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Ionizing Radiation for Quality Control and Mitigating Microbial Contamination and Mycotoxins in Pet Foods

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ABSTRACT

The increasing demand for safe and high-quality pet foods has intensified the pursuit of sustainable preservation techniques. Pet food recalls are often linked to pathogenic contaminants like *Salmonella, Escherichia coli, Campylobacter*, molds, and mycotoxins, persisting globally. Ionizing radiation has proven to be effective in mitigating microbial contamination and decontaminating mycotoxins, while minimizing the loss of food quality. However, no research or review articles have been pub
lished in this regard, emphasizing the novelty and originality of this review. This review provides recent insights into research findings on irradiation methods and their potential to sterilize and disinfect pet foods, addressing pathogens and mycotoxins with minimal impact on quality attributes. Additionally, the critical control points in various pet food manufacturing processes, preventive measures, and factors affecting irradiation for pet foods are reviewed. The insights provided in this review underscore the significance of adopting ionizing radiation as a viable and sustainable preservation technique in the pet food industry.

KEYWORDS

Ionizing radiation; pet foods; mycotoxins; microbial contamination; quality

Introduction

The pet food industry has exhibited significant global growth due to the rising preference for commercial pet foods as convenient and economical choices to meet pet nutritional needs.[1–4] Conversely, pet food recalls remain a global concern, caused by foodborne illnesses and frequent mycotoxin outbreaks linked to the consumption of contaminated commercial pet foods.[5–7] Ensuring pet food ingredients are free from contaminants, specifically disease-causing pathogens, toxins, antibiotic residues, and pesticides is vital for food safety and health.[7]

Pathogens, including *Salmonella* spp., *Escherichia coli, Campylobacter* spp., *Listeria monocytogenes*, and *Yersinia* spp., are predominantly associated with pet foodborne illnesses.[8,9] Consequently, strict quality control and inspection are necessary to mitigate potential contaminants. Thermal treatments like extrusion and sterilization are key to preventing pathogen entry in pet food processing.[10,11] However, subsequent processing and/or storage can encourage microbial growth, leading to foodborne pathogens in pet foods. This risk can be reduced with both thermal and non-thermal methods.[12] While thermal techniques are effective in reducing pathogens, they may deteriorate the final products' nutritional and sensory qualities and are ineffective against heat-resistant mycotoxins.[13,14] Thus, non-thermal preservation methods – cold plasma, UV radiation, pulsed

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light, and ionizing radiation – are emerging as effective alternatives to enhance food safety in the pet food industry while minimizing losses in physicochemical attributes.[15–17]

Among various non-thermal treatments, ionizing radiation demonstrates excellent capabilities in reducing biological and chemical hazards in foods, including mycotoxins.[18] Food irradiation – the controlled application of ionizing radiation energy – such as gamma rays, electron beams, and X-rays.[19] Consequently, irradiation technology is applicable to different commodities and has gained increasing attention in the pet food industry.[20] Studies confirm that irradiation at an average dose of 10 kGy poses no toxicological hazards or nutritional risks to food commodities.[21,22] Furthermore, gamma ray and electron beam irradiation have demonstrated superior performance compared to other physical and chemical treatments for decontaminating mycotoxins in cereal-based ingredients.[23–25]

The effects of irradiation on pet food vary with ingredient composition, processing methods, and packaging materials/methods used. While it effectively eliminates pathogens like *E. coli* and *Salmonella*, it may cause certain nutrient losses, such as thiamine, and alter the taste and texture of the food.[8,26] The complexity of pet food formulations, including by-products, bones, and offal, complicates the understanding of irradiation's effects on shelf life and safety.[27] Despite its widespread use in human food processing, research on irradiation in pet food remains limited, especially regarding the effects of different radiation sources and doses on microbial reduction, nutrient retention, and packaging interactions in various pet food formulations.[22,28]

Packaging materials play a crucial role for pet food safety, yet the effects of irradiation on packaging and pet food physicochemical properties during extended storage are largely unexplored.[29] While adopting irradiation in pet food processing can indirectly protect pet owners by reducing zoonotic pathogen transmission, its specific impact on human health remains understudied. Pet owners are increasingly concerned about the health risks of commercial pet food.[30] While irradiated food is generally considered safe for humans, its effects on pets are still unclear. Providing evidence of the benefits of irradiated pet food can help meet the growing demand for natural and healthier options.

The limited research on the effectiveness of irradiation for microbial reduction and mycotoxin decontamination highlights a critical gap in pet food safety. Our review aims to explore the role of various irradiation sources and dosage levels in sterilizing pathogens like *Salmonella, E. coli*, and *Listeria* while assessing its impact on pet food quality. Additionally, the lack of effective decontamination protocols for mycotoxins, particularly aflatoxin B1 (AFB1), contributes to the ongoing issue of pet food recalls.[18] The review is crucial for developing strategies to reduce mycotoxins in pet foods, thereby ensuring consumer trust. Moreover, the limited understanding of irradiation's impact on pet food nutrition highlights the need for research to preserve essential nutrients while meeting pets' nutritional needs.

Moreover, irradiation conditions for human food and animal feed are separately well-established, but guidelines for pet food are lacking due to variations in ingredient composition and nutritional requirements compared to them. This review addresses this gap by evaluating the effects of ionizing radiation in reducing pathogens and mycotoxins like AFB1, nutrient retention, and ensuring safety and quality in pet food.[18,21] However, there is a lack of information regarding the application of irradiation for decontaminating pet foods and its impact on physicochemical attributes. Therefore, this study comprehensively reviews the potential of irradiation to uphold the safety and quality of pet foods.

Market trends and cost analysis in the pet food sector

The global pet food market reached 103.3 billion USD in 2023 and is projected to grow at a compound annual growth rate (CAGR) of 4.4% from 2024 to 2030, reflecting sustained industry expansion.[31] In 2025, the United States led pet food revenue at 61.83 billion USD, significantly surpassing China, and United Kingdom.[32] The global pet food market is expected to surpass 195 billion USD by 2029, driven by the increasing rate of rising pet ownership worldwide.[32,33] The increasing trend of pet humanization – treating pets as integral family members – has fuelled demand for high-quality, and nutritionally balanced pet foods.[34,35] To satisfy evolving consumer expectations, manufacturers are shifting toward clean-label formulations, eliminating contaminants like pathogens and heavy metals.[36] Concurrently, the market has experienced a notable expansion in raw pet food production, highlighted by a five-fold rise in manufacturing plants from 2011 to 2017.[37] As health-conscious pet owners seek safer and more sustainable food options, this trend is prompting pet food companies to adopt advanced safety measures like irradiation, ethical sourcing, and ingredient transparency, to align with changing market demands.[38] Irradiation is increasingly recognized as an effective method to inactivate pathogens while preserving nutritional integrity, supporting the industry's transition toward minimally processed, preservative-free formulations.

Ionizing radiation offers excellent safety advantages for pet foods, however its implementation comes with considerable costs. Establishing an irradiation facility requires a large initial investment for procuring equipment and building installation, which accounts for 40% of the equipment purchased cost.[39] Ongoing operating expenses, including maintenance, labor, supplies, utilities, insurance, and overhead, are based on the total capital investment.[39,40] The costs vary depending on the irradiation method used, for instance, Cobalt-60 decays at a rate of about 1% each month, leading to an annual replacement cost equivalent to 12% of the original supply, whereas electron beam and X-ray methods avoid this issue. Similarly, the utility cost is calculated based on a 5% lamp efficiency, with the UV lamp lasting 3,000 hours of operation.[39] Despite the high costs, it enhances regulatory compliance and consumer trust by reducing microbial contamination by up to 99.9%, making it a preferred choice for premium pet food products.

