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Current Status and Effect of Irradiation on Food Processing & Preservation

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ABSTRACT
Food irradiation is one of the most thoroughly investigated food preservation techniques, which has been shown to be effective and safe through extensive research. This process involves exposing food to ionizing radiation in order to control foodborne pathogens, reduce microbial load and insect infestation, inhibit the germination of root crops, delay ripening and senescence, improve functional properties and extend the durable life of perishable produces. This study reviewed the basic principles, various effects, applications and the associated potential health risk, if any, posed to consumers as a result of consumption of irradiated food. The safety and consumption of irradiated foods have been extensively studied at national levels and in international bodies such as the World Health Organization (WHO), the Food and Agricultural Organization (FAO) and Codex Alimentarius and have concluded that foods irradiated under appropriate technologies are both safe and nutritionally adequate. The irradiation of foods at the optimum dose under good manufacturing practice conditions can be a safe and cost-effective method, resulting in enhanced shelf-life and hygienic quality with the least amount of compromise on the various nutritional attributes, whereas the consumer acceptance of irradiated fruits is a matter of providing the proper scientific information.
Keywords: *Irradiation, Nutritional value, Radiation sources, Food safety, Consumer acceptance*

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INTRODUCTION
Food irradiation is the processing of food products by ionizing radiation in order to control foodborne pathogens, reduce microbial load and insect infestation, inhibit the germination of root crops, and extend the durable life of perishable produce [34, 35]. Food irradiation, sometimes called "cold pasteurization," has been described as the "most extensively studied food processing technology in the history of humankind" and is endorsed or supported by virtually all medical and scientific organizations, yet the process is still considered a relatively "new" technology. Irradiated food does not become radioactive, as the particles that transmit radiation are not themselves radioactive. Irradiation technology can be used as an alternative method for the reduction of food losses which are caused either by insect infestation of grains and pulses, or of animal origin such as poultry and seafood [47]. Food irradiation has the potential to reduce pathogenic microorganisms and to inactive parasites that may be present in foods [47, 55], thus contributing to improvements in food hygiene and enhancing public health. Moreover, irradiation may serve as a quarantine treatment for many fruits, vegetables, nuts, cut flowers and animal origin products, thus facilitating international trade of such foods [27].
Irradiation is approved in more than 50 countries around the globe for a wide variety of food products, and the volume of food treated is estimated to exceed 500,000 metric tons annually worldwide; however, the extent of clearances is varying significantly, from a single food category (dried herbs, spices and vegetable seasonings) in Austria, Germany, and many other countries of the European Union to any food in Brazil [14, 15, 21, 22].

EFFECTS OF IONISING RADIATION
Physical effects

Physical effects include changes in crystallinity, permeability, surface structures and post irradiation aging effects. Radiation changes in the physical properties of a packaging material should not delay its function [29]. Since the Permeability is measure of the ease with which gases or vapours can penetrate through the polymer materials, it is a major consideration in the selection of a polymeric material for food packaging.

Kale [41] showed that, physical properties such as permeability, crystallinity, mechanical strength and IR spectra of irradiated polymers were unaffected at high doses carried out on the effect of radiation on polymeric films both single such as polypropylene, low density polyethylene (LDPE), PET and laminates (BOPP/LDPE, PET/LDPE, PET/PET/LDPE, PET/metalized PE/LDPE, PET/HDPE-LDPE, Polyolefin-Tie layer-Nylon-Tielayer-LDPE and 5 layer nylon coextruded film/Metalized PET). Study on different packaging films, permeating gases and analytical techniques have confirmed that, there is no modification in the permeability, crystallinity and shrinkage in regularly used packaging materials such as low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene, polyethylene terephthalate (PET), poly vinyl chloride and poly vinylidene chloride in the dose range of 0-8 kGy [24, 25]. Some researchers have shown that, changes in mechanical properties of certain polymers e.g. polyethylene can be minimized (when subjected to higher doses of radiation) using suitable stabilizers [7-9]. Also deterioration with respect to dosage was reduced after laminating of some polymers (e.g. polypropylene) with LDPE.

