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Review

Electron beam irradiation to control biohazards in seafood

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ABSTRACT

Seafood contributes significantly to world food security. However, supply of safe seafood is a challenge. Because of their inherent nature, diverse habitats and production processes, seafood products are highly prone to biohazards including pathogenic microorganism, viruses, and also parasites that can affect human health. Conventional processing technologies and hygienic practices are not fully compatible to eliminate these hazards. Exposure to ionizing radiation is a plausible cold process to enhance the safety of fishery products through inactivation of foodborne pathogens, without significantly affecting sensory properties of the food. Because of the penetration nature of radiation, the treatment can eliminate these organisms even from frozen, packaged, ready-to-ship fishery products. Whereas gamma radiations generated from radioisotopes of cobalt and cesium have been used for the purpose, the treatment has not met commercial success because of practical problems with respect to use of radioisotopes and poor consumer acceptance of food exposed to gamma rays. The treatment by electron beam is a commercially feasible method to ensure food safety. Electron beam irradiation has potential to reduce seafood-borne biohazards facilitating global seafood security.

1. Introduction

Food security is intricately related to availability of safe and nutritious food in adequate amounts for public consumption. A safe food provides nutritional benefits, causing negligible health risks to consumers. Supplying safe food to world population, which is likely to reach 9 billion by the year 2050, is posing challenges to food security. Mass food production systems to satisfy the rising consumer demands amidst industrial pollution and environmental changes are likely to result in poor food safety, indicated by increasing incidences of foodborne diseases in the recent decades (EFSA, 2020; INFOSAN, 2020; WHO, 2015). Although several control measures including management practices have been developed in recent years, such measures still pose limitations. This article, at the onset, will briefly discuss the various hazards associated with seafood. This will be followed by discussion on the uses of low dose radiation to enhance food safety. Later, the article will highlight the beneficial effects of electron beam irradiation to enhance microbial safety of fishery products and its commercial prospects.

2. Seafood in global food and nutritional security

Seafood, in a broader perspective, comprises of both finfish and shellfish items from marine, estuarine, brackish, and freshwater habitats and forms a sizeable component of the total world food production. In the year 2018, global seafood production was 179 million tons (MT), which included about 96 MT of capture fisheries, consisting of anchorites, Alaska pollock, skipjack tuna, herring, whiting and other finfish and shellfish encompassing several types of crustaceans, cephalopods and mollusks. An amount of 156 MT of seafood was used for human consumption, with an international trade of 67.1 MT, 44% of which included live, fresh or chilled items followed by frozen products at 35%. World seafood consumption is expected to reach 204 MT by the year 2030 (FAO, 2020). However, in many countries availability of wild fish has declined considerably, the shortfall in capture fisheries is increasingly met by aquaculture production (Hall et al., 2011, p. 92; Thurstan & Roberts, 2014). An amount of 82.1 MT of farmed fish and shellfish contributed to 46% of total production in 2018 (FAO, 2020).

Seafood species are rich in proteins and other nutrients, including peptides, essential amino acids, long-chain omega-3 polyunsaturated fatty acids, carotenoids, vitamins including vitamin B_{12}, and minerals (Venugopal, 2018). The consumer awareness of the nutritive value has reflected in the increase of global per capita fish consumption from 5.2 kg in 1961 to 19.7 kg in 2017 (FAO, 2020). The necessity to promote, sustainable fisheries including aquaculture for food security and nutrition have, therefore, been emphasized (Béné et al., 2015; FAO, 2020; World Bank, 2013).

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3. Safety aspects of seafood

For aquatic food security, seafood supply should not only be sufficient, sustainable, sound and shockproof, but also need to be safe (Jennings et al., 2016; Rice & Garcia, 2011). A food is safe when it poses a minimal health hazard to consumers. Fishery products, however, are highly prone to safety hazards because of their inherent nature and production processes. A food-borne hazard is defined as a biological, chemical or physical agent present or a condition of the food with potential to cause an adverse health effect to the consumer. Biological hazards are caused by living organisms, particularly pathogenic microorganisms, while heavy metals such as mercury and lead, polychlorinated biphenyls, dioxins, and others are responsible for chemical hazards. An estimate of the probability or severity of the hazard is considered risk (Garett et al., 1997). An emerging risk is defined as 'a risk resulting from a newly identified hazard to which a significant exposure may occur (EFSA, 2020). The illness caused by consumption of contaminated seafood can be broadly due to infections and/or intoxications. Symptoms of intoxication may include gastrointestinal distress, vomiting, headaches, among others (IFT, 2000(WHO, 2020); Khora, 2014).

The hazards associated with seafood can be grouped as those caused by (i) intrinsic characteristics, (ii) environmentally induced, (iii) process-induced, (iv) distribution-induced, and, (v) consumer-induced. The intrinsic characteristics are due to the wide biological diversities of fishery products such as diverse species of finfish, crustaceans or mollusks. The filter feeding nature of bivalve mollusks (oysters, scallops, mussels, clams and cockles) can result in significant accumulation of microorganisms in their alimentary tracts (Jennings et al., 2016; Sheng & Wang, 2021; Venugopal, 2006, chap. 10). Environmental habitats (ocean, river, brackish water, freshwater, farmed), oceanic levels (pelagic or demersal) and proximate compositions can also influence degree of hazards (Huss et al., 2003, p. 230; Venugopal & Gopakumar, 2017). In the recent decades, global warming has been reported to influence dominance and persistence of these hazards (Barange et al., 2014; EFSA, 2020). Food safety hazards associated with products from aquaculture differ according to region, habitat and environmental conditions, as well as methods of production and management (FAO/NACA/WHO, 1999). The procurement practices (capture or farming), processing practices and storage conditions as well as supply chains to diverse markets can also expose seafood to contamination by a variety of hazards affecting product safety. Process-related contamination can occur during skinning, filleting and other operations. De-shelled shellfish may be easily cross-contaminated in the absence of satisfactory hygienic environment (Venugopal, 2006, chap. 10). Consumer-induced food safety threats may be attributed to increased consumption of minimally processed seafood products, which are being developed essentially for their natural freshness and nutritional quality. These products may present certain risks in ensuring process-related safety (Kontominas et al., 2021; Olatunde & Benjakul, 2018).