Potential risks in pet food safety

Manufacturing of pet foods

Dry pet food

Dry pet food comprises complex mixture of grain flours, vegetable flours, rendered animal protein meal, animal and vegetable fats, and flavorings.[41] The initial step in the manufacturing process involves forming a dough through the blending of both dry and wet ingredients (Fig. 1). Prior to mixing, the dry ingredients are ground to create coarse flour, facilitating subsequent processing steps. Liquid ingredients are added with hot water to partially melt the existing fat.[42] This liquefied mixture is then poured onto the dry ingredient in the pre-conditioner, a closed vessel which maintained at about 98°C. Steam is injected into the system for an average of 60–110 sec until reaching the moisture level and consistency suitable for extrusion process.[11] Subsequently, the mixture is injected into a high-pressure (34–37 atm) and high-temperature (125–140°C) extruder.[11] The extrusion process serves to destruct viable spores and vegetative cells, as well as eliminate anti-nutritional components such as trypsin inhibitors found in legumes and vegetables.[10] According to Tran et al.[43] the extrusion step enhances the digestibility of pet foods through starch gelatinization and protein modification. Further, the process contributes to bringing the water content to 25%. Following extrusion, the cooked product is forced through a die at the edge of the extruder, where it is cut to the desired length by a knife to produce kibbles. These kibbles then pass through a forced air convection conveyor dryer (entrance temperature: 120–125°C; exit temperature: 38°C) for 15–20 min to achieve the finished product moisture level of 9–10%.[2] Reducing moisture content is crucial for maintaining the freshness and inhibiting bacterial growth and mold formation. It is noteworthy that non-uniform moisture and drying conditions may create favorable conditions for the growth of pathogenic microorganisms.[11]

Once dried, kibble is coated with liquified animal fat and flavorings to improve its appearance and palatability. The coating agent is maintained at approximately 49°C and sprayed on the kibble, mixed in the drum for about a min, and then cooled. This step is considered a potential contamination or a critical control point in the manufacturing process

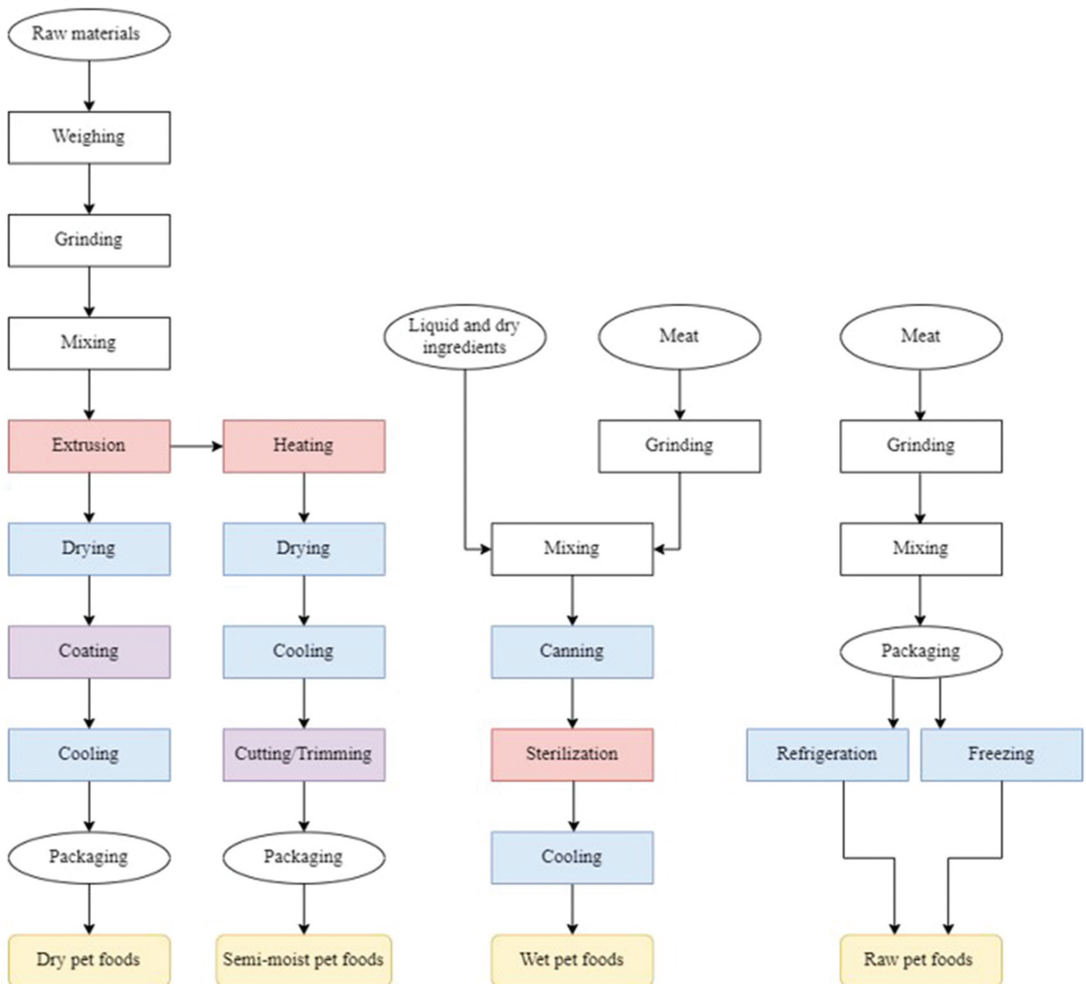

Figure 1. General manufacturing flow of different types of pet food.
Bacterial reduction, Microbial growth, Recontamination

of extruded pet foods.[43] The finished products are typically packed in plastic bags and stored at room temperature. Dry pet foods are the most common form in the pet food market, preferred by pet owners due to their long-term storage capability without the need of refrigeration.[10] However, it is attributed to low energy content, relatively poor palatability, and having hard and brittle structures.[2]

Semi-moist pet food

The manufacturing process of semi-moist pet foods closely resembles that of dry pet foods. It consists of meat or meat by-products, or a combination of meat and vegetable proteins, possibly combined with dry food compositions. This mixed composition ensures complete and balanced diets for pets while enhancing palatability through a pleasing texture. The production begins with the size reduction of dry ingredients. Finely-ground dry ingredients and liquid components are mixed and transferred to the pre-conditioning step, where the blend undergoes mixing, heating, and hydration via hot water or steam injection (Fig. 1). This process is essential for maintaining the moisture content at the optimum level, about 10–30%, required for the extrusion step.[44] Importantly, proper mixing of ingredients at this stage is necessary for ensuring product uniformity in semi-moist pet food production.[45]

The preconditioned materials are then moved to extrusion step, where they are cooked at 85–105°C for about 2 min and subsequently cut into pieces by a spinning knife at the edge of the extruder. The end product is cooled to room temperature (20°C) to achieve a soft texture with an optimum moisture level. Unlike dry pet foods, drying is not necessary after extrusion in order to maintain a higher moisture content in semi-moist pet foods.[43] Additionally, humectant and edible acids are often added before or during preconditioning to control the water activity and maintain the desired pH (5.0–5.5) in semi-moist pet foods.[44]

Semi-moist pet foods are convenient to feed, easy to store, and notably more palatable than dry pet foods. However, extended storage of semi-moist pet foods, even for a month, may lead to reduction in soft texture, resulting in lower palatability, reduced shelf-life, and decreased pet animal's satisfaction.[44]

Wet pet food

Wet pet food, also known as "canned" or "moist" pet foods, consists of commercially sterilized, low-acid products presented in formats resembling stews and pâtés in appearance. Its main components include fresh meat and meat by-products, namely, lung, liver, spleen, stomach, ground bone, meat trimmings, chicken trimmings, and fish trimmings.[46] The inclusion of fresh meat enhances the cohesiveness of mass characteristics in wet pet foods, attributed to the improved binding properties of meat fibers in fresh meat.[47]

The production of wet pet food involves pre-processing fresh meats, where the meat is initially cut into suitable-sized chunks ranging from 50–100 mm. These chunks are subsequently coarsely ground to 10–25 mm in size and further processed through grinding to produce meat particles ranging from 0.5–2 mm in size.[46] Simultaneously, the gravy for wet pet food is prepared in a separate vessel equipped with a high-speed agitator (Fig. 1). The gravy consists of approximately 87–90% water, with the remaining proportion comprising gelling and thickening agent, emulsifiers, starches, and colorants.[48] To prevent clump formation when these ingredients are mixed with water, steam is injected into the vessel, overcoming the potential impermeable cover formation. High-speed agitation ensures that each solid particle is surrounded by water, maintaining the uniform consistency of the product.[42]

The meat and gravy are blended, and the mixture is then suctioned by a piston and filled into a container. Food contents are sealed in airtight containers and moved to the sterilization process. Retorting, a conventional sterilization method, is employed in wet pet food production,[10] conducted at 121°C for at least 15 min using steam to achieve thermal lethality and destroy heat-resistant spores of *Clostridium botulinum* and other microorganisms.[49] During the whole process, the mix is screened for metal detection, particularly before filling and sterilization. After thermal treatment, the products are rapidly cooled to prevent a too soft texture or color change. The high water content contributes to hydrating pet foods and facilitates easy swallowing. However, the major drawback is the potential growth of thermophilic microorganisms causing spoilage if the cans are exposed to elevated temperatures for an extended period, as these microorganisms may not be fully eradicated by the retorting process.[46]

