavitation effect is favored in disinfection, cleaning, and processing in the food industry. US has been explored in fish and meat products for decontamination of microbes. Valenzuela et al. (2021) investigated the high-intensity US effect on beef muscle against *mesophilic*, *psychrophilic*, *Staphylococcus* spp., *and coliform bacteria*. They found reductions of 0.92, 1.25, ND, and 1.89 log CFU/ml, respectively, after a 9-day storage period. US had minimal effects on pH, color, water-holding capacity, and drip loss. Another study on chicken meat against mesophilic and lactic acid bacteria showed 3.7 and 2 log reductions, respectively, at 40 kHz and 10.3 W/cm^2 (Pinon et al., 2019).

UV light treatment

The application of UV light is well-established in the food industry. UV radiation is also referred to as nonionising radiation within 100–400 nm, and this spectrum is broadly classified into three categories, namely, UVA (315–400 nm), UVB (280–315 nm), and UVC (<280 nm; Hinds et al., 2019). Each wavelength has a specific effect on food materials. In pathogenic reduction, the germicidal wavelength of UVC is used, which damages the DNA of microbes, and UV-A light inactivates the microorganism due to oxidative disturbance (Canto et al., 2019, Hinds et al., 2019). In meat and fish products, UV light is applied, and a propounding effect on the inactivation of microbes and preservation of quality attributes has been found. Canto et al. (2019) studied the effect of UVC light on meat against *Salmonella* spp. The UVC treatment with 0.105–0.199 and 0.065–0.199 J/cm^2 showed 6.72–7.13 and 2.47–2.88 log CFU/g of *Salmonella* spp. in inoculated agar plates and caiman meat, respectively. Higher doses had a negative impact on color and lipid oxidation in caiman meat. Similarly, UVC radiation showed high efficiency against *S. Enteritidis*, *L. monocytogenes*, *S. aureus*, *enterohemorrhagic E. coli*, *Pseudomonas* spp., *Brochothrix thermospacta*, *Carnobacterium divergens*, and *E. coli* producing β-lactamase in chicken fillet (McLeod et al., 2018) and *E. coli* O157:H7 in goat meat (Degala et al., 2018). In bovine milk, UVC treatment reduced 2–4 log CFU/ml of total mesophilic aerobic bacteria, yeast mold, *S. typhimurium*, *L. monocytogenes*, *S. aureus*, and *E. coli*. Some challenges associated with UVC are low penetration and a negative impact on sensory properties, which can be overcome by designing a special UVC reactor with parameter optimization (Atik & Gumus, 2021). Likewise, UVC treatment of fruits, vegetables, and fruit juices was investigated. It showed high efficiency against *Salmonella* inactivation in blueberries and tomatoes (Huang & Chen, 2019). In cantaloupe melon juice, UVC was effective against *L. innocua* and *Alicyclobacillus* (Fundo et al., 2019), *B. cereus*, *Clostridium sporogenes*, *E. coli*, *S. Typhimurium*, and *L. monocytogenes* in coconut water (Bhullar et al., 2019; Pendyala et al., 2019), *Alicyclobacillus* spp. in orange juice (do Prado et al., 2019), *S. cerevisiae*, cocktails of yeasts and *E. coli* in tangerine–orange juice blend (Fenoglio et al., 2019), and *S. cerevisiae* in grape juice (Antonio-Gutiérrez et al., 2019) without significant effect on acidity, pH, soluble solids and color.

Pulsed light treatment

Pulsed light is an advancement in the UV delivery system for decontamination using high energy 0.01–50 J/cm^2 (1–20 flash/s; 200–1100 nm) for a short time. Compared with UV light, pulsed light has higher penetration and emission power with a lower build of temperature and is more effective for decontamination with lower changes in sensory attributes (Bryant et al., 2021; Hinds et al., 2019). The efficiency of pulsed light on the inactivation of microbes is well-established. Bryant et al. (2021) investigated the use of pulsed light against *E. coli* K12 on goat meat and beef surfaces and found 1.66 and 1.74 log CFU/ml reductions at 1.27 J/cm^2 for 60. A pulsed light dose of 95.2 J/cm^2 showed maximum log reductions of 4.0, 4.5, and 5.33 against *E. coli* (MTCC 433) in orange, pineapple juice, and tender coconut water, respectively. Pulsed light is more effective for transparent juices than for cloudy juices (Preetha et al., 2020). UV light (mercury vapor lamps) and pulse light (xenon lamps) are means to inactivate microbes in food products, but the possibility of contamination along with the life span of lamps becomes a major problem in the food industry. LEDs are another advancement in UV light and have several advantages over conventional sources, such as a high life span, less energy consumption, and lower emission. Dos Anjos et al. (2020) investigated the effect of blue light in milk on the inactivation of *S. aureus*, *E. coli*, *P. aeruginosa*, *S. typhimurium*, and *Mycobacterium fortuitum* and achieved an approximately 5 log reduction using 720 J/cm^2 for 2 h of treatment time. An in vitro study by Inagaki et al. (2020) demonstrated that irradiation with a deep UV LED (DUV-LED) of 280 ± 5 nm wavelength rapidly inactivated SARS-CoV-2 obtained from a COVID-19 patient. They further outlined that the development of devices equipped with DUV-LEDs is expected to prevent virus invasion through the air and after touching contaminated objects.