Chemical effects

Chemical effects include evolution of radiolysis products, migration of radiolytic products of the polymers and degradation of antioxidants [64]. Radiolytic degradation should neither be toxic nor affect the sensory qualities of the packed product. Hydroxyl radicals and hydrogen peroxide generated upon the irradiation of water molecules are highly reactive and readily react with most aromatic compounds, carboxylic acids, ketones, aldehydes, and thiols [58]. During irradiation, ions and free radicals are produced. These highly reactive materials are responsible for the colour changes in irradiated polymers and could migrate into food and affect taste, odour and safety [59, 66]. Most food packaging materials are originated from polymers. They may be susceptible to chemical changes (after ionizing radiation) that are the result of two reactions, cross-linking (polymerization) and chain scission (degradation). Both reactions are generally relative to dose, and depend on dose rate and the oxygen content of the atmosphere in which the polymer is irradiated [3].

Also post irradiation aging effects could be the result of trapped radicals in crystalline regions of polymers [7, 8]. It must be noted that the radiation induced changes depend on the polymer composition (additives), processing history of the plastic and the irradiation conditions (presence of oxygen, temperature, dose and dose rate).For example, plastic films containing a phenyl group or an amide linkage (are known to stabilize the polymer) are the most radiation resistant, due to their increased resonance energy [66]. Therefore, radiation resistant of polystyrene, polyester and polyamide is due to the high energy requirement to form cross-links [13].

Biological effect

The biological effect of ionising radiation is inversely related to the size and complexity of the organism. The DNA damage may be due to direct but random strikes of the ionising radiation that causes the formation of lesions on either both or one of the DNA strands. Double strand lesions are almost invariably lethal [16]. This direct effect on DNA predominates under dry conditions, such as when dry spores are irradiated. Alternatively, the radiations may produce free radicals from other molecules, especially water, which diffuse towards and cause damage to the DNA [26].

TECHNOLOGIES

Irradiation treatments are also sometimes classified as radappertization, radicidation and radurization [19]. Efficiency illustration of the different radiation technologies (electron beam, X-ray, gamma rays)

Electron irradiation

Electron irradiation uses electrons accelerated in an electric field to a velocity close to the speed of light. Electrons are particulate radiation and, as any other particulate radiation, have a limited range in matter. For this reason, electrons do not penetrate the product beyond a few centimeters, depending on product density. As food is travels perpendicular to the beam direction, this spot of incident electrons is scanned across food [60].It performs best when used on low-density, uniformly packaged products. Therefore, it can effectively inactivate foodborne pathogens on the surface of the slices, with the least negative effect [32, 37].

Gamma irradiation

Gamma radiation is radiation of photons in the gamma part of the electromagnetic spectrum. Cobalt-60 is produced in a nuclear reactor via neutron bombardment of highly refined cobalt-59 (^{59}Co) pellets, while cesium-137 is produced as a result of uranium fission. Food irradiation using cobalt-60 is the preferred method by most processors, because the deeper penetration enables administering treatment to entire industrial pallets or totes, reducing the need for material handling. Presently, caesium-137 is used only in small hospital units to treat blood before transfusion to prevent Graft-versus-host disease. Radioactive material must be monitored and carefully stored to shield workers and the environment from its gamma rays. The gamma radiation cannot be switched off and when not being used to treat food, must be stored in a water pool to absorb the radiation energy and protect workers from exposure if they must enter the irradiation room [32].

X-ray irradiation

X-rays are generated by colliding accelerated electrons with a dense material (target) such as tantalum or tungsten in a process known as bremsstrahlung-conversion. The high-energy electron beams have limited penetration power and are suitable only for foods of relatively shallow depth [58]. Although X-rays have been shown to be more penetrating than gamma rays from cobalt-60 and cesium-137 with the added benefit that the electronic source stops radiating when switched off, the efficiency of conversion from electrons to X-rays is generally less than 10% and this has hindered the use of machine sourced radiation so far [34].However the X-ray efficiency can be increased with atomic number of the target material and also with increasing E-beam energy [44]. They also permit dose uniformity, but these systems generally have low energetic efficiency during the conversion of electron energy to photon radiation requiring much more electrical energy than other systems.