Raw pet food

In recent times, there has been a global increase in the practice of feeding raw meat-based diets to dogs and cats.[50] These diets typically consists of raw muscle meat, organs, fat, cartilage, and bones, all of which are ground and mixed with other ingredients for either homemade or commercial purposes (Fig. 1).[51] Raw pet foods are commonly available in raw (fresh or frozen), air-dried, or freeze-dried forms.[52,53] Some pet owners choose to prepare homemade raw diets for their pets to increase firmness, reduce stool volume, enhance palatability, improve oral and dental hygiene, and provide a perceived healthier diet.[37] However, it is important to note that there are associated health risks with feeding raw pet food. For instance, the presence of zoonotic pathogens in raw pet foods, including Shiga toxin-producing *E. coli, Salmonella* spp, *Clostridium* spp, *L. monocytogenes, Yersinia* spp, and *Campylobacter jejuni*, can pose serious health issues to both pets and humans.[54] Perhaps, there is a possibility of intestinal damage due to the availability of bones in raw diets. Moreover, raw pet food is generally more expensive than conventional pet foods.[50]

Hazard analysis in pet foods

Multiple pet food recalls have occurred due to the existence of pathogenic bacteria, molds, mycotoxin contamination, toxic levels of vitamin D, and other factors.[55] The presence of these contaminants in the finished product poses health risks to pets. To mitigate these risks, an effective hazard analysis should be established, identifying potential hazards and preventing microbial contamination, mixing errors, and formulation-based adulterations during the manufacturing process.[38] Pet food recalls result from various chemical and biological hazards, as illustrated in Fig. 2.

Chemical hazard

Pet food industries have encountered challenges in maintaining food safety, primarily due to recurrent recalls linked to different chemical hazards, including mycotoxin contamination, ingredient adulteration, and the presence of trace minerals and elevated vitamins proportion, etc. (Fig. 2).[55] Among them, the most prevalent natural contaminant in pet food is mycotoxin,[56] produced by filamentous fungi that can contaminate cereals such as corn, wheat, barley, soy, and peanuts, used as raw material in pet food production.[57] These crops, cultivated in hot and humid climatic conditions conductive to mold growth,[58] are inherently susceptible to mold contamination that cannot be prevented in the field,[5] making them an ideal substrate for fungal development, especially mycotoxin producers.[59] The consumption of mycotoxin-contaminated feed poses potential health risks to pets.[60]

Several mycotoxins have been reported in pet foods, including aflatoxin, deoxynivalenol (DON/ vomitoxin), fumonisin, and ochratoxin.[5] The four principal aflatoxins of concern in pet food are

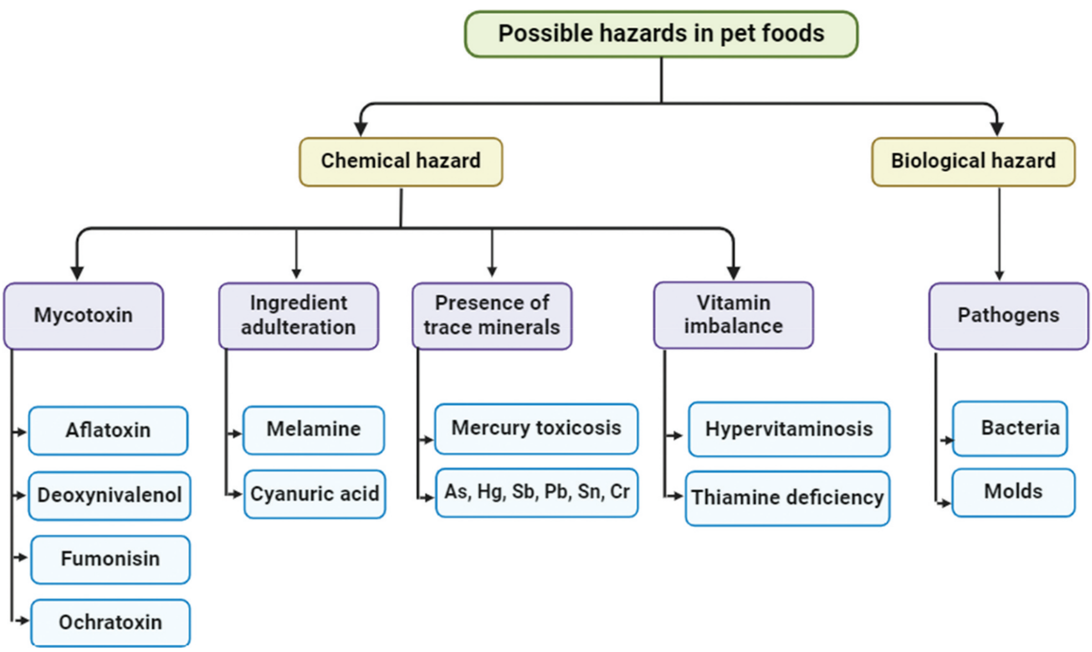

Figure 2. Possible hazards in pet foods.

aflatoxin B1 (AFB1), aflatoxin B2 (AFB2), aflatoxin G1 (AFG1), and aflatoxin G2 (AFG2). Corn, cottonseed meal, rice, and other food ingredients are more susceptible to aflatoxin-producing fungi.[61,62] Aflatoxin-contaminated feed primarily causes liver damage and, in some cases death in pets. Besides, it can be immunosuppressive, nephrotoxic, and/or carcinogenic, and may induce hemolytic anemia and coagulopathies in dogs and cats.[63] DON, the prominent mycotoxin, can cause severe effects in pets with common symptoms including severe vomiting and, in some cases, death.[5] The carcinogenic effects in pets are possibly caused by fumonisin, which has two types, namely fumonisin B1 (FB1) and fumonisin B2 (FB2).[64]

Table 1 illustrates pet food recalls related to mycotoxin contamination. Commercial dry pet food have been detected with higher concentrations of fumonisin,[65,66,68] deoxynivalenol, and zearalenone.[67] Additionally, AFB1 was detected at relatively high concentrations in dry dog foods.[7] Surprisingly, premium quality dry pet foods were also found to contain DON, ochratoxin A, and fumonisin.[69,70] Furthermore, certain cat foods were found to contain AFB1, DON, ochratoxin A, zearalenone, and fumonisin.[3,17] Various mycotoxins elicit distinct health consequences in pets. Despite aflatoxin having a lower concentration compared to other mycotoxins, its impact on pet health is remarkably high. Notably, acute and chronic forms of toxicity in pets depend on the amount of contamination and the duration of exposure.[7,63,69] Consequently, the FDA has established maximum action levels for AFB1, DON, and fumonisin in pet animal feed at 20 ppb, 5 ppm, and 10 µg/g, respectively (Table 2).[71,72] Additionally, the European Commission[73] recommends different mycotoxin limits in animal feed. For instance, the upper limits for DON and fumonisin are both set at 5000 µg/kg, while zearalenone, ochratoxin A, and AFB1 have limits of 100, 50, and 20 µg/kg, respectively.[67,68,73] Although, the recommendations from the FDA and the European Commission may differ, they share a common emphasis on maintaining low aflatoxin levels in pet foods. This

Table 1. Mycotoxin detected in commercial pet foods.

	Detected toxins						
Type of feed	Total aflatoxin	Aflatoxin B1	Deoxynivalenol	Ochratoxin A	Zearalenone	Fumonisin	References
Commercial dry dog foods	0.54–3.66	0.27–1.26 ng/g	NR	0.84–9.93 ng/g	NR	23.75–365.82 ng/g	[65]
Commercial dog foods	ND	NR	ND	3.6 µg/kg	51 µg/kg	122 µg/kg	[66]
Commercial dry dog foods	NR	<0.05 µg/kg	124 µg/kg	0.4 µg/kg	19.8 µg/kg	<5.0 µg/kg	[67]
Commercial dry cat foods	NR	<0.05 µg/kg	104 µg/kg	0.43 µg/kg	33.8 µg/kg	54 µg/kg	
Dry dog foods	8.82 µg/kg	NR	429.67 µg/kg	2.66 µg/kg	90.89 µg/kg	1221.02 µg/kg	[68]
Dry dog foods	NR	30.3–242.7 µg/kg	22.8–421.3 µg/kg	15.1–17.3 µg/kg	54.5–389.2 µg/kg	FB1: 6.6–191.9 µg/kg	[7]
Standard extruded dog foods (SD), premium extruded dog foods (PD)	NR	NR	SD: 99.4 µg/kg PD: 57.7 µg/kg	SD: 21.7 µg/kg PD: 41.1 µg/kg	NR	SD: 500 µg/kg PD: 66.6 µg/kg	[69]
Dry pet foods (premium (P): standard (S): complementary (C)	NR	NR	NR	NR	NR	P: 0.45 µg/kg S: 2.97 µg/kg C: 4.4 µg/kg	[70]
Dry and wet dog and cat foods	NR	18.4 µg/kg	NR	2.83–3.38 µg/kg	NR	NR	[3]
Cat foods and dog foods	NR	NR	22.2–618.4 ng/g	NR	0.3–30.3 ng/g	17.9–53.0 ng/g	[17]

NR:Not reported; ND: Not detected; FB1: Fumonisin B1.