3.1. Biohazards

Biological hazards, often referred to as biohazards, are caused by pathogenic bacteria, viruses, parasites and toxins. Habitats, processing and distribution can also cause these hazards. Microorganisms including pathogens, viruses and parasites from raw sewage and industrial bio-waste can contaminate water bodies, which in turn, enter fishery products. Such contaminations can also happen from sources including fishing vessel, processing units, handling equipments, and from workers. Farmed fish and shellfish are likely to be contaminated by disease-causing bacteria, viruses, fungi and parasites. Filter feeding shellfish are highly sensitive to microbial contamination. Freshwater fish such as carps may get contaminated, especially in multispecies aquaculture systems (Leung & Bates, 2013; FAO/NACA/WHO, 1999). Survival of these organisms in the fish muscle is influenced by its nutritional composition, extrinsic factors like temperature, gas environment, and processing factors (ICMSF, 2018).Toxins arising from proliferation of poisonous algae such as dinoflagellates and diatoms popularly known as 'red tide' may contaminate seafood. In addition, parasites can infest marine, freshwater, as well as farm-raised fish and shellfish (Huss et al., 2003, p. 230; Vezzulli et al., 2013).

3.1.1. Pathogenic microorganisms

Pathogenic organisms are capable of causing illness, either by infecting the host or by producing toxins that make the host ill. The major pathogenic microorganisms responsible for most seafood-borne hazards include *Salmonella* spp. *Staphylococcus aureus, Shigella, Vibrio* spp. such as *V. cholerae,* and *V. parahaemolyticus*, *Yersinia enterocolitica,* and pathogenic *Escherichia coli.* Outbreaks of seafood-associated *Salmonella* infections have been implicated in around 1 million diseases including 350–400 deaths, annually, in the U.S. (CDC, 2017; Zhang et al., 2015). *Shigellas* pp., particularly, *S. dysenteriae* causes shigellosis, characterized by diarrhea, fever, abdominal cramps and severe fluid loss. *Vibrio* spp. can occur in marine and estuarine waters. *V. vulnificus* and *V. parahaemolyticus* are important human pathogens that are hosted by fish. *V. mimicus,* closely related to *V. cholera,* may be transmitted by raw oysters, fish, prawns, squid, and crayfish, and causes gastroenteritis in humans**.** Marinated raw fishery products can be carriers of *V. cholerae* *(*(FAO and WHO, 2020)Wang et al., 2015; Vezzulli et al., 2013). The pathogenic *E. coli* may encompass enteropathogenic, enterotoxigenic, enteroinvasive and enterohaemorhagic strains. Shiga toxin–producing *E. coli* (STEC), including enterotoxigenic *E. coli* O157 and many non-O157 serotypes are important causes of diseases. The cytotoxin producing *E. coli* 0157:H7, which may be transferred from feed to fish, is a common pathogen of the human gastrointestinal tract (Tarr, 1995).

Seafood can get contaminated with Clostridia from ocean sediments, particularly, *C. botulinum*, a ubiquitous, spore-forming, anaerobic organism that releases a neurotoxin, responsible botulism, a lethal paralytic disease. *C. botulinum* type E is found in aquatic environments. The clinical symptoms of botulism toxin–induced illnesses vary greatly by the serotype and degree of exposure to the toxin (Lalitha & Thampuran, 2006). *Listeria monocytogenes,* a causative agent for listeriosis in humans, is of particular relevance in minimally processed and ready-to-eat (RTE) items including RTE seafood items (Huss et al., 2000). *S. aureus* may contaminate processed fishery products, possibly through food handlers. The bacterium may elaborate enterotoxin on improperly stored seafood. Oysters and fish have been identified responsible for outbreaks of *Y. enterocolitica,* a psychrotrophic bacterium. *Pfiesteria piscicida* and Pfiesteria-like microbes are considered emerging pathogens (IFT, 2000).

Aquacultured fish may get contaminated by *Campylobacter* spp. through poultry-based feed. *Plesiomonas shigelloides* (formerly known *Aeromonas shigelloides*) is an emerging cold-tolerant gram-positive pathogen, which has been isolated from freshwater fish and shellfish (FAO/NACA/WHO, 1999). *Aeromonas hydrophila* releases both cytotoxic enterotoxins and hemolysins. The pathogen can be attributed to nausea, abdominal cramps, and other diseases of the infected person. Seafood can also be carriers of the pathogen, Klebsiellae, belonging to the order Enterobacterales (Gautam et al., 2015).

Viruses such as rotavirus, norovirus, adenovirus, astrovirus, and parvovirus may contaminate food of animal origin during all stages of the supply chain and are considered major causes gastrointestinal illness (Shukla et al., 2018). Although viruses do not multiply in foods, they may persist for extended periods of time (EFSA, 2011a). Consumption of raw bivalve shellfish can be major reason of infection (Garett et al., 1997). Hepatitis A virus (HAV) infection is the leading cause of human hepatitis, mollusk being a major matrix of transmission. Consumption of the HAV-infected bivalves affects approximately 1.5 million people annually. The viruses can cause paralysis, meningitis, respiratory illness and myocarditis among others. The contamination of bivalve shellfish with norovirus from human faecal sources is recognized as an important human health risk (Khora, 2014; Lowther et al., 2012; Sánchez, 2015).Table 1 shows relative risks of various foodborne hazards. Pathogenic microorganisms are responsible for hazards at least 1000 times more than chemical contaminants.

As shown in Table 2, those consumed raw without any cooking such as raw fish such as sushi or fresh or frozen mussels, clam, oysters are exposed to maximum hazards to human health, while consumption of sterilized foods pose minimum threats.

In addition to potential contamination, possible resistance to antibiotic drugs by pathogenic organisms is another serious problem. Analysis of a total of 730 aqua-cultured samples including fish and shellfish during the period 2006 to 2011 showed that 217 (29.7%) were positive for *Salmonella* and a total of 43.3% of the isolates were drug-resistant (Zhang et al., 2015). *V. parahaemolyticus* isolated worldwide during the period 2000 to 2017 were resistant to gentamicin, ampicillin and other antibiotics (Obaidat et al., 2017). *E. coli*, *P. aeruginosa* and *S. aureus isolated from* raw and imported seafood items have also displayed antimicrobial resistance (Boss et al., 2016). Furthermore, the ability of pathogens including *L. monocytogenes*, *Y. enterocolitica* and *A. hydrophila* to survive under refrigerated temperatures poses threat to the safety of chilled seafood (Palumbo, 1986).

Global warming can influence predominance of various bacteria, parasites, fungi, viruses, vectors and invasive species (EFSA, 2020; Rice & Garcia, 2011; Hall et al., 2002). Sea warming patterns have coincided with the unexpected emergence of *Vibrio* infections (Baker-Austin et al., 2013). Changes in other environmental factors, such as salinity and pH, may also result in changes in pathogen distribution and virulence. Surface seawater warming and increased nutrients input leads to the profusion of toxin-producing algae causing outbreaks of seafood contamination (Marques et al., 2010).The microbiological safety of fishery products including cultured items and shellfish have been discussed (Sheng & Wang, 2021; Venugopal & Gopakumar, 2017; Lalitha & Thampuran, 2006; Khora, 2014; FAO/NACA/WHO, 1999). Table 3 points out seafood borne illnesses associated with some important bacterial pathogens.