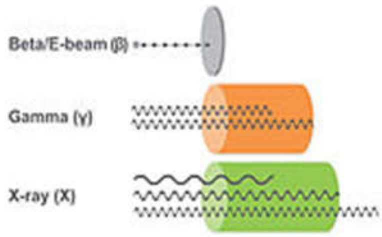

Illustration of the penetration properties of the different radiation technologies (electron beam, X-ray, gamma rays)

DOSIMETRY

Radiation dosimetry is the measurement of the absorbed dose in matter and products resulting from the exposure to radiation [11]. "Dose" (short for *radiation absorbed dose*) is the physical quantity governing the radiation processing of food, relating to the beneficial effects to be achieved. It is essential to monitor and document the absorbed dose during each production run [52].It is measured in the SI unit known as the gray (Gy). One gray of radiation is equal to 1 joule of energy absorbed per kilogram of food material. In radiation processing of foods, the doses are generally measured in kilograys (kGy, 1,000 Gy).The measurement of radiation dose is referred to as dosimetry and involves exposing dosimeters jointly with the treated food item [49]. Dosimeters are small components attached to the irradiated product made of materials that, when exposed to ionizing radiation, change specific, measurable physical attributes to a degree that can be correlated to the dose received. Standards that describe calibration and operation for radiation dosimetry, as well as procedures to relate the measured dose to the effects achieved and to report and document such results, are maintained by the American Society for Testing and Materials (ASTM international). On the basis of the dose of radiation the application is generally divided into three main categories:

Low dose applications (up to 1 kGy)

- Sprout inhibition in bulbs and tubers 0.03-0.15 kGy
- Delay in fruit ripening 0.25-0.75 kGy
- Insect disinfestation including quarantine treatment and elimination of food borne parasites 0.07-1.00 kGy

Medium dose applications (1 kGy to 10 kGy)

- Reduction of spoilage microbes to prolong shelf-life of meat, poultry and seafoods under refrigeration 1.50–3.00 kGy
- Reduction of pathogenic microbes in fresh and frozen meat, poultry and seafoods 3.00–7.00 kGy
- Reducing the number of microorganisms in spices to improve hygienic quality 10.00 kGy

High dose applications (above 10 kGy)

These doses are above those currently permitted in the USA for commercial food items by the FDA. The European Union countries allow dried herbs and spices to be irradiated to a maximum dose of 15 kGy which is equal to an "overall average dose" of 10 kGy as defined under EU Directives (*i.e.* at the maximum dose uniformity ratio [maximum dose / minimum dose] of 3 allowed in the EU and using the relationship that "overall average dose" for dried herbs and spices is equal to the average of the sum of the maximum dose and minimum dose). Though these doses are approved for noncommercial applications, such as sterilizing frozen meat for NASA astronauts (doses of 44 kGy) [65] and food for hospital patients.

Packaging for irradiated foods

The radiation treatment can be applied after packaging, so re-contamination or reinfestation of the products is avoided. In 2001, the FDA illustrated gamma rays, E-beam and X-ray to be equal in conditions of levels and types of radiolysis products formed in the packaging materials [15, 25]. Polymers such as polyethylene, polypropylene, poly vinyl chloride, polystyrene, polyethylene terephthalate and polyamide are some of the most common plastic packaging materials presently available. They all contain additives that vary in nature and quantity for obtaining certain useful.

Some studies have shown, Irradiation can change some physical and chemical properties of polymeric packaging materials and the changes depend on the type of polymer, irradiation conditions and processing exposure [28, 54]. For this reason any packaging materials must be confirmed by FDA before use in food irradiation [13, 56]. Nowadays, flexible packages have been developed which tend to be multi-layer films with different barrier properties because, no single flexible material has all the chemical, physical and protective characteristics needed for packaging radiation-processed food [10, 64].