Table 2. Permissible maximum level of mycotoxins present in ingredients intended for use in pet food production.

Mycotoxin	Type of ingredient	Action level	References
Total aflatoxin	Corn, cottonseed meal, rice, peanut products and other animal feedstuffs	20 ppb	[71]
Deoxynivalenol	Grains and grain by-products	5 ppm	[71]
Total fumonisin	Corn and corn by-products	Not exceed 10 ppm	[64]
Ochratoxin A	NR	0.3 mg/kg of body weight	[71]

NR:Not reported.

underscores the critical impact of aflatoxin on pet health, highlighting the need for stringent measures to ensure the safety of pet food.[60]

Certain food industries engage in illegal activities by adding prohibited adulterants to pet foods to maximize profits. An infamous case in 2007 involved melamine and cyanuric contamination, resulting in hundreds of pet deaths and numerous cases of acute kidney failure in the United States.[74,75] The FDA investigation revealed intentional mislabeling of imported wheat gluten and rice protein concentrates with poor-quality substitutes containing melamine.[76,77] Melamine, a non-protein nitrogen source, was added to boost crude protein content in the feed, causing destructive crystals in pets' kidneys and renal failure.[78] To address such health threats to pets, regular checks and notifications are essential to control these malicious practices in the pet food industry.

Various ingredients used in pet food production may contain trace metals that pose health risks to pets.[79] Cats, especially susceptible to mercury, are exposed to organic mercury through fish and aquatic animal tissues in their food. Quantifying total mercury in pet food is challenging, and there are no recommended safety limits for trace minerals in dog dietary intake.[80,81] Additionally, wheat bran has higher concentrations of metals like Al, Ba, Cr, Fe, Pb, Sn, and U compared to whole corn and broken rice.[82] Soil fertilization and pesticide use in crop production contribute to metal accumulation. Animal-based products, such as pork fat, may have elevated levels of As, Hg, and Sb due to waste food ingredients. To address these concerns and control chemical hazards in pet foods, it is crucial to conduct quality analyses of trace elements and establish standard safe limits for these minerals, ensuring the long-term health of our pets.

Perhaps excessive addition of cholecalciferol (vitamin D_3) and methionine can cause hypervitaminosis A, and anorexia and vomiting in dogs and cats.[56,83] In Australia, thiamine deficiency in pet foods, attributed to the use of sulfur dioxide as preservatives, has caused polioencephalomalacia in dogs and cats, resulting in severe neurological disorders.[84] These instances underscore the crucial importance of maintaining safety and quality in every step of the pet food processing line to ensure the well-being of our pets.

Biological hazard

The most pet food recalls have been attributed to the risks posed by food pathogens (Fig. 2). Various bacterial species, such as *Salmonella* spp., *Listeria* spp., *E. coli, Enterobacteriaceae* spp., *Staphylococcus aureus, Clostridium perfringens, Clostridium botulinum, Aeromonas spp*., *Campylobacter* spp., and human Shiga toxin-producing *E. coli* can be implicated in bacterial hazards associated with pet foods.[55,85,86] For instance, in 2018, the Food and Drug Administration (FDA) reported a pet food recall due to the potential contamination of *Salmonella* in raw meat.[55] The ingestion of contaminated food can lead to watery diarrhea, and in severe cases, bloody diarrhea accompanied by vomiting, fever, inappetence, lethargy, abdominal pain, and progressive degradation.[87] Urinary tract infection is the most common disease in dogs and cats caused by *E. coli*.[88]

Bilung et al.[89] reported that dogs were infected by *L. monocytogenes* due to the consumption of human leftovers. *Salmonella, Listeria*, and *E. coli* were detected in different types of pet food samples (Table 3).[90,91] Notably, *Salmonella* and *Listeria* were absent in dry pet food samples.[86,92] However,

Table 3. Bacterial contamination in different types of pet foods.

Type of pet food	Number of samples	Identified bacterial pathogens	References
Pet foods	130	• Coliforms • *Salmonella* spp. • *E. coli*	[90]
Pet foods	165 (99 canned and 66 dry products)	• *Salmonella* (41%) • *Listeria* spp. (64%)	[91]
Pet foods	32 (Dry – 8; Wet – 8; Treat – 8; Human leftover – 8)	• *L. monocytogenes*	[89]
Dry pet food	20	• *Enterobacteriaceae* strains • *E. coli*	[92]
Dry pet food	NR	• *Salmonella*	[93]
Dry dog food	5	• *Staphylococci*	[86]
Dry cat food	120	• *Salmonella*	[94]
Pet chew	108	• Sulfite reducing *Clostridium* • *Salmonella*	[95]
Pig ear treat	102	• *Salmonella*	[96]
Pet treats	NR	• *Salmonella*	[97]
Raw meat based diet	196	• *Salmonella* • *L. monocytogenes*	[94]
Raw meat based diet	47	• *Salmonella* Typhimurium • *Salmonella* London	[54]
Raw meat based diet	NR	• *Campylobacter* • *Y. enterocolitica* • *Y. pseudotuberculosis* • *Salmonella*	[98]
Frozen raw meat based diet	NR	• *E coli* • *L monocytogenes* • *Salmonella*	[99]
Frozen packs of raw meat based diet	60	• *C. perfringens* • *Salmonella* • *Campylobacter coli* • *C. jejuni*	[100]
Raw dog food containing poultry meat	39	• *E. coli* (>5×10^1 CFU/g)	[101]
Raw meat based diet	60	• *Salmonella enterica* subsp. *enterica* • *S.* Infantis • *S.* Typhimurium • *S.* Schwarzengrund	[102]

NR:not reported.

there have been reported outbreaks of *Salmonella* contamination associated with dry dog and cat foods,[93,94] as well as pet treats and pet chews.[95–97]

Meanwhile, the incidence of microbial contamination in raw pet food is relatively higher due to favorable growth conditions for pathogens, such as high water activity, abundant nutrient availability, and greater exposure to the environment.[103] In raw beef, *Campylobacter* was the most common pathogen (21%), while raw pork contained *Y. enterocolitica* (15%).[98] Raw pet food was found to be contaminated with *E. coli* and *Salmonella enterica* subsp. Enterica including *S.* Infantis, *S.* Typhimurium, and *S.* Schwarzengrund.[101,102] Frozen raw meat, particularly chicken, beef, and duck, was found to have *Salmonella* contamination.[99] Additionally, other studies have shown that frozen raw meat can be contaminated with *E. coli, L. monocytogenes, C. perfringens, Campylobacter coli*, and *C. jejuni*.[99,100] The evidence suggests a higher likelihood of pathogenic contamination in both raw and frozen forms of pet food, emphasizing the importance of implementing hygienic quality measures. Furthermore, molds have been detected in pet food samples, particularly dry pet foods. Błajet-Kosicka et al.[67] reported that *Aspergillus* (35%), *Mucor* (10%), and *Penicillium* (8%) were observed in dry pet food samples. In addition, dry pet foods were found to contain *Aspergillus* (67%), *Rhizopus, Mucor, Fusarium*, and *Penicillium*.[104]