Table 1
Relative risks of various foodborne hazards.

Ranking	Hazard	Relative risk
1	Microbial pathogens	1, 00, 000
2	Pollutant chemicals	100
3	Natural toxins	100
4	Pesticide residue	1
5	Food additive	1

Adapted from Ashwell, 1990.

Table 2
Seafood hazard categories in order of decreasing risks.

Category	Description
1	Those consumed raw without any cooking such as raw fish such as sushi or fresh or frozen mussels, clam, oysters
2	Non-heat processed raw foods often consumed with additional cooking. E.g. fresh or frozen fish and shellfish
3	Lightly preserved fish products (with $<$ 6% salt in water phase, pH $>$ 5.0). e.g. salted, marinated, fermented seafood
4	Semi-preserved fish (Salt $>$6%) or pH $<$ 5.0 with added preservatives, such as salted, marinated fish, caviar
5	Mildly heat-processed (pasteurized, cooked, hot smoked) fish products
6	Heat processed (sterilized, packed in sealed containers)

Adapted from Khora, 2014.

Table 3
Seafood borne illnesses associated with some bacterial pathogens.

Pathogenic bacteria	Seafood vector	Minimum dose for infection[a]	Clinical symptoms
***Salmonella* spp.**	Shrimp, Mollusks	>10	Fever, headache, nausea, vomiting, abdominal pain, and diarrhea
Shigella	Mollusks	10^1 to 10^2	Severe diarrhea, cramps, vomiting
Vibrio parahaemolyticus	Crustaceans	10^5 to 10^6	Diarrhea, nausea, vomiting
V. cholerae	Shellfish	10^5 to 10^6	Abdominal pain, vomiting diarrhea, dehydration, and possible death
***Clostridium botulinum* type E**	Shellfish, smoked	0.01–1.0 mg toxin per g	Paralysis, diarrhea, death
Yersinia enterocolitica	Shellfish	10^7 to 10^9	Diarrhea, vomiting, fever
Staphylococcus aureus	Seafood	10^5 to 10^6	Diarrhea, cramps, vomiting
Aeromonas hydrophila	Shellfish	10^5 to 10^6	Vomiting, diarrhea

[a] Colony forming units, except for *Clostridium botulinum* type E Adapted from Lalitha & Thampuran, 2006.

3.1.2. Parasites

Food-borne parasites are considered a global threat to food safety. The main reason for human parasitic infection is consumption of raw or inadequately cooked fish. The most common parasites associated with fish include (1) round worms such as Anisakid nematodes, (2) tapeworms and (3) digenetic trematode (Gajadhar, 2015; Wekell et al., 1994), Roundworms (nematodes) are common in marine organisms and include *Anisakis* spp. such as *A. simplex*, *Capillariasis* spp., *Trichuris* spp., *Trichinella* spp. and others. Anisakids are among the most common nematodes of marine fishes leading to their commercial value. Cod, whitefish, salmonids, and other species can carry *Trichinella spiralis. A. simplex* can be found in crustaceans, squid, fish, and marine mammals. *Opisthorchis viverrini* and *O. felineus* are disease-causing parasitic agents responsible for human opisthorchiasis. The smallest of the parasites include single-celled protozoa encompassing *Entameba histolytica*, *Giardia* spp. and *Toxoplasma* spp. Infestations are largely attributed to helminths, protozoa, and arthropods, which can infest the body of marine, freshwater, and farm-raised shellfish. Metacercariae, the infective stage of these parasites, are found in the edible tissues of freshwater fish and shellfish. Korea had been one of hyperendemic countries of human parasitic infections until 1970s. A successful national program was launched to control parasites, which helped decrease of *Ascaris* and other intestinal nematodes, *Paragonimus*, *Taenia*, and intestinal protozoa, but *Clonorchissinensis* and intestinal trematodes are still prevalent locally in endemic areas (Hong & Yong, 2020). The agent responsible *P. westermani,* the lung fluke that infects humans are freshwater crabs and crayfish. *Clonorchissinensis,* the Chinese liver fluke, belonging to the class Trematoda, is highly endemic, which was recently detected in freshwater fish at a level of contamination as high 62% (Sohn et al., 2021).

3.2. Recent seafood-borne safety outbreaks

The World Health Organization (WHO, 2020) observed that food containing harmful bacteria, viruses, parasites and also chemical substances, are responsible for more than 200 diseases – ranging from diarrhea to cancers, which annually make an estimated 600 million people fall sick and cause 420,000 deaths (WHO, 2015). INFOSAN, the global network of national authorities of almost all member states of FAO and WHO reported 104 food safety events, which were attributed to 56 biological and other hazards during the first three quarters of 2020. The biological hazards were caused mostly by *Salmonella* spp (INFOSAN, 2020). In the year 2017, as many as 841 food-borne disease outbreaks were reported by 50 states in the US, resulting in 14,481 illnesses, 827 hospitalizations, 20 deaths, and 14 food recalls. The hazards were caused mainly by *Salmonella* (23 cases) followed by *L. monocytogenes*, *E. coli*, and *C. botulinum*. Other pathogens included norovirus, *Shigella*, *Pseudomonas* spp. *B. cereus*, *Campylobacter* spp. and *Enterococcus faecalis*. Mollusks and oysters were responsible for 41 outbreaks, while fish caused 37 outbreaks (CDC, 2017). Bacterial infections, specifically by pathogenic *E. coli* were the primary cause of outbreaks in the Republic of Korea, while both bacterial (predominantly *Salmonella*) and viral infections accounted for most outbreaks in the US (Kim & Kim, 2021). *E. coli* outbreaks have caused at least 26 deaths and over 2,000 infections in Germany, Sweden and other countries (FAO, 2011). Waterborne outbreaks of parasitic protozoa such as the *Cryptosporidium* have happened in the US in the 1990s (IFT, 2000). About four million cases of foodborne infectious diseases are reported to occur annually in Australia (Hall et al., 2002). Shrimp are an important commodity in the international fisheries trade. *Salmonella* and *Listeria* have been isolated from shrimps and shrimp products on a regular basis since the 1980s (Norhana et al., 2010). Seafood items intended for exports have been often recognized not to comply with mandatory microbial quality criteria set out by importing countries including EU, the US and Japan. Presence of *Salmonella* spp. such as *S.* Typhimurium and *S.* Enteritidis has been periodically reported in Asian seafood exports (Kontominas et al., 2021). Microbiological quality of seafood imported from 12 countries by the US showed that out of a total of 171 salmon, shrimp, and tilapia samples, 27 items had average plate count above 7 log colony forming units (CFU) per g. About 17.5 and 32% of the samples were positive for *Salmonella* and *Shigella*, respectively. Shrimp showed presence of *V. parahaemolyticus*, *L. monocytogenes* and *E. coli* in the samples ranged from 4.1% to 9.4% (Wang et al., 2011). A study on the quality of 109 imported block frozen peeled, and headless shrimp in Egypt showed that total viable count of the samples varied from 4.8×10^3 to 7.7×10^8 CFU per g. The levels of Enterobacteriaceae, coliform and *S. aureus* in the samples were 5.1×10^4, 4.1×10^3 and 5.9×10^2 CFU per g, respectively; many did not conform to the regulatory specifications (Abd-El-Aziz & &Moharram, 2016).

