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Review Paper

Food irradiation – perspectives, challenges and questions

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A B S T R A C T

Application of the irradiation process in the food technology is recognized as a significant factor for achievement of the food safety in the chains of the distribution and general consumption. This position is based on the numerous scientific and research studies which confirmed benefits and uniqueness of the treatment with ionizing radiation, as well as the limits of usage. Last decade and post corona period are characterized with increased global demands for safe food in all segments of the industry due to higher awareness of the consumers regarding quality and safety of the food on the market. Technological innovations such as electron beam and X-Ray sources improved the ways for the facilities to fulfil obligatory safety standards and reduce their operational costs. Irradiation services is now more accessible to the food producers easing its inclusion in the food technology process. Beside that, needs for the establishing sustainable agricultural development and reducing quantity of the waste containing non consumed food, indicate some new applications and perspectives of the irradiation process.

1. Introduction

Food irradiation is the technological process which use a strictly controlled dose of ionizing radiation, to protect foodstuffs from deterioration caused by microorganisms, insects, and metabolic activity to prolong their shelf life without leaving any residual effect on processed foods, unlike preservatives and chemical pesticides (*Pavlov et al*., 2020). This activity provide pasteurization and sterilization of the food products without raising their temperature (cold process) and does not induce alteration of food attributes (taste, structure, visual appearance, nutrient content) when the recommended doses are used. Foodstuffs are processed by ionizing radiation after being packed into final consumer packaging which is a unique feature of food irradiation technology (*Molins*, 2001) and provide food safety in all segments of the production and distribution to the markets. Beside irradiation with ionizing radiation, some other types of the radiation such as UV is commonly used for food treatment (*Bisht at al*., 2021), as well as ozone treatment, and all these technologies can be characterized with different benefits and drawbacks. Process of the irradiation of the foodstuff with ionizing radiation will be subject of this review paper contributing to the presentation of the benefits, limitations and disadvantages of the food irradiation process as well as perspectives of this technological process.

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2. Ionizing radiation

Ionizing radiation is characterized with extremely short wavelengths and high intensity inducing changes in atom structure by expelling an electron from the orbit thus forming a reactive ion specie. This process cannot make changes in the atom nuclei so irradiated atoms are not radioactive after treatment and material quickly loses this absorbed energy. Effects of the irradiation can be distinguished as direct and indirect ones. In the direct effect, cell components such as carbohydrates, DNA, and lipids are directly damaged by ionizing radiation whereas in indirect effect, free radicals and reactive species from water radiolysis react with cells or food components. This free radicals has very short live and they are cannot be identified in the water component of the foodstuff after irradiation. Since the main ingredient of fresh products is water so indirect effect is the principal mechanism for ionizing irradiation treatment (*Fan at al*., 2020). On the other side, after irradiation of the dry products, longer live transient free radicals are formed which can be used for determination of the irradiated products. The mentioned effects of ionizing radiation treatment destroying different micro-organisms, bacteria, pests or insects, preventing sprouting and slowing down the ripening and aging of the treated fruit and vegetables. Induced radiolytic byproducts are not unique just to irradiation process since similar or identical products can be found in food that has been cooked or pasteurised which significantly complicate post detection of the irradiation process. Ionizing radiations are also well-known useful for inactivating different pathogens in various food products (Jeong et al., 2015). Gamma and X-rays can penetrate food to a depth of about 1m whereas an electron beam can only penetrate foods to a depth of about 3cm similar as soft X-rays which is useful characteristic used for specific purposes such as irradiation of the surface of the eggs. (*Kataoka at al*., 2021)

Sources of the gamma radiation are mostly consisted from radioactive isotope Cobalt-60 or in some cases Cesium-137. Gamma rays provide good penetration depths enabling efficient process of the irradiation which can be easily monitored and controlled. Due to the complicate protection issues to prevent radiation exposures gamma sources are now replacing with electron beam and X-rays sources as more accepted alternative.

Electron beams can be described as a focused stream of high-energy electrons produced in electron accelerator with energies up to 10 MeV and moderate penetrating depth due to reaction with the irradiated material. Accelerators are characterized with smaller health hazard and environmental impact since radiation is generated only when needed contrary to the gamma sources but the equipment used are more complex and difficult for maintenance.

X-rays radiation is focused electromagnetic radiation generated in the high energy X-Ray tubes with energies up to 5 MeV or 7.5 MeV, characterized with high penetrating power similar to gamma radiation and minimal environmental impact such electron beam sources.