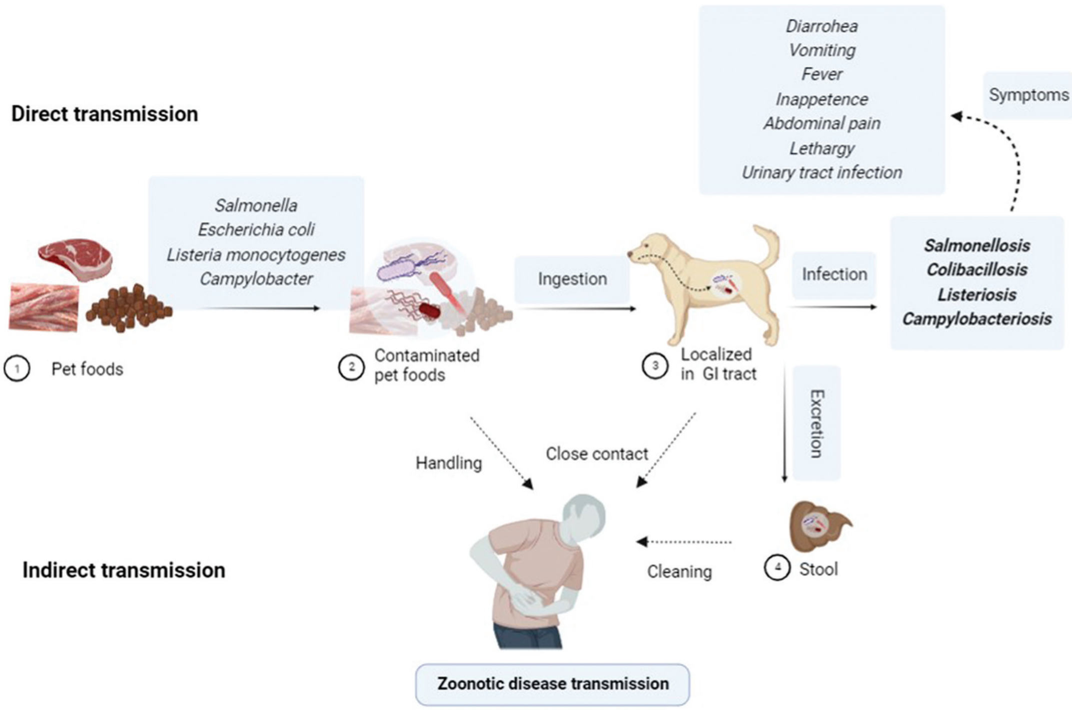

Figure 3. Direct and indirect transmission of zoonotic pathogens in pets and humans via pet foods.

Moreover, these pathogens can potentially not only have a direct impact on companion animals but also an indirect impact on humans sharing the same space with them.[105] *Salmonella* spp., *L. monocytogenes, and E. coli* become colonized in the gastrointestinal tract of infected dogs and cats through the ingestion of contaminated commercial pet foods. Infected animals shed *Salmonella* in the feces and saliva for a prolonged time, while *L. monocytogenes* is only spread via stool.[53,89] Perhaps, infected animals do not exhibit clinical symptoms, thereby, acting as carriers for these pathogens.[106] The transmission of pathogens occurs during the handling of contaminated pet food products,[52,94,97,107,108] feeding, and close contact with infected pets (Fig. 3).[109] As a consequence, pet owners are indirectly at risk of infection. Therefore, it is crucial to control and disinfect the initial point of pathogen transmission.

Possible control measures to minimize safety risks in pet foods

Preventive measures during processing

Hazard analysis of critical control points (HACCP)

The primary preventive measure involves ensuring the effectiveness of the existing HACCP system throughout the entire processing line of a pet food company. Immediate actions need to be taken if there is an inability to control potential hazards. Moreover, quality control and assurance should adopt preventive techniques to address mixing errors and formulation-based adulterations during the manufacturing process.[38] Moreover, processing steps such as de-hulling, grinding/milling, thermal treatments (extrusion, sterilization), drying, cooling, and coating are critical control points for the occurrence of the three major hazards (refer to Fig. 2). Technical faults and human carelessness may impact the quality of pet foods, ultimately affecting the health of pets. Therefore, the overall flow of pet food manufacturing must declare that certain steps involve the effective reduction of pathogens and other potential hazards in pet foods.

Drying

The drying step is crucial in the manufacturing of pet foods, significantly influencing the prevention of nutritional loss, maintenance of water activity for microbial growth and control, and minimization of operational costs.[110,111] Therefore, choosing appropriate drying techniques, such as conventional heated air drying, microwave drying, infrared drying, and fluidized bed drying, is essential to achieve the aforementioned objectives in pet food production.[110] Conventional heated air drying contributes to reducing moisture levels but poses safety concerns and the potential for case hardening.[112] Infrared drying minimizes quality reduction while rapidly drying food material and eliminating harmful mold spores. Nevertheless, improvements are needed to enhance the throughput of the drying process to meet the producers' requirements.[113,114] While the fluidized bed drying method can quickly inactivate anti-nutritional factors in soybeans compared to the conventional method, it demands more energy power, and there is an risk of excessive cracking and breakage.[115] All four methods have their pros and cons. Therefore, the selection of a suitable drying technique should consider factors such as product type and specifications, target pathogens, and quality profiles.[116]

Antimicrobials

Recently, antimicrobials and chemical agents have been employed to decontaminate pathogenic microorganisms in animal feeds, including pet foods.[117] Chen et al.[118] studied the impact of plant-derived antimicrobials, combined with either vegetable oil or chitosan, on reducing *Salmonella* Schwarzengrund in dry pet foods. The results revealed that the most effective bactericidal effect against *Salmonella* Schwarzengrund on dry pet foods was observed with 2% trans-cinnamaldehyde in 5% vegetable oil or 1% chitosan.[118] Likewise, Wales et al.[119] reported that the use of chemicals such as organic acids and formaldehyde are used for the decontamination of pet food. However, these chemicals were found to be minimally effective in reducing pathogen load. Thus, there is a critical need for identifying novel and safe strategies to inactivate pathogens, including *Salmonella*, on dry pet foods.

Preventive measures after processing

Thermal treatment

Thermal treatment is widely utilized to eliminate or reduce pathogenic and spoilage microorganisms in foods, being a relatively easy, effective, and reliable method.[120] However, it adversely affects organoleptic properties and protein digestibility due to maillard reaction, denaturation, and aggregation in animal-originated protein ingredients.[80] Furthermore, Witaszak et al.[17] reported that heat treatments such as high temperature baking and extrusion could reduce mycotoxin concentration to a certain extent. However, mycotoxins cannot be completely destroyed by thermal treatments due to their stable chemical structure, which allows them to withstand extreme temperature conditions.[121] Therefore, additional physical means should be incorporated into the production line to effectively decontaminate mycotoxins.

Non-thermal technologies

Non-thermal technologies, such as ultraviolet (UV) pulsed light, cold plasma, and irradiation, are gaining popularity due to well-known advantages, including safety and minimal nutrient degradation.[122–124] UV-pulsed light involves inactivating surface microorganisms using short pulses of intense broad spectrum 'white light' in the spectral band between 200 and 280 nm.[25,125] Subedi and Roopesh[126] reported that *Salmonella* was effectively destroyed by UV pulsed light intensity at 395 nm intensity, with hot air fluidization and vibration exposure to dry pet foods for 30 min, compared to individual treatments. A major drawback is that dry pet food pellets are opaque, preventing light pulses from passing through, and thus, bacteria on the bottom surface may not be exposed. In the case of cold plasma, it operates within the temperature range of 25–65°C and involves the ionization of gas to generate free radicals, including ions and electrons.[127] It has been extensively considered in food-related studies for the decontamination of pathogenic microorganisms on the surface of food and their toxins.[123] In contrast, Yadav and Roopesh[128] reported that *Salmonella* showed the greatest resistance to in-package atmospheric cold plasma when the water activity reached 0.13 in freeze dried pet foods. Therefore, both non-thermal technologies were not effective to sterilize pathogens, particularly *Salmonella*, in dry pet foods. These techniques could be applied for the surface decontamination of pet food ingredients, such as total aerobic bacteria at the initial processing steps. However, further studies are required to identify suitable analytical conditions to completely sterilize pathogens that can survive in low-moisture foods, especially dry pet foods.

History in ionizing radiation with pet foods

Food irradiation is a process that exposes food to ionizing radiations, such as gamma rays emitted from the radioisotopes ^{60}Co and ^{137}Cs, or, high-energy electrons and X-rays produced by machine sources.[18] Ionizing radiations can produce ionized atoms by "kicking" the electron from the outermost orbit of the subjected material.[19] The generated ionized atoms contribute to damaging the nucleic acids of microbes through direct and indirect mechanisms.[18] In the direct method, energetic photons or electrons directly breakdown the covalent and hydrogen bonds of DNA molecules in microbes.[129] In the indirect method, radiolytic products such as H^+, OH^-, and reactive oxygen species ($HO^\cdot$, $H^\cdot$, $H^\bullet$, $HO^\bullet$, $HO_2^\bullet$, and H_2O_2) are formed, which then attack the DNA of microorganisms present in foods.[129,130] Based on the microbial sterilization mechanism, irradiation has been applied to eliminate or to reduce the presence of pathogenic microorganisms, such as *Aeromonas hydrophila, Arcobacter butzleri, Campylobacter jejuni, L. monocytogenes, Salmonella* spp., *Staphylococcus aureus, E. coli* O157:H7, *Yersinia enterocolitica*, yeasts, molds, and others, in various food matrices.[27]

Furthermore, irradiation is effective in microbial intervention and mycotoxin decontamination in pet foods while minimizing changes to quality attributes. It has been demonstrated that food can be treated with irradiation either before or after packaging without the need for heating, the addition of preservatives, or other processing steps.[29] Additionally, it can sterilize large quantities of food materials in both batch and continuous process efficiently.[131,132] Consequently, it is feasible for the commercial application of various types of pet foods. Calado et al.[122] reported that these irradiation sources used emit too low energy to induce radioactivity in any exposed material. These advantages solidly demonstrate that ionizing radiation is commercial feasible for sterilizing pet foods as well.