3.2.1. *Control of seafood-borne microbial hazards*

The above discussed scenario, particularly frequent incidences of *Salmonella*, *Vibrio*, and viruses such as hepatitis A and E, and norovirus and *Listeria* in the highly traded fresh and frozen shrimp and shrimp products stress the need for better control measures for pathogen elimination. Recent efforts to control these hazards include the Food Safety Objectives (FSOs) and Performance Objectives (POs), which are distinct levels of foodborne hazards that cannot be exceeded at the point of consumption and earlier in the food chain, respectively. These objectives can be met by good agricultural practices and good hygienic practices (GAPs and GHPs, respectively) and Hazard Analysis Critical Control Point (HACCP) (ICMSF, 2018). Foodborne viral infections, being a major cause of human illness, have attracted risk assessment and management strategies for their control (Bosch et al., 2018; EFSA, 2011a; Shukla et al., 2018). A practical guide is available for information interchange around seafood safety and food safety systems (Soares et al., 2016, p. 200). The U.S. FDA operates a mandatory safety program under the provisions of the Federal Food, Drug and Cosmetic (FD&C) Act, the Public Health Service Act, and related regulations. The National Shellfish Sanitation Program (NSSP) promotes and improves the sanitation of shellfish including oysters, clams, mussels, and scallops (FDA, 2020). In view of the increasing incidences of hazards, it has been felt that public health authorities are likely to face new challenges to guarantee seafood safety and to sustain consumers' confidence in processed fishery products, particularly in a warmer world (Marques et al., 2010). INFOSAN has called for stronger steps to protect consumer health against foodborne diseases (INFOSAN, 2020). It is likely that the current measures may not be fully adequate to guarantee food safety and therefore, additional control measure(s) may be required (Norhana et al., 2010).The following discussion is intended to suggest potentials of electron beam irradiation to control seafood-borne biohazards.

4. Radiation processing

Radiation processing is finding increasing uses in recent times, essentially for the, control of food-borne biohazards including phytosanitary problems associated with agricultural commodities. Generally known as 'cold pasteurization' it improves the hygienic quality of food through inactivation of foodborne pathogens, as it does not significantly raise the temperature of the products, and therefore, does not affect flavor, aroma, and color of the foods. The high penetration capacity of the radiation helps its use as an intervention process to control biohazards even in frozen, packaged food items. It is to be emphasized that irradiation of food is justified only when it fulfills a technological need such as hygienization and is not a substitute for good manufacturing practices. The advantages of irradiation to improve safety of muscle foods and other food products have been discussed by several authors (Agbaka & &Ibrahim, 2020; Eustice, 2020; Ashraf et al., 2019; Ehlermann, 2016; Maherani et al., 2016; Arvanitoyannis et al., 2009; (Molins et al., 2001)IFT, 2000).The general aspects of food irradiation are briefly discussed, followed by potentials of electron beam irradiation of seafood.

4.1. *General aspects*

The technology of food irradiation was initiated using ionizing radiations emitted by the radioisotopes, cobalt ($_{27}Co^{60}$) and cesium ($_{55}Cs^{137}$). The $_{27}Co^{60}$ (having a half-life, 5.27 years) is made by neutron bombardment of natural cobalt, $_{27}Co^{59}$. The isotope emits two gamma rays of 1.17 and 1.33 million electron volts (MeV), thereby stabilizing as nickel. The other isotope, $_{55}{}^{137}$Cesium, is formed during nuclear fission of uranium and emits a weaker gamma ray of 0.66 MeV. In view of consumer concerns regarding the use of radioisotopes for food purposes and associated problems, in recent times, interests are focused on alternate radiation sources, namely, electron beam and X-rays for the treatment of foods, food irradiation. In order to optimize the process parameters for radiation treatment of a food item for specific purpose, it is important that the radiological, toxicological, and as well as the nutritional safety and wholesomeness aspects of the treatment are established. These are briefly mentioned below:

The initial effect of irradiation on food is essentially the radiolysis of water resulting in the formation of free radicals, as shown below:

$$\begin{aligned} H_2O \rightarrow\ & OH\ (2.7)\ +\ e^-_{aq}\ (2.7) \\ & +\ H\ (0.55)\ +\ H_3O+\ (0.45) \end{aligned}$$

These free radicals include solvated electron e^-_{aq}, hydroxyl radical ($OH\cdot$), proton ($\cdot H\cdot$), and protonated water (H_3O^+). (The figures in parentheses indicate G values, viz., the relative amounts of species formed as a result of absorption of 100 ev of absorbed energy). The free radicals are very reactive, and can interact among themselves or with food constituents, resulting in chemical changes. The presence of oxygen during irradiation and subsequent storage has an important influence on the changes due to possible formation of ozone (O_3), a very powerful oxidizing agent. Presence of liquid water in the food helps free radicals diffuse in the material resulting in significant radiolytic changes. The radiolytic changes are influenced by the nature of food components, absorbed radiation dose, temperature, viscosity and composition of the food, and also the atmosphere (such as air, nitrogen or vacuum) in contact with the food. These changes are minimum in frozen or dry foods due to poor diffusivity of free radicals (Ehlermann, 2016; Molins et al., 2001).

The radiation absorbed by any materials including food during irradiation is quantified by 'radiation absorbed dose' (denoted as 'rad'). The unit (SI) for radiation is the Gray ('Gy'), which is equal to the absorption of energy equivalent to 1 J per kg of absorbing material. One 'Gy' is equivalent to 100 rad, 1000 Gy = 1 kGy. During irradiation of food, the absorbed dose decreases continuously with increasing depth of the food and at about 5 cm of depth, the limit of penetration is reached. Since uniform absorption of dose by the material is not attained, the ratio of highest dose (D_{max}) to lowest dose (D_{min}) is taken as dose uniformity ratio or overdose ratio. Average dose (D_{av}) is the value obtained by dividing the total dose measured by the number of measurements. As per 'good irradiation practices' the dose range should be as narrow as technically feasible. The ratio of maximum to minimum doses in radiation processed foods is usually in the range of 2–3 (Kunz & &Strasser, 2016; Molins et al., 2001). It is essential that an irradiated food be identified for the purpose of process standardization, regulatory requirements, consumer information and trade. At the recommended irradiation doses for specific food applications, there are no major chemical, physical, or sensory changes in foods. Therefore, sensitive techniques are required to measure the changes in food. Some promising methods for detecting these changes include gas chromatographic measurements of alkanes, alkenes, 2-alkylcyclobutanones in lipid rich foods, electron spin resonance (ESR) for detecting free radicals in foods containing bones and shells, such as shellfish, thermo-luminescence for food containing silicate minerals, and DNA comet assay for low fat food (Chauhan et al., 2009).