With the emergence of antibiotic- and antifungal-resistant microorganisms, antimicrobial photodynamic treatment (aPDT) has been developed as an innovative microbial control strategy owing to its multitarget mode of action. This is a light-based method wherein a photosensitizer (PS), when illuminated with adequate light in the presence of oxygen, the results in the generation of abundant ROS that further react with multiple targets within microbial cells, eventually causing viability loss with research evidence of up to eight log cycle pathogenic cell reduction. Although still in a conceptualized state, the application of aPDT is already gaining immense attention in many different agri-food products and associated processes, including food production, industrial processing, storage, retail, and distribution (Prado-Silva et al., 2022). The use of natural compounds as PSs against foodborne microbes is an interesting approach to aPDT since compounds such as chlorophyllin, curcumin, hypericin, and riboflavin have been approved as food additives. Huang et al. (2020) applied aPDT with curcumin as a PS and blue LED (fluence of 0.54 J/cm^2) for photodynamic inactivation of *L. monocytogenes*. A recent publication showed that global-priority multidrug resistant microorganisms (including *E. coli*, *S. aureus*, *E faecium*, *P. aeruginosa*, and *Enterococcus fecalis*) are easily killed by aPDT with MB (a phenothiazinium dye) and red light (Sabino et al., 2020). Acidified curcumin at 10 mg/L was pulverized by conventional spray-atomization or aerosolization on the inoculated surface of spinach, lettuce, and tomatoes before UV-A irradiation. A reduction of approximately 3 log CFU/cm^2 by either of the techniques in *E. coli* and *L. innocua* populations was observed (de Oliveira et al., 2018). Simmons et al. (2021) determined the effectiveness of a pulsed-xenon UV (PX-UV) disinfection system in reducing the SARS-CoV-2 concentration on hard surfaces and N95 respirators. This proved the ability of PX-UV devices to minimize the environmental and personal protective equipment bioburden and improve both healthcare worker and patient safety, hence reducing the risk of exposure to viral pathogens.

Irradiation

The application of ionizing irradiation to various food commodities to improve microbial safety and product quality and ensure food preservation is an emerging technology in the industrial food sector (Mrityunjoy et al., 2019). Food irradiation has very diverse applications, from inhibition of sprouting to extending the shelf-life of meat, fish, egg, seafood, fruits and vegetables, milk and dairy products, and so on (Cho & Ha, 2019; Pi et al., 2021). Food irradiation includes high-energy gamma rays, accelerated electron beams, and X-rays. Minimal processing of fruits and vegetables by irradiation is the most promising commercial approach aiming to reduce decontamination and food-borne pathogens (Fernandes & Prakash, 2020). DNA molecules are damaged when exposed to ionizing radiation, thus causing cell injury and death. Virus is the most resistant to irradiation, while molds and vegetative bacteria are the least resistant. The quantity of does varies from 2.0 to 4.8 kGy to inactivate the biological material (Bisht et al., 2021; Pi et al., 2021). Ayranci et al. (2020) studied the effect of gamma radiation on meat against *Shigella* spp., *Staphylococcus* spp., *Salmonella* spp., *Vibrio* spp., *Pseudomonas* spp., and *Listeria* spp. The irradiation dose of 8 kGy reduced 6 log pathogens in the meat sample. Cho and Ha (2019) concluded that sliced ham treated with 0.8 kGy X-ray irradiation reduced *S. Typhimurium*, *E. coli*, and *L. monocytogenes* by 5.7, 7.2, and 6.9 log CFU/g, respectively. Irradiation treatment for meat and fish products may reduce the risk of inflammatory bowel diseases and urinary tract infection (Xu et al., 2019). Similarly, irradiation effects were studied in dairy products. Cheese treated with 0.6 kGy X-ray irradiation had 5 log reductions of *E. coli* O157:H7, *S. enterica*, *S. typhimurium*, and *L. monocytogenes* without altering textural and color attributes of products. Likewise, irradiation treatment of fruits, vegetables, and fruit juice was investigated. X-ray and gamma irradiation had high efficiency against pathogenic microbial inactivation in spinach leaves (Lim and Ha, 2021b) and apple juice (Fernandes & Prakash, 2020; Lim & Ha, 2021a) without affecting pH, TPC, and color. Afrough et al. (2020) demonstrated strong evidence of X-ray irradiation being effective for the inactivation of zoonotic viruses belonging to the medically important families of Flaviviridae, Nairoviridae, Phenuiviridae, and Togaviridae.