Effect of irradiation on pet foods

Microbial inactivation

Ionizing radiation is considered as an effective physical method for decontaminating pathogens in foods.[133] It disrupts the DNA and cellular structures of pathogens in food, preventing their ability to replicate and cause harm. The high-energy radiation generates free radicals, damages microbial DNA, and denatures proteins, rendering the microorganisms inactive and ultimately protecting against bacterial contamination in food.[134,135] Therefore, ionizing radiation has been applied in various contexts, including animal feed,[136] meat and meat products,[137–139] rice,[140] beef jerky,[141] pork jerky,[142,143] and pet foods.

Zhu et al.[28] reported that irradiation doses of 4 and 6 kGy were sufficient to effectively destroy 92% and 99% of the total microbial load in pet foods, respectively (Table 4). The study found that *Salmonella* was inactivated in any irradiated pet food samples. The microbial inactivation effect is particularly crucial for raw pet foods compared to other.[103] Raw pet foods primarily consist of uncooked meat, edible bones, and organs from ruminants, pigs, poultry, horses, and fish.[100] These ingredients are excellent sources of pathogens, and raw pet foods are not sterilized before storage.[102,150] Therefore, the transmission of pathogens described in section 2.1 may contaminate

Table 4. Effect of different sources and doses of irradiation on microbial inactivation in different pet food ingredients.

Irradiation method	Target pathogen	Type of pet food	Source of ingredient	Treated dosage level	Destruction level	References
Electron beam irradiation	Total aerobic bacteria	Pet food	Not defined	6 kGy	99%	[28]
	Total aerobic bacteria	Pet treat	Pork jerky	4 kGy	100%	[143]
	Coliform				100%	
	Total aerobic bacteria	Raw pet food	Frozen duck	3 kGy	100%	[144]
	Coliform				100%	
	Total aerobic bacteria	Raw pet food	Frozen duck	3 kGy	76.19%	[145]
	Salmonella	Raw pet food	Poultry meat	1.8 kGy	100%	[146]
	Campylobacter				100%	
Gamma irradiation	Total aerobic bacteria	Raw pet food	Chicken meat	2 kGy	61.48%	[147]
	Coliforms				38.06%	
X-ray irradiation	*Salmonella enterica*	Pet treat and raw pet food	Tuna fillets	0.6 kGy	100%	[148]
	Total aerobic bacteria	Raw pet food	Beef chub	2.4 kGy	2.4 log CFU/g	[149]

raw pet foods and pose health hazards to pets. In accordance, Lewis et al.[146] reported that *Salmonella* and *Campylobacter* were completely eliminated in poultry meat when exposed to about 1.0 and 1.8 kGy of electron beam irradiation. However, *E. coli*, coli forms, and psychrotrophs were significantly reduced but not sterilized. In contrast, Arshad et al.[144] declared that electron beam irradiation at a 3 kGy dose completely decontaminated the total aerobic bacteria and coliform load from frozen duck meat samples. Thus, the irradiation dose required to destroy a certain pathogen needs to be clearly determined. Interestingly, Arshad et al.[147] reported that gamma irradiation up to 7 kGy dose was sufficient to decontaminate *Salmonella* spp. and other pathogens in chicken meat and extend shelf life of meat and meat products. However, An et al.[145] emphasized that *Salmonella* Typhimurium inoculated in frozen duck meat exhibited more resistance to 7 kGy of dose produced by electron beam irradiation. Gamage et al.[149] studied the effect of X-ray irradiation at a 2.4 kGy dose level in beef-chubs. The results showed that irradiated beef-chubs reached about 2.4 log CFU/g for total aerobic bacteria, while non-irradiated beef-chubs reached about 7.5 log CFU/g within 13 days. The delay in microbial growth of irradiated samples may indicate a longer lag time required by radiation-injured cells to repair and subsequently grow.[149]

Moreover, Kim et al.[143] demonstrated that electron beam irradiation at 4 kGy sterilized total aerobic bacteria and coli forms in pork jerky. This suggests that pet food jerky treats could be irradiated by electron beat at low absorbed dose levels. Additionally, packaged pet foods often include fish protein sources such as salmon, mackerel, whitefish, herring, and walleye, which are susceptible to microbial contamination. Interestingly, Mahmoud et al.[148] reported that X-ray is an excellent preservative technology for seafood products intended to be consumed raw. The study emphasized that 0.6 kGy of X-ray irradiation sterilized a 3-strains mixture of *S. enterica* (*S. Enteritidis* E190–88, *S. Typhimurium* ATCC 14028S and *S. Bareilly* ATCC 9115) on tuna fillets. Therefore, irradiation could be considered to effectively sterilize meat and meat products, using doses even below 10 kGy, to eliminate zoonotic pathogens in raw and processed pet foods.

Mycotoxin decontamination

Ionizing radiation, whether using gamma rays or electron beams, is a potential intervention for reducing mycotoxins in foods, including pet foods.[25,151] The oxidative radicals generated from water radiolysis are responsible for mycotoxin degradation, and they are also sensitive to irradiation.[122] Mir et al.[58] emphasized that ionizing radiation could effectively destroy mycotoxins

Table 5. Effect of different sources and doses of irradiation on mycotoxin decontamination in different pet food ingredients.

Irradiation method	Target mycotoxin/s	Type of pet food	Source of ingredient	Treated dosage level	Degradation level	References
Gamma irradiation	Aflatoxin B1 Ochratoxin A	Dry and semi-moist pet foods	Maize	10 kGy	90% 40%	[23]
	Aflatoxin B1 Aflatoxin B2 Ochratoxin A	Dry and semi-moist pet foods	Maize	20 kGy	40.1% 33.3% 61.1%	[153]
	Aflatoxin B1	Dry and semi-moist pet foods	Maize seeds	10 kGy	90%	[152]
	Aflatoxin B1	Dry, semi-moist and wet pet foods	Soybean and soybean oil	10 kGy	62.20%	[25]
	Aflatoxin B1	Dry and semi-moist pet foods	Corn	10 kGy	84%	[154]
	Ochratoxin A	Dry and semi-moist pet foods	Wheat flour	30.5 kGy	24%	[122]
Electron beam irradiation	Aflatoxin B1	Dry and semi-moist pet foods	Maize slurry	20 kGy	61%	[24]

without raising temperature. As so far, the application of irradiation techniques to destroy mycotoxins in pet foods is currently limited. Therefore, research studies investigating ionizing radiation to decontaminate mycotoxins in different cereal-based ingredients are being considered.

It has been identified that maize products are common sources of aflatoxins in commercial pet foods, especially dog foods.[105] Additionally, dogs are more susceptible to aflatoxins.[17] Mohamed et al.[24] reported that 20 kGy of electron beam irradiation reduced aflatoxin levels by 61% in maize slurry, observed in 61% of the samples. Markov et al.[152] investigated gamma ray irradiation in artificially and naturally contaminated AFBI in whole maize seeds. A 5 kGy dose reduced approximately 60% of artificially inoculated AFB1 with a concentrations of 50 μg/kg, whereas an 84% reduction was observed at 10 kGy (Table 5). Moreover, 5 kGy and 10 kGy doses of gamma ray irradiation effectively reduced AFB1 in non-inoculated whole maize seeds by up to 69.8% and 94.5%, respectively. Zhang et al.[25] reported gamma ray irradiation at 10 kGy dose could significantly reduce AFB1 by 62.20% in soybean incubated for 30 days; interestingly, a complete destruction of AFB1 was detected in all samples exposed at 30 kGy of gamma ray irradiation. In fact, AFB1 degradation was positively correlated with the increasing dose of irradiation.[154] Ghanem et al.[154] demonstrated that the application of 6 kGy and 10 kGy doses of gamma ray irradiation reduced AFB1 by about 66% vs. 90% in barley, 75 vs. 86% in bran, and 72 vs. 84% in corn, respectively. All these results suggest that higher doses of gamma ray irradiation are extremely effective in eliminating AFB1 mycotoxin from cereal-based ingredients.[25]

Khalil et al.[153] reported that the AFB1 and OTA cannot be effectively reduced at 2.5 and 3.5 kGy of gamma ray irradiation in maize, as the energy produced from such dosage level is not sufficient to destabilize their chemical structure. However, 6.0 kGy of gamma ray irradiation was adequate to completely decontaminate them in maize. Similarly, the destruction of total aflatoxin, AFB1, and OTA in maize grains by gamma ray irradiation was studied by Gillani et al.[23] The author reported that 15 kGy exhibited excellent sterilization against all mycotoxins. In fact, 10 kGy had better contribution to reducing total aflatoxin (89%), and AFB1 (93%), but OTA reduction was lower than 50%.[23] These findings showed that OTA has a strong and stable chemical structure compared to AFB1. Overall, ionizing radiation has the potential to effectively destroy major mycotoxins in different ingredients used in pet food production. However, the majority of these studies were conducted on gamma ray irradiation and raw ingredients. Therefore, further investigations on pet foods using other types of ionizing radiation are essential to provide a solid conclusion.