Irradiation does not cause significant changes in food nutritional quality. A Joint Expert Committee under the aegis of FAO, International Atomic Energy Agency and WHO (FAO/IAEA/WHO) concluded in 1980 that "irradiation of foods up to the dose of 10 kGy introduces no special nutritional or microbiological problems" (ICGFI, 1987, pp. 14–18). In general, most food nutrients are unaffected by irradiation at the doses employed. Some minor decreases in certain vitamins have been reported, but not enough loss to cause their deficiency when irradiated foods along with other foods are consumed (Ravindran & Jaiswal, 2019; Molins et al., 2001; Diehl, 1995). Irradiation, because of its ability to eliminate vegetative forms of bacterial pathogens as well as parasites, has potential for use as a critical control point (CCP) in food processing operations (Molins et al., 2001). Food irradiation is approved by as many as 60 countries for several food commodities including spices, fruit, vegetables, meat and poultry. Since 2010, there has been a notable increase in the production and trade of irradiated foods (Maherani et al., 2016). Currently, about 500,000 tons of foods are being irradiated every year in about 200 large scale irradiators (Nordion, 2021). For identification purposes, the irradiated foods need to bear the international symbol for irradiation ('RADURA') on the packages and carry the statement "Treated with radiation" or "Treated by irradiation" on the food label. The international standards and national regulations for food irradiation are well-established. Rationalization and greater consistency in regulations would be advantageous for the future growth food irradiation. Lack of necessary harmonization of regulations among nations, however, is currently restricting international trade of irradiated food (Agbaka & &Ibrahim, 2020; Roberts, 2016). In the US, introduction of irradiated foods into the marketplace has gone quietly, supported by positive consumer responses. However, in some countries, particularly in Europe, consumer concerns have been felt (Eustice, 2020; Galati et al., 2019; Munir & Federighi, 2020). Adverse concerns, however, can be alleviated by proper education to make consumers understand the technology and its appropriate benefits (Bevelacqua & JavadMortazavi, 2020; Maherani et al., 2016).

4.2. Electron beam irradiation

Public concerns on the use of radioisotopes for food purposes have made food irradiation technology moving from isotope irradiation to electron beam (E-beam) and X-rays. An E-beam is produced by Van de Graaff generators or linear accelerators (LINAC). Generally, electrons are accelerated using either one or two 10 MeV, 18 kW S-Band microwave-based linear accelerators (National Center for Electron Beam Research (NCEBR, 2021). Other production methods include direct-current systems, microwave linear accelerators and radio-frequency accelerators (Cleland, 2006). Unlike gamma rays, E-beam production can be switched on or off depending on the need. The turn off facility helps decrease costs and enables in-house facilities. E-beams are easier to maneuver with a magnetic field. Further, the facilities are free from concerns associated with transportation, installation and operation, unlike gamma rays facilities. However, like gamma sources, E-beam must also be installed in a concrete room to contain electrons. For food decontamination, the electron accelerators use voltages in the range 100–200 kV for electron acceleration, which takes place in vacuum. The accelerated electrons irradiate the surfaces of the materials passing the beam on a conveyor (Lung et al., 2015; Miller et al., 2013, pp. 1–34). The effects of gamma rays and electron beams on food constituents, are comparable. When an E-beam penetrates an aqueous medium, the dose somewhat below the surface, say 2 cm, is about 25% higher than at the surface. This is due to the formation of secondary electrons that, because of their lower energy, are more effectively absorbed than the primary electrons. The absorbed dose decreases with increasing depth and at about 5 cm the limit of penetration is reached. In contrast, the absorbed dose decreases continuously with gamma and X-rays as a function of thickness of the product being treated (Hayashi, 1991). A guide on the use of electron beams for microbiological decontamination of surfaces is available, which gives suggestions for the measurements of dosimetry and for establishing the appropriate effective dose (Miller et al., 2013, pp. 1–34) (Fig. 1).

The E-beam technology has been used for quite sometimes to sterilize medical devices and is now approved by the US FDA for food purposes (Lung et al., 2015). Although electrons are less penetrating than gamma rays, they can be very useful for irradiating large volumes of free flowing food items, such as grains or packages of foods such as fish fillets not more than 8–10 cm thickness with a density of 1 g/cm^3 (Pillai & Shayanfar, 2017). The choice to use one or two E-beam sources depends on the research question, the product dimensions, the density of the materials, and the expected dose distribution within the product. During commercial irradiation of ground beef for example, both E-beam sources are utilized to obtain a very uniform dose distribution (NCEBR, 2021). Fig. 1 indicates symbolic representation of E-beam processing, while Fig. 2 shows an E-beam irradiator.

In addition to E-beam, X-rays, another type of electromagnetic radiations, are also beneficial for food treatment. X-rays are generated by converting an electron beam (up to 5 MeV). For production of X-rays, electrons coming out of the LINAC strike against a high atomic number material such as tantalum to generate X-rays. X-rays have wavelengths between ultraviolet and gamma rays and have penetrating power comparable to gamma rays. X-ray penetrates foods more slowly than

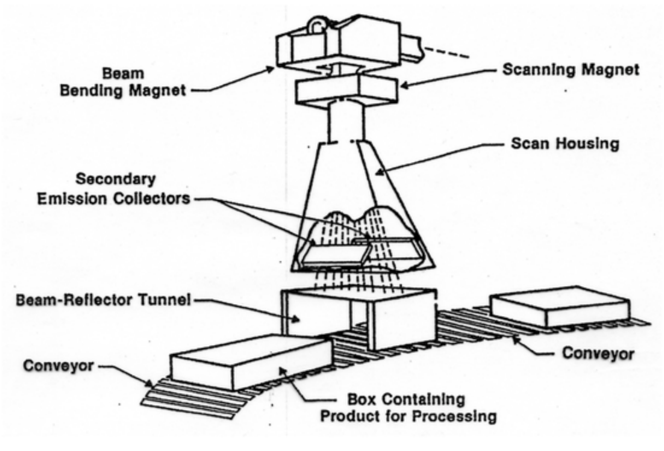

Fig. 1. Symbolic representation of electron beam processing of food products.