CFR Citation Packaging Materials Max Dose [kGy]

- Nitrocellulose-coated cellophane 10
- Glassine paper 10
- Wax-coated paperboard 10
- Polyolefin film 10
- Section 179.45(b) Kraft paper 0.5
- Polyethylene terephthalate film (basic polymer) 10
- Polystyrene film 10
- Rubber hydrochloride film 10
- Vinylidene chloride-vinyl chloride copolymer film 10
- Nylon 11 [polyamide-11] 10
- Section 179.45(c) Ethylene-vinyl acetate copolymer 30
- Polyethylene film (basic polymer) 60
- Section 179.45(d) Polyethylene terephthalate film 60
- Nylon 6 [polyamide-6] 60
- Vinyl chloride-vinyl acetate copolymer film 60

Applications of Food Irradiation

In order to provide consumers a year-round supply of various sprouting foods, such as potatoes, yams, garlic and onions, storage durations of up to several months are often necessary [1, 5]. Sprouting prevention and reduced rotting and weight loss have been observed in potatoes, garlic, onions and yams in the range of 50 -150 Gy [47]. The shelf-life of many fruits and vegetables, meat, poultry, fish and seafood can be considerably prolonged by treatment with irradiation. Exposure to a low dose of radiation has been demonstrated to slow down the ripening of bananas, mangoes and papaya, control fungal rot in strawberries and inhibit sprouting in potato tubers, onion bulbs, yams and other sprouting plant foods [62, 63]. Spices, herbs and vegetable seasonings are valued for their distinctive flavours, colours and aromas. However, they are often contaminated with microorganisms because of the environment and processing conditions under which they are produced [34]. Irradiation has since emerged as an alternative and widely used in the food industry for the decontamination of dried food ingredients [21]. In addition to the improvement of hygienic quality of various foods, irradiation has also been used as a method for decontaminating medicinal herbs [22]. The major problem encountered in preservation of grains and grain products is insect infestation. Irradiation has been shown to be an effective pest control method for these commodities and a good alternative to methyl bromide, the most widely used fumigant for insect control, which is being phased out due to its ozone depleting properties. In addition, ionising radiation can be used to destroy chlorophyll b in vegetable oil resulting in protection of oil from photooxidation and elimination of undesirable colour change in oil processing industry [9]. Ionising radiation has been shown to reduce the number of disease-causing bacteria such as *Listeria monocytogenes* [50, 4], *Escherichia coli* O157:H7 [4, 18], *Salmonella* [36, 61], *Clostridium botulinum* [46], *Vibrio parahaemolyticus* [36] etc. in various food commodities and allow food to be irradiated in its final packaging. The fresh plants from which spices are derived are almost always contaminated by microorganisms from the soil, windblown dust and by bird droppings. During the drying process, these microorganisms can grow to population densities exceeding 10^6 organisms per gram of material [47]. The commercial irradiation of spices has been approved and practiced in many countries for several years. Doses of 5 -10 kGy usually give quite satisfactory results (elimination of bacteria, mold spores and insects) without negative impact on chemical or sensory properties [43].

LABELING

Labeling laws differ from country to country. While Codex Alimentarius represents the global standard in particular under the WTO-agreement, member states are free to convert those standards into national regulations.

US Labeling

The Radura logo, as required by U.S. Food and Drug Administration regulations to show a food has been treated with ionizing radiation.

The US defines irradiated foods as foods in which the irradiation causes a material change in the food, or a material change in the consequences that may result from the use of the food. This definition does not include foods where one of the ingredients is irradiated. This definition is not consistent with the Codex Alimentarius. All irradiated foods must bear the Radura symbol at the point of sale and the term "irradiated" or a derivative there of, in conjunction with explicit language describing the change in the food or its conditions of use (CFR - Code of Federal Regulations).The Radura logo as regulated by FDA is slightly different from the international version as proposed in Codex Alimentarius (General Standard for the Labelling of Pre-packaged Foods. CODEX STAN 1-1985).

EU Labelling

The European union follows the Alimentarius provision to label irradiated ingredients down to the last molecule. However, there is no option provided to use the RADURA-logo use this logo voluntarily. The European Union is particularly strict in enforcing irradiation labeling requiring its member countries to perform tests on a cross section of food items in the market-place and to report to the European Commission; the results are published annually in the OJ of the European Communities.