Quality attributes

Ionizing radiation has been reported to cause lipid oxidation and protein degradation and oxidation.[155,156] These effects directly influence on volatile compounds of foods, altering flavor and aroma. Likewise, the vast majority of chemical compounds produced by the irradiation process, such as aldehydes, ketones, peroxides, lipid oxidation products, furan, etc., are also generated in thermal processing.[157] Koppel et al.[47] compared the volatile compounds produced by baking and extrusion in dry pet foods. Accordingly, 2-decen-1-ol, 2-ethyl-2-hexenal, 3-octen-2-one, 2-butyl-furan, 3-hydroxytoluene, and 1-R-α-pinene were only present in extruded samples, contributing to distinct flavors and odors. However, the differences in the intensity of flavor, aroma, and the amount of lipid and protein oxidation are mainly dependent on the proportion of those volatile compounds. For example, dry pet foods may generate fish flavor or rancid fatty acid flavor, which occurs due to the formation of hexanal, heptanal, octanal from the oxidation of fatty acids during thermal treatments.[47] In irradiation, higher proportion of sulfur-containing compounds, such as 2,3-dimethyl disulfide, thiobismethane, 3-methoxy-1-propene, thioacetic acid methyl ester, and toluene, are produced, reducing the acceptance of products due to unpleasant flavors.[158] Therefore, irradiation may alter the sensory attributes of pet food due to the production of various volatile compounds.

Moreover, dry pet food may contain a certain amount of tannins produced from cereals and pulse flour.[1] Nevertheless, the presence of tannins in trace amount can cause vomiting, diarrhea, abdominal discomfort, and reduce digestibility and palatability in both dogs and cats. El-Adawy[159] reported that 10 kGy of irradiation greatly reduced to different tannin levels in various raw flour. The author stated that tannin levels were reduced in lentils, peas, kidney beans, and chickpeas to about 21.7%, 22.9%, 25%, and 28.1%, respectively. Considering overall sensory attributes, irradiation at moderate dose levels would be compatible to maintain the physicochemical properties in pet foods.

Trace metals

Ionizing radiation does not reduce trace metal levels in food but can alter their chemical state.[27,160] Regulatory bodies ensure that the levels of trace metals and radiolytic products formed during irradiation remain safe.[27] To optimize irradiation conditions, it is important to minimize radiolytic product formation while ensuring effective microbial inactivation. Studies should be conducted to identify and quantify radiolytic products formed in irradiated pet food containing trace metals to understand potential health risks and develop mitigation strategies.

Factors affecting quality and safety of pet foods by irradiation

Type of irradiation

Different kinetic energies of electron beam, X-ray, and gamma ray irradiation sources can vary their effects on pet foods.[161,162] For microbial sterilization, a substantial number of electrons with enough kinetic energy, up to 10 MeV, is crucial.[161] Accordingly, the FDA permits the use of accelerated electrons and X-rays with energies up to 10 MeV and 5.0 MeV, respectively, for the food irradiation process.[19,163] However, it is noteworthy that another IAEA consultant's meeting has recommended increasing the X-ray energy limit to 7.5 MeV.[164] Regarding gamma rays, ^{60}Co releases photons with energies of 1.33 MeV and 1.17 MeV, while ^{137}Cs emits photons at an energy of 0.66 MeV.[157] Under these conditions, these sources would efficiently sterilize pathogens in pet foods.

The penetration depth of different irradiation sources can impact the sterilization of pathogens and overall quality of pet foods.[18,165] The effectiveness of electron beam irradiation in decontamination is influenced by factors such as food size, thickness, direction (single-side or double-side exposure), and packaging.[134] As the penetration depth of electron beam accelerators (8 cm) is less than X-ray (20 cm) and gamma ray (40 cm) irradiation.[18,22] Therefore, electron beams are suitable for individual or small packages of pet foods, while, gamma rays and X-rays are more appropriate for bulk-packaged pet foods.

Remarkably, X-rays penetrate foods more slowly than gamma ray irradiation and much more deeply than electron beams.[16] It is important to note that X-ray irradiation has gained attention as a viable microbial reduction strategy due to its proven efficacy, minimal environmental impact, and potential for direct installation in commercial processing lines.[166] However, the use of X-rays for food processing is limited because of the poor conversion of electron beam to X-rays (about 10% at 5 MeV) and a lower dose rate compared to electron beams.[16,167] Due to differences in penetration depth, there are possibilities for altering the quality characteristics of pet food, such as texture. This can result in damage to the cross-linkages of food matrix, leading to a reduction in hardness, crispiness, and crunchiness in dry pet foods, as well as a loss of soft and chewy texture in semi-moist pet foods.[42,47] Therefore, the design of pet food irradiation should take into account the kinetic energy and penetration depth of the irradiation source, considering the primary objectives, and the physical and chemical characteristics of the pet foods.

Absorbed dose level

The amount of energy absorbed by a mass of material exposed to the ionizing radiation is referred to as absorbed dose, and it plays a vital role in microbial sterilization, given that radiation energy is typically fixed.[168] This is particularly significant because the disintegration of bacterial cell membranes and mold cell wall structures is often associated with a dose-dependent manner.[169] Moreover, the dose level can vary based on the target biomolecule or compound. For example, Abouzeid et al.[170] recorded that a 5 kGy dose of gamma ray irradiation could significantly reduce the initial microbial load of *Fusarium verticillioides* by up to 99.9% in infected corn. However, even a 20 kGy of gamma ray irradiation was insufficient to eliminate fumonisin in maize slurry.[24] This clearly demonstrates that a dose effective for sterilizing fungi may not be adequate for eliminating toxins produced by them. Therefore, the precise dose required for a specific application should be considered in terms of contamination level, the associated hazard, radiation efficacy, resistance of microorganisms, and factors related to food manufacturing, storage, and distribution.[171]

The FDA has stipulated that the radiation pasteurization of non-frozen red meats is permissible with a maximum dose of 4.5 kGy, while for frozen red meats, the maximum allowable dose is 7.0 kGy.[171] Since irradiation has not yet been employed for pet foods, there are no established recommended doses for various intentions. Considering three levels of preservative effects of irradiation, we suggest possible applications for pet foods as follows:

- Radappertization (>10 kGy). The target dose level is determined irrespective of food composition, making this method suitable for frozen raw pet foods. Additionally, it could be applied for the decontamination of mycotoxins in cereals and their by-products before being used in pet food production.
- Radicidation (2.5–10 kGy): This range is commonly used to eliminate *Salmonella* in foods. As many pet food recalls are associated with *Salmonella* contamination, this method is highly recommended for all types of pet foods.
- Radurization (<2 kGy): This method, applicable at the end of the processing line of dry pet foods before storage, can be combined with other food preservation techniques extend the shelf life of products. While dry and semi-moist pet foods produced using the extrusion technique are generally stable for long time, there is a possibility of contamination before packaging. Therefore, incorporating radurization as a final step in the processing line is a viable approach to mitigate this risk.

Processing conditions

The lethal effects of irradiation on pathogenic microorganisms become pronounced when the process occurs at elevated temperatures.[172] However, in practical applications, food samples are generally exposed to ionizing radiation at room temperature (20–25°C) to prevent adverse changes in food components. Additionally, it has been observed that the resistance of microorganisms increases when irradiation is conducted at frozen temperatures.[173] This phenomenon is attributed to variations in the activation energies of chemical reactions with temperature, leading to changes in the yield of radiolytic products and a reduction in the mobility of free radicals.[168,172] To address this challenge, a combination of irradiation with other preservation technique can be employed. For example, mild heating of meat at 77°C before irradiation not only sterilizes microbial enzyme activity but also reduces required irradiation doses.[174] This approach helps mitigate the impact of increased resistance observed at frozen temperatures, allowing for effective microbial sterilization while maintaining the quality of the food product.