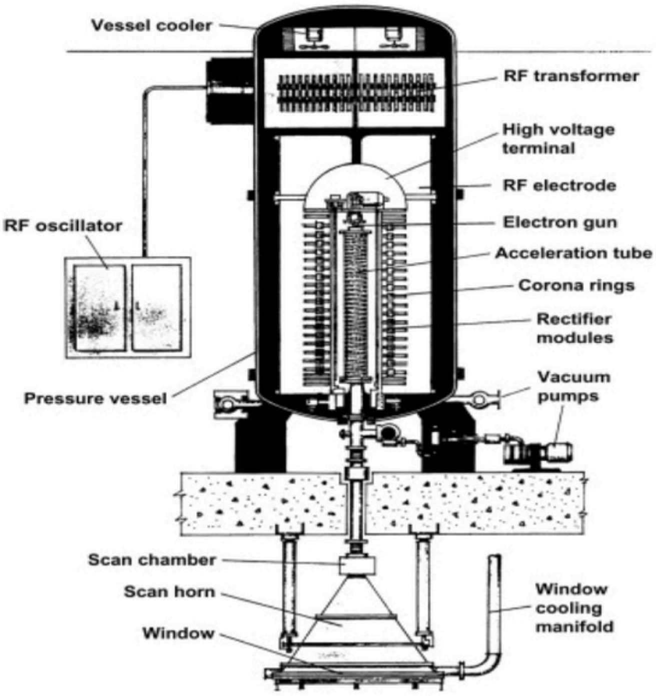

Fig. 2. Electron beam irradiator. Courtesy, Agbaka and &Ibrahim (2020), with permission.

gamma irradiation but much more deeply than electron beams. There is agreement in the scientific community that X-ray treatment of food at 7.5 MeV can be safe (Cleland, 2006). An X-ray dose of 2 kGy effectively eliminated 10^4 CFU/g of *L. monocytogenes* per g of smoked mullet, without affecting its sensory quality (Robertson et al., 2006). The use of X-ray for food processing, however, is limited because of poor conversion of E-beam to X-rays and its dose rate, which is much less than that of E-beam. Table 4 presents comparison of gamma rays, E-beam and X-rays with respect to their food applications.

Table 4
Advantages and disadvantages of ionizing radiations from different sources.

Type of source	Advantages	Disadvantages
Gamma rays from Cobalt-60 and Caesium-137	Unidirectional, good penetration, reliable, Proven technology Maximum penetration, 300 mm	Low energy and intensity Continuous emission Licensing tightly regulated Characterized as nuclear and hence consumer concerns Limited suppliers
Electron beam (E-beam)	High efficiency and intensity On and off operation Directions can be adjusted with a magnetic field Maximum penetration, 38 mm from 10 MeV Less shielding requirement compared with gamma irradiation facility Faster processing than by X-ray	Limited penetration (0.5 cm per MeV) Limited range of operations
X-ray	Hybrid of electron beam and gamma rays Small radiation area Simple conveyors Higher penetration	Low conversion efficiency Higher cost than E-beam irradiation Faster than gamma ray processing High heat in converter plate Dose rate lower than E-beam

Adapted from Agbaka & &Ibrahim, 2020; Miller et al., 2013, pp. 1–34; Hayashi et al., 1991.

4.3. Control of biohazards by E-beam irradiation

Radicidation is a specific case of food irradiation where sufficient dose of ionizing radiation is applied to eliminate viable specific non-spore-forming pathogenic microorganisms. Adhesion of these organisms to food surfaces and their internalization of muscle tissue limit conventional processing and chemical sanitization methods such as by sodium hypochlorite and aqueous chlorine dioxide. The penetrating nature of E-beam helps sanitization of foods, particularly frozen items, such as shrimp, fillets, and minced fish blocks. The dose required depends on the nature of the product and treatment conditions ((Molins et al., 2001)Radomyski et al., 1994).Electron beam irradiation has been approved for food irradiation and its advances have been summarized (Lung et al., 2015).

4.3.1. Inactivation of bacterial pathogens

Pathogenic microorganisms are generally very sensitive to radiation. Irradiation causes their inactivation essentially due to scission of single or double strands of DNA caused by the free radical, $OH^{\cdot}$ In addition, the radiation can also damage membrane and other structures causing sub-lethal injury to living cells. Predmore et al. (2015) observed that E-beam irradiation disrupted virion structure, and degraded proteins and genomic RNA of viruses including murine noro virus (MNV-1) and Tulane virus (TV), suggesting that mechanism of inactivation of E-beam is comparable to gamma irradiation. The radiation sensitivity of microorganisms is defined as the dose required for the inactivation of 90% of microbial population, and is expressed as D_{10} value. Viruses are most resistant to irradiation, while parasites are the least resistant. The relative radiation resistance of microorganisms can be summarized as follows viruses > spores > gram positive bacteria > gram-negative bacteria > yeasts and molds > parasites. The D_{10} values, however, are influenced by the nature of microbial genera and species, conditions of treatment such as medium, temperature, presence of oxygen, food components, pH, water activity, and others. Microorganisms such as *Deinococcus radiodurans* and, *Acinetobacter radioresistens* may show extreme radiation resistance, but they are not food pathogens. There is no evidence of formation of mutants of microorganisms that can affect food safety. Studies have shown that irradiation at a dose ranging 2–6 kGy can effectively eliminate pathogens such as *Salmonella* spp and *S. aureus* as well as emerging pathogens such as *Campylobacter*, *L. monocytogenes*, *E. coli* O157:H7, *V. cholera.* The topic of radiation microbiology has been discussed by several authors (Munir & Federighi, 2020; Pedreschi & &Mariotti-Celis, 2020; IFT, 2015; Sommers & Rajkowski, 2011; Farkas, 1998; Monk, 1995; Radomyski et al., 1994).