Other postharvest treatments adopted mainly for decontamination of fresh produce include irradiation, gas phase treatment (fumigation with potent antimicrobial gases (C_2H_4O, ClO_2, ozone), advanced oxidative processes (hydroxyl radicals generated from ozone or hydrogen peroxide) and disinfection using chlorine, ethanol, organic acids, electrolyzed water, and so on (Bridges et al., 2018; Song et al., 2020). Heat shock, US, natural and chemical antimicrobial agents (as disinfectants), bacteriophages, and so on, can help inhibit the formation of biofilms (Salaheen et al., 2015). These methods (e.g., manothermosonication) used in synergy popularly known as "hurdle technology" have shown significant pathogenic destruction, as discussed below.

Hurdle technology

Hurdle technology is defined as a combination and intelligent use of existing preservation techniques by putting microbes in a hostile environment to create homeostasis, metabolic exhaustion, stress reactions, and multitarget preservation in food. The limitation associated with different inactivation techniques leads to the development, optimization, and adoption of hurdle technology in the food processing sector to improve food safety along with the nutritional and sensory attributes of food products (Aaliya et al., 2021). The use of HPP with other techniques reduced the required pressure and treatment time with less adverse effects on the quality of meat and fish products than the use of HPP only. Along with HPP, other effective treatment means, such as refrigeration, the use of nitrile, sodium lactate, and smart packaging can enhance the storability of meat and fish-based products for a longer period (Chai & Sheen, 2021). High pressure in combination with liquid smoke, freezing, papaya extract, allyl isothiocyanate, carvacrol, acetic acid, nisin, and UV showed 5–7 log reduction of *S. enterica*, *E. coli*, and *L. monocytogenes* (Chai & Sheen, 2021; Chen et al., 2022; Chuang et al., 2020; Lee et al., 2021). The combination of HPP and UV radiation was investigated in tilapia fillets for decontamination efficacy. HPP and UV radiation (220 MPa for 10 min at 25°C and 0.103 J/cm^2) reduced the total aerobic psychrotrophic count, total aerobic mesophilic count, and Enterobacteriaceae count by 3–5 CFU/g (Monteiro et al., 2018). Fonteles et al. (2021) studied the combined effect of US and ozone on cashew apple juice. US alone cannot reduce the microbial count, but combined treatment shows reductions of 3.3 and 1.2 CFU/ml for total mesophilic aerobic bacteria and yeasts and molds, respectively. The treated juice is microbiologically stable for 30 days with higher flavonoid content and little degradation of vitamin C. Likewise, supercritical CO_2 and high-power USs were applied in chicken breast against mesophilic bacteria and yeasts and molds for 6 log reduction (Morbiato et al., 2019); MAP and UV radiation in tilapia fillets against *E. coli* O157:H7 and *S. typhimurium* for 1.13 and 0.7 log reduction (Lázaro et al., 2020); US and plasma-activated water in chicken meat and skin against *S. aureus* and *E. coli* by 0.83 and 1.33 log reduction (Royintarat et al., 2020); ozonated and electrolyzed water in goat meat against *E. coli* K12 by 1.03 log reduction, aqueous ozone and UVC in beef meat against *E. coli* by 1.7 log reduction (Perez et al., 2022); organic acid in combination with atmospheric CP (ACP) in poultry meat surface against *S. typhimurium* by >2.5 log reduction (Yadav & Roopesh, 2022); US and lysozyme in liquid whole egg against *S. typhimurium* by 4.26 log reduction (Bi et al., 2020). US and ozone in cashew apple juice against total mesophilic aerobic bacteria, yeasts and molds by 3.3 and 1.2 CFU/ml (Fonteles et al. 2021); US, PS, blue light in orange juice against *E. coli*, and *S. aureus* by 4.26 and 2.35 log reduction (Bhavya & Hebbar 2019); krypton--chlorine excilamp and ohmic heating against *E. coli* in apple juice by 4.6 log reduction (Kim, Park et al., 2020) and many more. Similarly, various combinations of advanced techniques have successfully been applied in apple juice, such as UV-A light and fumaric acid (Jeon & Ha, 2020), combined HPP and dimethyl dicarbonate (Petrus et al., 2019), US treatment mixed with fumaric acid (Park & Ha, 2019a), shear stress and moderate electric field (Mok et al., 2019), and UVC-LED irradiation (Xiang et al., 2020b).