The presence and/or exclusion of oxygen can significantly influence the impact of irradiation on pet foods as the availability of oxygen during irradiation has been found to enhance the lethal effect.[173] Molecular oxygen, with its two unpaired electrons, acts as a diradical to form peroxyradical (RO.), which can undergo further reactions. Additionally, oxygen forms ozone during the irradiation process, serving as a potent oxidant.[172] Conversely, the exclusion of oxygen is advantageous, particularly when the food is mainly composed of fat, as it helps to prevent oxidative deterioration. Another benefit is that radiation in the absence of oxygen results in less degradation of vitamin E and thiamin.[174] Dry pet food contains a relatively high level of oils and fats; hence, the presence of oxygen may accelerate lipid and proteins oxidation, contributing to the rancidity of dry kibbles.[175]

Food matrix

Raw materials in pet foods are sourced from plant-based or animal-based food ingredients.[176] The selection of these raw ingredients is primarily based on meeting the nutritional requirements of pets. Typically, a pet food comprises 30–70% carbohydrates, 15–25% protein, 10–15% fats, and trace amounts of vitamins and minerals (Table 6).[110] The percentage of water content varies across different types of pet foods. Different characteristics, especially water content and activity, of pet foods can vary their microbial growth during storage (Table 3). Despite having low water activity, dry pet foods have been found to harbor pathogenic bacteria as *Salmonella*, *L. monocytogenes*, and *E. coli* can survive in low-moisture foods with a water activity < 0.85.[177–179] Typically, pathogenic bacteria and molds exhibit preference for growth and multiplication above water activities of 0.91 and 0.80, respectively.[180,181] The radiolysis of water molecules contributes to microbial inactivation and extends the shelf life of pet foods (Fig. 4).

Furthermore, the sources of carbohydrates for pet food rations include corn, oat, wheat, barley, rice, edible grains, and cereal/grain by-products.[51] Exposure of cereals to free radicals generated during irradiation treatment may lead to hydrolysis, oxidative decomposition, and depolymerization of their

Table 6. Nutritional composition of pet foods and their primary sources. Adapted from Olatunde and Atungulu.[110]

Nutrient	Weight in dry basis (%)	Sources
Carbohydrates	30–70	Wheat, corn, rice, barley, oats
Proteins	15–25	Chicken, egg, beef, turkey, lamb, soybeans, fish meal
Fats	10–15	Chicken or pork fat, cottonseed oil, vegetable oil, soybean oil, fish oil, safflower oil, etc.
Vitamins and minerals		Fruits and vegetables (Ca, P, Mg, Na, Cl-, S, K)

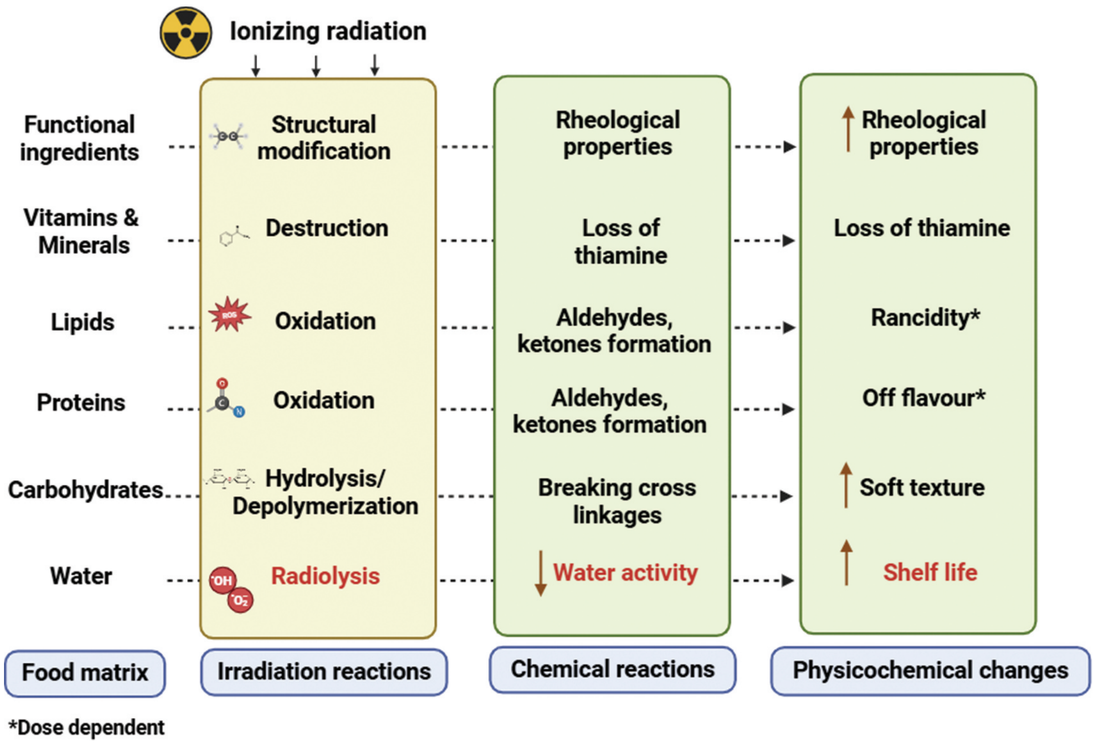

Figure 4. Changes in food matrix of pet foods by ionizing radiation.

polysaccharides.[182] This process can reduce viscosity and increase the solubility of starch molecules in pet food, resulting in a soft texture.[183]

Similarly, the primary protein sources in pet foods include poultry by-product meal, meat and bone meal, corn gluten meal, and soybean meal. These sources are utilized to provide balanced amino acids and enhance digestibility in pets.[184] Protein oxidation can be accelerated by ionizing radiation, affecting the peptide linkages of protein biomolecules.[185] This may contribute to the release of sulfur-containing volatile compounds, leading to the generation of undesirable flavors.[186] Such changes directly impact the palatability of pet food.

The fat sources used in pet food include rendered fats and oils from lard, tallow, poultry fat, and fish oil, providing supplementary energy, characteristic aromas, and nutrients to pets.[2] Irradiation induces lipid oxidation via the breakdown of fatty acids, leading to the production of aldehydes such as hexanal, pentanal, nonanal, and benzaldehyde.[146,158] However, protein and lipid oxidation in foods are often associated with higher doses.[186]

Synthetic ingredients are incorporated to balance the requirements of essential vitamins (A, B_{12}, D_3, and E; ribolavin; niacin; folic acid) and minerals (Ca, Mg, K, P).[51] Both fat soluble vitamins (A, E) and water soluble vitamins (C, B_1) are more sensitive to the irradiation process.[187] The loss of thiamine increases with higher doses, and since thiamine is essential for the physiological activities of cats, supplementary sources are required when cat foods are irradiated.

Soy protein concentrates and soy protein isolate are used in pet foods due to their high-protein solubility, water-binding, and fat emulsification functionalities.[184] In fact, irradiation has been investigated for improving such functional properties in cereal and animal-originated food products, making it not a serious issue.[188–190] Considering the effect of irradiation on pet food composition, the quality changes are obviously dose-dependent. Therefore, determining a suitable dose is crucial to achieve both safety and quality objectives.

Conclusion

The review highlighted the effectiveness of ionizing radiation when applied to pet foods depends on the ingredients used, nutritional requirement of the pet, type of pet food, and packaging techniques. Also, it emphasized that the specific source of ionizing radiation and dosage level must be carefully chosen based on the type of pathogen and its load, the type of mycotoxin and its concentration, the pet food type, and the potential for nutrient degradation. The lack of information on these factors has hindered the widespread use of irradiation in the pet food industry.

Future studies should focus on optimizing ionizing radiation dosages for different pet foods to ensure microbial safety without compromising nutritional quality. Therefore, investigating long-term effects on nutrient stability and conducting consumer acceptance surveys are crucial. Additionally, research should explore the economic feasibility of ionizing radiation for pet food manufacturers. It is also important to assess the environmental impact of ionizing radiation processes to ensure sustainability.

Moreover, future research in the pet food industry should pay attention to certain key areas to improve the safety and quality of irradiated pet food. Developing novel packaging materials that can effectively withstand ionizing radiation while preserving pet food properties, along with exploring eco-friendly or biodegradable options to reduce the environmental impact of irradiation. Additionally, studying the synergistic effects of other non-thermal preservation techniques, such as cold plasma, UV light, and natural preservatives, could enhance pathogen reduction and mycotoxin decontamination while minimizing nutrient loss. Long-term studies on the impact of irradiated pet food on pet health and behavior are also crucial. These studies will help assess the nutritional effects and ensure the safety and benefits of irradiated food for pets. Lastly, collaboration with regulatory bodies to establish clear guidelines and standards will be essential for widespread adoption and consumer trust.

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