Electron beam irradiation at an absorbed dose of 1 kGy reduced the viability of mixtures of O157 and non-O157 verotoxigenic *E. coli* (VTEC) and *Salmonella* serovars from fresh beef surfaces. *Salmonella* and *E. coli* showed a reduction of ≤ 1.9 and ≤ 4.0 log CFU /g, respectively (Kundu et al., 2014). The D_{10} values at 4 °C of 40 shiga toxin-producing *E. coli* (STEC) isolates suspended in lean ground beef ranged from 0.16 to 0.48 kGy, with a mean of 0.31 kGy. The isolates associated with illness outbreaks had a lower mean D_{10} value of 0.27 kGy (Sommers et al., 2015). The treatment at 3 kGy could eliminate *E.coli* O157:H7, *S.* Typhimurium, *L. monocytogenes* and *B. cereus* (Waje et al., 2009). Inoculated pack studies have shown that *L. monocytogenes*, *Staphylococcus aureus*, and *Salmonella* spp. in frozen (−20 °C) seafood samples had low D_{10} values in the ranges of 0.43–0.66, 0.48 to 0.71, and 0.47–0.70 kGy, respectively. Irradiation under frozen conditions with 2.25 kGy resulted in a significant reduction in *Salmonella* by 5 logs; the reduction was maintained in frozen samples for over a period of 3 months, indicating the effectiveness of this method (Sommers & Rajkowski, 2011). *K. pneumoniae* is sensitive to gamma radiation, with D_{10} values in the range of 0.116–0.277 kGy. No recovery of *K. pneumoniae* in 1.5 kGy irradiated fish during 12 days of storage at 4 °C was observed (Gautam et al., 2015). A dose of 1 kGy in combination with traditional depuration improved the hygienic quality of shellfish. The treatment eliminated *V. cholerae*, and *V. parahemolyticus*, from shellfish (Mallett et al., 1991).

4.3.2. Control of viruses

Irradiation has limitation to control viruses because of their high resistance. A high dose of 8.7–16.3 kGy was required to eliminate Tulane virus (TV) to non-detectable levels from agricultural products (Ahmed et al., 2020; Predmore et al., 2015). Nevertheless, irradiation at lower doses can significantly reduce virus carriage numbers thereby enhancing the hygienic quality of hard-shelled clam and oyster. The E-beam irradiation of whole oyster at 5 kGy reduced marine noro virus (MNV) and hepatitis virus (HAV) by 26 and 91% respectively (Praveen et al., 2013). A D_{10} value of 2 kGy was determined for the depletion of hepatitis A virus in clams and oysters while a slightly higher D_{10} value of 2.4 kGy was required for rotavirus SA11 (Mallett et al., 1991). As compared to microbial pathogens, their toxins require higher doses for inactivation (Predmore et al., 2015). Table 5 gives D_{10} values of several microorganisms in fish/shellfish and other matrices under different treatment conditions.

4.4. Inactivation of parasites

Low doses of E-beam can eliminate parasites from chilled and frozen fish and also insects from dry fishery products. A low dose of 1.0 kGy is a safer treatment that can replace fumigation, as it can inactivate protozoan or helminth parasites (Thayer, 2004). Tapeworms (such as *Dipylidium*, *Diphyllobothrium latum*, *D. yonagoense*, and *D. pacificum*) and *Anisakis simplex* can be inactivated by the process. The parasite, *Toxoplasma gondii* is readily inactivated by irradiation at doses of 0.25 kGy (Loaharanu & Murrell, 1994). These suggest potential role radiation including E-beam in improving food safety. Thayer (2004) convincingly argues that physicians and other health care professionals should also be advocated for the irradiation of foods to prevent the transmission of infection.

Table 5
D_{10} values of some microorganisms in fish/shellfish and other media.

Microorganism	Medium	Temp. (°C)	Matrix	D_{10} value
Vibrio cholerae	Prawn	−10 ± 2	Air	0.11
V. flavialis	Shrimp paste	−20	Vacuum	0.44
V. mimucus	Shrimp paste	−20	Vacuum	0.75
V. parahaemolyticus	Shrimp, 1% salt	−20	Vacuum/air	0.44/0.07
V. vulnificus	Shrimp paste	−20	Vacuum/air	0.30/0.35
***Vibrio* spp.**	Frozen food	−20	–	0.04–0.44
V. alginolyticus	Shrimp paste	−20	Vacuum	0.19
Aeromonas hydrophila	Fish	0	Air	0.14
A. hydrophila	Shrimp paste	0	Air	0.09–0.11
Shigella flexneri	Shrimp paste	Frozen	–	0.22
***Salmonella* Paratyphi A**	Oyster paste	5	–	0.75
***S.* Paratyphi B**	Oyster paste	5	–	0.85
***S.* Typhimurium**	Frozen seafood	−20	–	0.47 to 0.70
***S.* Typhi**	Crab meat	–	–	0.87
Streptococcus fecalis	Shrimp paste	–	–	5.0–7.5
Bacillus cereus	Shrimp/fish	0–2	Air	0.2–0.3
Listeria monocytogenes	Shrimp/fish	0–2	Air	0.15–0.25
Listeria monocytogenes	Seafood	−20	Air	0.43 to 0.66
Yersinia enterocoliticus	Shrimp/fish	0–2	Air	0.10–0.15
Hepatitis A virus	Clam, oyster	–	Air	2.02
Staphylococcus aureus	Frozen seafood	−20	Air	0.48 to 0.71
Klebsiella pneumoniae	Fish		Air	0.136
Campylobacter jejuni	Frozen food	−20	–	0.18–0.32
***E. coli* O157:H7**	Frozen food	−20	–	0.30–0.98
***Salmonella* spp.**	0.18–0.92	0.37–1.28	–	0.29–0.95
Shigella dysentariae	Shrimp	−18	–	0.22
Shigella flexneri	Shrimp	−18	–	0.41
Alcaligenes spp.	Fermented vegetable	Ambient	Air	0.47

Sources: Radomyski et al., 1994; Monk et al., 1995; Venugopal et al., 1999; Sommers & Rajkowski, 2011; Munir & Federighi, 2020.

4.5. Other benefits

In addition to control of biohazards, irradiation of seafood has other advantages including extension of refrigerated shelf life of fresh products and inactivation of insects in dried products. Contaminations by spoilage-causing gram-negative microorganisms are responsible for the rapid spoilage of fishery products. During ice storage, psychrotrophic spoilage organisms, which are highly proteolytic, predominate causing breakdown of fish proteins leading to spoilage (Huss et al., 2003, p. 230; Venugopal, 1990; Zhang et al., 2020). Most of these organisms have generally lower D_{10} values (Sommers & Rajkowski, 2011; Monk et al., 1995). Irradiation of fresh fish, at doses ranging from 1 to 3 kGy, therefore results in preferential inactivation of spoilage causing organisms leading to extension of shelf life under chilled conditions (Arvanitoyannis et al., 2008; Venugopal, 2006, chap. 10; Venugopal et al., 1999). Infestations of blow-fly are the major cause of losses in dried fish caused by insects such as flesh flies (Sarcophagidae), beetles (*Dermestes*, *Cornestes,* and *Necrobiaspp*) and mites (*Lardoglyphus*), which may enter fish during processing, particularly sun-drying). These insects could be inactivated by E-beam irradiation. A dose of 0.15 kGy can prevent development of insects in dried fish at a moisture level below 20%. At doses ranging from 0.15 to 0.4 kGy insect pests are inactivated. Although some pests may be alive in the treated products, they will not complete the process of development or reproduction (Venugopal et al., 1999). Table 6 depicts effects of irradiation on disinfestation of dried fish.