2.2.3 | Retailing, handling, and distribution of food

Contamination of pathogens occurs at any stage of the food system. Proper handling and management after postprocessing is necessary to put off any contamination or outbreaks during distribution, retailing and at the consumer level. Good cooking and kitchen management practices, the use of sanitizers and disinfectants, hand washing and sanitation, and cleaning utensil will reduce accumulation, growth, and cross-contamination.

3 | DETECTION, RISK ASSESSMENT, SURVEILLANCE, AND MONITORING OF PATHOGENS

Rapid identification of the route of infection and targeted detection of causative organisms are crucial for the control of foodborne outbreaks. The source can be investigated using various detection methods illustrated in Figure 4. Conventional culture methods, including colony count estimation, usually have the chance of underestimating the pathogen number owing to the presence of viable but nonculturable microorganisms (Gilmartin & O'Kennedy, 2012). With immunological techniques, reagent specificity, process complexity and optimization of the use of antibodies always remain critical issues (Shanker et al., 2014). Such limitations urge more sensitive molecular-based assays for the quick detection of pathogens, such as next-generation sequencing (NGS), quantitative and digital polymerase chain reaction (qPCR and dPCR), immunomagnetic separation assays, florescence in situ hybridization (FISH), DNA microarrays, direct epifluorescence filter techniques, latex agglutination tests, and flow cytometry (Dhama et al., 2013; Habtamu et al., 2011). An extensively used application of NGS is whole-genome sequencing (WGS), an analytical approach being exploited in determining the whole genomic sequence of an organism, foodborne pathogen routine monitoring and surveillance, tracing contamination sources, demarcating transmission routes in the farm-to-fork continuum and assimilating genomic data into microbiological risk assessment (EFSA and ECDC, 2018).

On-site cost-effective rapid analytical detection techniques are a new challenge over classic methods. Combinations of chemical engineering, biosensors, microfluids, and nanotechnology have promising potential (Azinheiro et al., 2020). Nanomaterials have the advantage