Safety, security and wholesomeness aspects

Hundreds of animal feeding studies of irradiated food, including multigenerational studies, have been performed since 1950. Endpoints investigated have included sub chronic and chronic changes in metabolism, histopathology, and function of most systems; reproductive effects; growth; teratogenicity; and mutagenicity. A large number of studies have been performed; meta-studies have supported the safety of irradiated food (WHO, 1994). Based on the experimental findings of WHO, FAO and IAEA, Codex has set out the maximum absorbed dose delivered to a food should not exceed 10kGy and the energy level of X-rays and electrons generated from machine sources operated at or below 5 MeV and 10 MeV respectively, in part, to prevent induced radioactivity in the irradiated food [33].The possible toxicological effects of consuming irradiated foods have been extensively studied since the 1950s [53]. Feeding trails involved a variety of laboratory diets and food components given to human and different species of animals including rats, mice, dogs, quails, hamsters, chickens, pigs and monkeys have been conducted to assess the toxicological safety of irradiated foods [39]. Several generations of animals fed diets irradiated with doses ranging from 25 to 50 kGy, which is considerably higher than dose used for human foods, suffered no mutagenic, teratogenic and oncogenic ill effect attributed to the consumption of irradiated diet [42].

Processing of food by ionizing radiation causes a multitude of chemical changes. This is why it is so effective in inducing beneficial modifications. For comparison, cooking, smoking, salting etc. as traditional techniques cause even changes in the identity of a food and result in a new product; in some cases (green beans) cooking even removes a toxic compound. Considering food irradiation it is undisputable that many chemical changes occur, and from the beginning of the research into this method the innocuity of newly formed compounds was a main topic. The results, the state of the art, and the mainstream of science are that irradiated food in general is safe to consume [17]. The safety of the technology has been repeatedly considered and judged acceptable on available evidence. This has resulted in international bodies including the World Health Organization (WHO), the Food and Agriculture Organization (FAO), the International Atomic Energy Agency (IAEA) and Codex Alimentarius commending the process [45].

Public Impact and Opinion: Acceptance and trade

Irradiation has not been widely adopted due to an asserted negative public perception, the concerns expressed by some consumer groups and the reluctance of many food producers [48]. Consumer perception of foods treated with irradiation is more negative than those processed by other means. "People think the product is radioactive," said Harlan Clemmons, president of Sadex, a food irradiation company based in Sioux City, Iowa [30].But when the process is made clear to them they will become more in favour [45, 47].On the other hand, other studies indicate the number of consumers concerned about the safety of irradiated food has decreased in the last 10 years and continues to be less than the

number of those concerned about pesticide residues, microbiological contamination, and other food related concerns. Such numbers are comparable to those of people with no concern about food additives and preservatives. Consumers, given a choice and access to irradiated products, appear ready to buy it in considerably large numbers [12].
The use of the treatment as a commercial food process depends on its acceptance by consumers. Frequently, consumers are conservative and they are reluctant to accept products processed by new technologies like as food irradiation method. The main worries of consumer organizations included safety, nutrition, detection, and labeling of irradiated products [40]. Giving science-based information on food irradiation leads to positive consumer approaches [3, 5, 23]. Fox [23] reported that, consumer awareness of food irradiation was 29%. Also, 80% of consumers were unsure about the safety of irradiated foods. Only 11% of the interviewers expressed that irradiated foods are safe. It should be noted that upon hearing a benefit statement of food irradiation, level of positive attitude increased significantly (62%) towards irradiated foods. On the other hand, unfavourable description of irradiation has a great negative effect on consumer acceptance of irradiated foods. Recent study showed a low level of awareness among consumers about the food irradiation processing. 76.5% of the interviewed people did not know that irradiation could be used as a method for food preservation. 46% of them expressed that irradiated food means the same as radioactive food. Nevertheless, 91% stated that if they knew that ‘‘irradiated’’ is not ‘‘radioactive’’ and that proper irradiation enhances food safety they would become consumers of irradiated food. 95.8% of the interviewers were not familiar with the ‘‘Radura’’ symbol. However, 55.8% of people expressed that they would buy irradiated food because of the Radura symbol [40]. It shows that the labeling of irradiated products (the Radura symbol coupled with either “treated with ionizing radiation” or “irradiated”) is the key issue with the consumers. Because the words "radiation" and "irradiation" may have negative connotations, the labelling requirement has been viewed as an obstacle to consumer acceptance. Some researchers believe that an alternative wording, e.g. "electronically pasteurized," would be helpful [51]. These results confirm the importance of training the public on the controversy, technology, and the benefits of irradiation. Several countries have regulatory approvals in place for irradiation of one or more food products. But all these countries are not practically using the technology for a restricted number of food products [38, 47]. China, USA and Ukraine make up about three quarters of the whole food irradiated in the world. There is a role for respected professional bodies to inform consumers of the advantages and limitations of the technology so that they can make informed decisions on buying and eating irradiated foods [45, 47].