Combination of irradiation with other treatments can synergistically enhance shelf life. For example, antimicrobial treatment with nisin, fish protein coating and irradiation at 2 kGy enhanced refrigerated shelf life of seer fish steaks from 7 to 34 days (Kakatkar et al., 2017). A combination of hurdles including reduced water activity, packaging and gamma-irradiation at 2.5 kGy gave shelf-stable, ready-to-eat shrimps (Kanatt et al., 2006). E-beam irradiation of salted and seasoned short-

Table 6
Benefits of irradiation on disinfestation and shelf life of dried fish.

Fish	Irradiation dose (kGy)	Insects	Post-irradiation shelf life	Remarks
Bombay duck	0.25	Not identified	1 year	Packaging in high density polyethylene
Croaker	0.25	Not identified	1 year	Packaging in high density polyethylene
Mackerel	0.30	Not identified	9 months	Packaging in high density polyethylene
Mackerel	0.3	*D. maculatus*	5 months	Heavy damage if not irradiated
Mackerel, salted, dried	0.5–0.75	*Necrobia* spp.	6 months	Product contains 40% moisture and 12% salt
Milk fish, smoked	4	Mold growth	5–15 weeks	Sorbate (0.1%) dip before irradiation
Shark	0.5–0.75	*Necrobia* spp.	6 months	Product contains 40% moisture and 12% salt
Rohu fish (freshwater)	0.25–1	Not identified	6 months	Sorbate (0.1%) dip before irradiation, Packaging in 0.1 mm polyethylene.

Adapted from Venugopal, 2006, chap. 10; Venugopal et al., 1999.

necked clam at 0.5, 1, 2 and 5 kGy significantly reduced initial flora of bivalve mollusk. There was no adverse change of sensory score except for the color of onion irradiated at 5 kGy (Kim et al., 2009). The potential benefits of seafood irradiation by E-beam are summarized in Table 7.

4.6. *Commercial prospects of E-beam irradiation*

Over the last couple of decades, E-beam irradiation has received greater attention for pathogen decontamination of food, because of its better consumer acceptability than gamma irradiation. The health and economic benefits associated with E-beam processing are reduction in biohazards caused by *Salmonella, E. coli* O157:H7, *L. monocytogenes* and other pathogens, resulting in enhanced food safety and hence, better seafood security. The major advantages of E-beam are its environmentally friendly and cost-effective nature. In 1997 the U.S. FDA approved a maximum dose of 3 kGy and 7.0 kGy to eliminate pathogens from fresh or frozen, uncooked poultry and frozen red meat, respectively **(**Maherani et al., 2016**)**. The FDA, later amended its current food additive regulations to allow the use of ionizing radiations at a maximum permitted dose of 6.0 kGy to inactivate food-borne pathogens in crustaceans including crab, shrimp, lobster, crayfish and prawns. The approval refers to raw, frozen, cooked, partially cooked, shelled or dried crustaceans or cooked, or ready-to-cook, crustaceans processed with spices. The treatment can also reduce, but not entirely eliminate the number of pathogens including *L. monocytogenes*, *S. aureus*, *Vibrio*, *Salmonella*, *Shigella* and *E. coli.* An upper limit of 10 MeV for E-beam and 7.5 MeV for X-rays have been approved (US FDA, 2014). E-beam linear accelerators have been commercially used to eradicate *Salmonella* from mechanically deboned poultry meat (Sadat & Volle, 2000). The treatment can be useful for large volumes of food items such as fish fillets, packaged blocks of frozen seafood having thickness up to 8–10 cm. The irradiation process is also commercially used to eliminate *Vibrio* from oyster (Kontominas et al., 2021). Studies have indicated that about 20% of potential consumers were willing to consume irradiated oysters because of its enhanced safety (Pillai & Shayanfar, 2017). The US CDC has observed that food irradiation is the next logical step to reduce the burden of food-borne diseases in the US. The National Center for Electron Beam Research (NCEBR) at Texas, US is engaged in the promotion of E-Beam and X-ray technologies for improvement of food safety (NCEBR, 2021). An X-ray facility is under construction in the U.S. to cater to more than 30 clients including exporters of poultry and beef for pasteurization of their products (CCR-UCDAVIS, 2021).

The Opinion by the European Food Safety Authority Panel of the European Union, which provides independent scientific advice and communicates on existing and emerging risks associated with the food chain, confirms that there are no microbiological risks to the use of food irradiation and its consequences on the food microflora. The Opinion recommends that irradiation should be considered as one of several approaches to reducing pathogens in food and thus helping to ensure protection of consumers' health. It was pointed out that along in conjunction with an integrated food safety management program including GAP, GHP, GMP and HACCP, and depending on the dose applied, food irradiation can contribute to improved consumer safety by reducing food-borne pathogens (EFSA, 2011b). Synergistic effects of irradiation with other food processing methods such as modified atmosphere packaging, refrigeration, freezing and heating offer promise and therefore, are likely to be more commercially applied in the coming years. There is much potential to use E-beam in this regard. Seafood treated with ionizing radiation must be stored, handled, and cooked in the same way as non-irradiated foods. Sanitized fishery products are highly suitable for immuno-compromised people who are vulnerable to food-borne diseases (Mohácsi-Farkas, 2016).

Table 7
Advantages of E-beam irradiation of seafood.

Elimination of pathogens in fresh and frozen seafood
Hygienization of individually quick frozen (IQF) fishery products
Hygienization of minimally processed products
Reduction of pathogens in live products such as hard-shell clams
Hygienization of aqua-feed
Hygienization of fish meal
Extension of shelf life of fresh fish under chilled condition
Elimination of parasites from dried fishery products
Possibility of combination of irradiation with other food processing methods for better quality

5. Conclusions

The article briefly pointed out the various biohazards associated with different seafood items. The characteristic nature of fishery production, processing, trade and social practices in some parts of the world to consume raw fish, all warrant increasing efforts to control these hazards. Whereas conventional control measures have limitations, E-beam irradiation can be an effective intervention treatment to enhance seafood safety. Radicidation treatment by E-beam is a safe, efficient, environmental friendly and energy efficient process to significantly reduce biohazards, particularly microbial pathogens of public health significance and also parasites. A variety of products including frozen blocks of seafood, individually quick frozen (IQF) shrimp and other shellfish, fish fillets, among others can be treated by radiation under packaged conditions. The treatment has negligible effects on wholesomeness and sensory quality of fishery products. The treated products can remain safe and protected from microbial contamination, thereby enabling domestic as well as international trade, contributing towards aquatic food security.

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Declaration of competing interest

None.

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