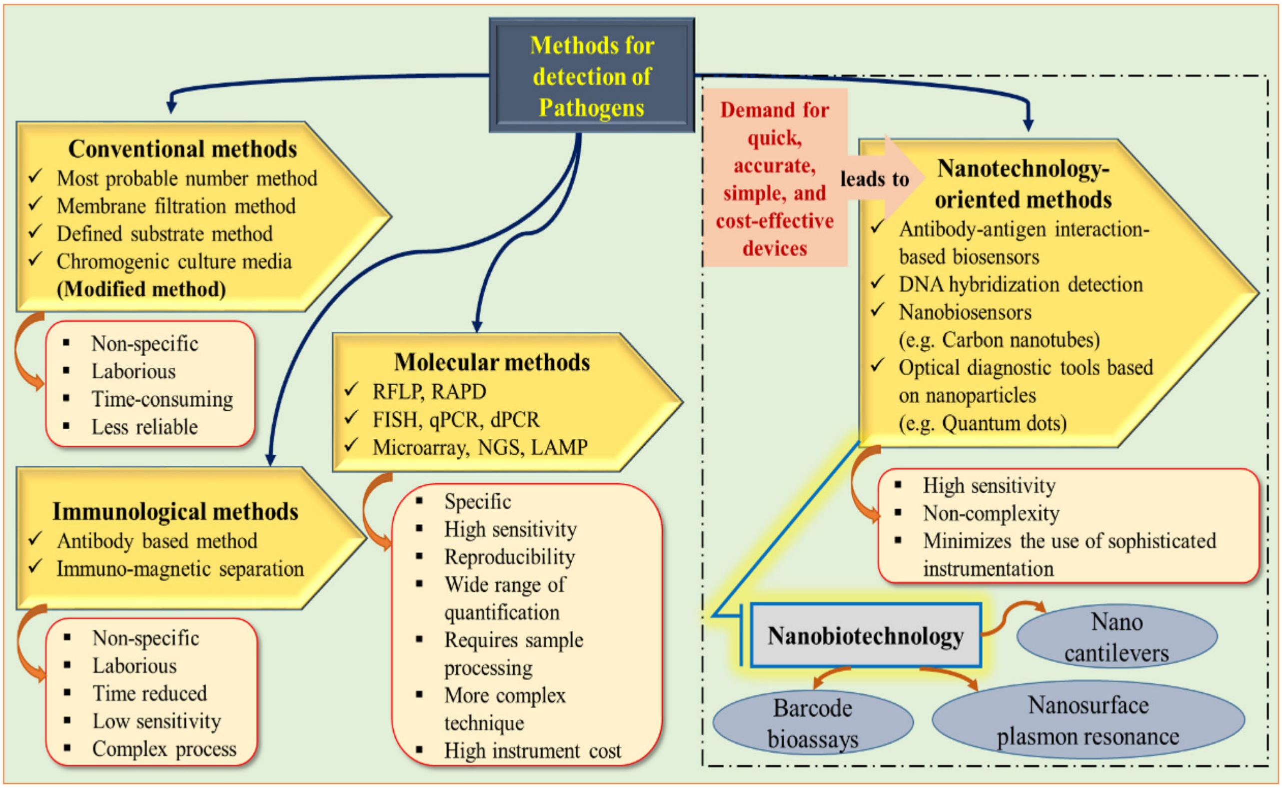

FIGURE 4 Methods for the detection of pathogens. *Source*: Shanker et al. (2020)

of a large surface area, allowing numerous biomolecules and reaction sites to interact with a target species. This property coupled with the superior optical and electronic properties of nanomaterials enables the development of sensitive nanobiosensors with improved response times for accurate detection (Sahoo et al., 2021). The electrical properties of the Au NPs were harnessed for the development of a piezoelectric biosensor for "real-time" detection of a foodborne pathogen, *E. coli* O157:H7 (Gilmartin & O' Kennedy, 2012). Nanoparticles have been used to eliminate *E. coli* and *Campylobacter* from poultry products (Manuja et al., 2012). In milk samples, *L. monocytogenes* was detected using magnetic nanoparticle-based immunomagnetic separation coupled with real-time PCR (Shanker et al., 2020). A fluorescent barcoded DNA assay based on two nanoparticles was invented for the rapid identification of *S. enteritidis*. A hand-held chip based on a nanosensor detected *cytochrome b* genes in animal foods (Zhang et al., 2009).

4 | CONCLUSIONS AND PREVENTIVE CONTROL MEASURES

The emergence and transmission of zoonotic pathogens through the food system is under the frontline of global awareness, of which SARS-CoV-2 is the latest alarming example to think. The COVID pandemic advocates for the design, planning and policy making, monitoring, enforcement and intervention of safety measures to safeguard against any future biosecurity threats and global emergence. A proactive-response strategy with the involvement of local governance, health experts, economic experts, food policy and security and the political community could reduce the emergence of infectious disease threats by strengthening global food, nutrition, and socioeconomic security. Real-time traceability by improving quick response time and accuracy in the obtained data across each and every stage must be combined with transparent communication to the decision makers to minimize the transmission and break the cycle. Policy makers must pay attention to planning and prioritizing action, as the occurrence of events such as foodborne zoonotic pathogens and food safety are progressively related to globalized food systems. The serious impact of the current COVID-19 situation and its widespread impact on the food system will provide the sensitivity, encouragement and opportunity to policy makers, decision makers, producers, consumers, and every segment of the supply chain to focus on reorganizing and restructuring the food system for delivery to the global population. Recent outbreaks provide another reason to think outside the box to update the food supply chain from farm to fork. A top-down stringent approach is needed to produce safe fresh fruits and vegetables, meat and dairy products free from infectious pathogens, preventing food hazards and any foodborne outbreaks. Prevention and control of pathogens is not easy. However, some essential measures could be effective in reducing the contamination risk and crucial to be implemented in farms and processing centers (Heredia & García, 2018): (1) hygienic management practices and sorting out sick animals, (2) precautions at both the farm and processing levels, (3) carefully organized measures, including animal testing and widespread domestic and wildlife vaccination, (4) chilling after slaughtering of animals, (5) animal health education, (6) application of phyto-nutrient rich feed and antibiotics, (7) advanced processing techniques in food processing, (8) proper cooking, cleaning and sanitization practices in the kitchen, (9) shun cross-contamination and raw or undercooked consumption of animal products, and (10) regular inspection, monitoring and sampling of products. Timely diagnosis and response to emerging infectious agents requires a collaborative, coordinated, interdisciplinary, responsible, cross-sectoral strategy by ministries and institutions involved in trade, health and agriculture at regional, national, and global levels. Robust effective safety interventions and rigorous implementation throughout farm and domestic level, processing, packaging, and distribution systems will certainly generate safe food and a healthy world.

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CONFLICT OF INTEREST

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