According to the IAEA Database of Industrial Irradaition facilities DIIF, today there are 294 active facilities worldwide, from which is 184 categorized as gamma irradiators while rest of 110 employs electron beam or X-ray technology. Distribution of the facilities can be connected to the level of the implementation of the irradiation technology not just for the food processing so almost 20% of the facilities are located in the USA.

The choice of irradiation method and the dose applied will depend on the material treated and the intended purpose for treatment and the effectiveness of process depends on proper delivery of dose and its reliable measurement. It is important that the techniques used for dose determination are standardized and carried out accurately and that the process is monitored and controlled. During the irradiation process foodstuff are not in direct contact with the radiation source and their integrity is fully preserved.

3. Food irradiation process

Food products can be divided in two categories, food products with higher moisture content (fresh products) and products with lower moisture content. The irradiation process is determined by type of the product as well as purpose of the treatment and is characterized by applied dose of the irradiation. Ionizing radiation process is very effective for sterilization whether is used for medical consumables or foodstuff since induced effects on the living cells while minimum effects on the non-living material are detected.

The SI unit of ionizing radiation for absorbed dose is a Gray (Gy) and corresponds to the absorption of one joule of energy in a mass of one kilogram (1Gy = 1J/kg). Duration of the time that material is exposed to the ionizing radiation and the strength of the source (energy of the electrons or X-rays or activity of the gamma source) determine the irradiation absorbed dose.

According to the applied doses, process of the irradiation can be divided in 3 catogeries: (*Mshelia at al.*, 2023)

- **Radurization** is low dose irradiation process (0,75-2,5 kGy) equivalent to the food and beverage pasteurization and is commonly used as tool for the phytosanitary irradiation for the sprout inhibition and ripening delay as well as insect and parasite elimination extending shelf life and minimizing microbial burden (*Golding at al.*, 2023).
- **Radicidation** is middle dose irradiation process (2,5-10 kGy) are useful for the reduction of the number of the various non-spore forming pathogens such as disease-causing bacteria like *Salmonella, E. coli* and *Listeria* in fresh products (meat, poultry, seafood etc.) and inactivation of the enzymes which can significantly extend shelf life (*Gautam at al.*, 2023).
- **Radappertization** is high-dose irradiation (more than 10 kGy), particularly important to produce meat, poultry, and fishery products which are shelf-stable at ambient temperature. (Plaček et al., 2004). Today, application of high-dose irradiation of food products has been expanded to the sterilization of ready-to-eat (RTE) food, hospital diets (including food for immuno-compromised patients), and space food (*Feliciano et al.*, 2014; *Song et al.*, 2012)

Although all international standards define 10 kGy as maximum limit, use of higher doses is allowed if necessary for a legitimate technological purposes which include examples such as microbial decontamination of the dried herbs and spices (European Union 15 kGy, Australia 30 kGy) and sterilization e.g. space food. (USA 42 kGy for food for astronauts). (*Feng at al.*, 2017, *Feliciano et al.*, 2018). Some scientific studies noted occurrence of undesirable specific sensory characteristics like off-odour, decrease viscosity, discoloration/darkening, lipid oxidation, and decrease in its textural properties. However, these problems can be solved by combining irradiation with other treatment technologies (*Odueke et al.*, 2017, *Chen et al.*, 2016).

The first ever application of an electron accelerator to food irradation is processing of the spices for the sausage production 1958 in Stuttgart, Germany. This facility became obsolete almost the same year since Germany introduced a general ban on food irradiation due to lack of scientific and confident evidences for the safety of the irradiated food. (*Ehlermann*, 2016).

The first legislation act which is addressed to irradiation process is *Food Additive Amendment* enacted by US Congress in 1958. where all sources of the ionization are recognized as food additives. This act enable introduction of the food irradiation in the legislation regarding food safety. From that period use of the irradiation facilities is increased although general acceptance is not achieved due to public fear of the nuclear issues, especially during *Cold war* and nuclear threats as well as nuclear accidents such as Chernobyl and Fukushima. Nevertheless, in 2019, it was reported that irradiation of agricultural products is carried out in more than 60 countries of the world and more than 200,000 tons of irradiated products are produced annually in Europe (*Obodovskiy*, 2019).