CRITICISM AND CONCERNS ABOUT FOOD IRRADIATION

Concerns have been expressed by public interest groups and public health experts that irradiation, as a non-preventive measure, might disguise or otherwise divert attention away from poor working conditions, sanitation, and poor food-handling procedures that lead to contamination in the first place. Processors of irradiated food are subject to all existing regulations, inspections, and potential penalties regarding plant safety and sanitation; including fines, recalls, and criminal prosecutions. But critics of the practice claim that a lack of regulatory oversight (such as regular food processing plant inspections) necessitates irradiation [31]. Irradiation cannot successfully be used to mask quality issues other than pathogens. As with heat pasteurization (for example, milk), processing by ionizing radiation can contribute to eliminate pathogen risks from solid food (example meat or lettuce) [57]. For comparison, milk heat pasteurization is not being alleged to be a method "to cover up poor food quality"; consequently, food irradiation should not be accused to serve such criminal purposes. Concerns and objections include the possibility that food irradiation might do any of the following:

- Mask spoiled food
- Preferentially kill "good" bacteria and encourage growth of "bad" bacteria
- Devitalize and denature irradiated food
- Cause chemical changes that are harmful to the consumer
- Not destroy bacterial toxins which are already present

While food irradiation can in some cases maintain the quality (i.e. general appearance and "inner" quality) of certain perishable food for a longer period of time, it cannot undo spoilage that occurred prior to irradiation. Under a HACCP-concept (Hazard Analysis and Critical Control Point) radiation processing can serve and contribute as an ultimate critical control point before the food reaches the consumer.
Opponents of food irradiation and consumer activists argue that the final proof is missing that irradiated food is "safe" (i.e. not unwholesome) and that the lack of long-term studies should be a further reason not to permit food irradiation [68]. Opponents also refer to a number of scientific publications reporting significant negative effects of irradiated food, for example

- Polyploidy in malnourished Indian children
- Increase of aflatoxin production by irradiated microorganisms
- Vitamin deficiencies at extremely high doses to the complete diet
- Non-vitamin effects at higher doses (free radicals)

However, those experiments could be either not verified in later experiments, could not be clearly attributed to the radiation effect, or could be attributed to an inappropriate design of the experiment etc. [17].

CONCLUSIONS

In the world today, 500000 tons of foods are irradiated every year among spices, meat, fresh fruits and vegetables. Despite the clear benefits of the food irradiation, this method remains under estimated in the food trade. Irradiation does not cause any significant loss of macronutrients. Proteins, fats and carbohydrates undergo little modify in nutritional value through irradiation even with doses over 10 kGy, though there may be sensory changes. In the same way, the essential amino acids, essential fatty acids, minerals and trace elements are also unchanged. There can be a decrease in certain vitamins (mostly thiamine) but these are of the same order of magnitude as occurs in other manufacturing processes such as drying or canning (thermal sterilization) [2]. It has not been commonly accepted and approved yet [44]. Food irradiation is approved for use in over 60 countries worldwide for different products, such as grains, herbs and spices, poultry, seafood, and ground beef [44]. The main factor in the way of commercial application of the food irradiation process is consumer acceptance. From our point of view, as consumer safety questions are discussed, food preservation throughout radiation contribution to food safety will reach the same recognition as the sterilization of medical products has in terms of preventing the spread infectious disease. For this reason, scientists have the responsibility to help the consumer understand the radiation process and it's potential to improve our lives and protect our health.

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