4. Safety of the irradiated foodstuffs and labeling

After first implementation of the irradiation to foodstuff many research groups start investigation of the effects of the irradiation process and safety of the treated food regarding formed radiolytic byproducts and sensory attributes. International groups of experts evaluated periodically the results of wholesomeness testing and in 1980. decision is issued as "…the irradiation of any food commodity to an overall average dose of 10 kGy presents no toxicological hazard, hence, toxicological testing of food so treated no longer required…", and "…irradiation of foods up to an overall average dose of 10 kGy introduces no specific nutritional or microbiological problems…" (*WHO*, 1981). In 1997, an FAO/IAEA/WHO Study Group on High Dose Irradiation examined the results of safety studies carried out on foods irradiated in the dose range 25–60 kGy to achieve the intended technological objective of radappertization. The conclusion was that such foods are both safe to consume and nutritionally adequate (*WHO*, 1999). In 2011, the European Food Safety Authority (EFSA) reviewed the evidence and reasserted the opinion that food irradiation is safe (*EFSA*, 2011) with conclusions that there are no microbiological risks for the consumer linked to the use of food irradiation and its consequences on the food microflora and that most of the chemical substances formed during irradiation were also formed in food that has been subjected to other processing treatments and that the quantities in which they occur in irradiated food were not significantly higher than those being formed in heat treatments.

When food is irradiated, water molecules may split and form free radicals which can react with food components, potentially forming new compounds called radiolytic products such as 2-alkylcyclobutanones (2-ACBs), furans and other volatile compounds as well as free radical-derived products from the reaction of free radicals with proteins, carbohydrates and lipids. Scientific research indicates that the chemical changes induced by food irradiation are qualitatively similar to those produced by conventional cooking methods but are generally less extensive. Some vitamins, particularly B1 and A, E, and K, can be somewhat sensitive to irradiation, the losses are comparable to or less than those that occur during conventional food processing methods like canning or heat pasteurization. (Ravindran at al, 2019) With proper dose control and processing conditions, nutritional losses in irradiated foods can be minimized, maintaining the food's nutritional quality. Since the materials used for packaging are exposed to radiation during the treatment, these materials must be radiation resistance and no mitigation of the toxic substances into food is allowed nor production of the additional sensory attributes or affect on the present ones. (*Verde et al*., 2013).

Mandatory specific labeling of the irradiated foods and foodstuff establish need for the development of the reliable and validated analytical techniques for the detection of the irradiated food, both defined in Codex Alimentarius. All irradiated food products must be labeled with "Radura" sign which represent plant-like image placed in the circle with solid lower half and dashed upper half indicating penetration of the radiation. In most cases this symbol is green colored indicating ecological nature of the process. (FDA, 2008). Aim of the labeling is to ensure that consumers are fully informed whether foods, or ingredients within them, have been irradiated since irradiation is not fully accepted in all countries while some countries strictly ban irradiation of the foodstuff (*Barkai-Golan at al*, 2017).

As each technological process, food treatment with ionizing radiation can be characterized with benefits, limits and disadvantages which are usually confirmed with scientific research. While benefits are mostly already stated in the text, as major limitations must be noted:

- Irradiation has no effect on the viruses and prions
- Some spore-forming bacteria such as Bacillus and Clostridium species are radiation resistant so radiation treatment with doses below 10 kGy can only reduce the number of spores, but in conjunction with freezing can prevent the growth of spores (*Markland at al*., 2016).
- Irradiation is not suitable for some fruits and vegetables such as tomatoes, grapes and cucumber due to reduction in some vitamins and possible loss of color and texture (Hwang et al. 2015; Mohamed, 2016).
- Irradiation of lipid products such as egg and dairies using high doses in an oxygen rich environment can lead to hydrogen peroxide formation, resulting to unpleasant odour and flavour (*Feng et al.*, 2017; *Ham et al.*, 2017)
- Although nutritional values of the irradiated foodstuff is not significantly decreased, slight reduction in vitamin content such as vitamin-C and vitamin-E.

5. Perspectives of the food irradiation

The acceptance of the food irradiation process is balancing between two opposite poles, major scientific approval and confirmation and consumer doubts and skepticism based on the lack of the information and false presumptions regarding radioactivity. Food irradiation is often linked with radioactive contamination of the food and environment generally which commonly induce rejection of the irradiated food. The European Union has strict food safety regulations so advanced irradiation technologies must be regulated and confirmed. But diverse regulatory standards make difficult task to fully implement challenging requirements including mandatory labeling practices and extensive authorization procedures which create barriers to worldwide trade in the situation where organic and natural food is fully promoted. Additional public interest include waste reduction and sustainable development where food irradiation can play significant role since it can minimize food waste and food post-harvest losses which are major reasons for the global lack of safe food. The changes in the consumer habits and increased need for the production ready-to-eat and packaged food will open some perspectives for the ionizing irradiation industry which can be summarized as:

- The increasing global need for safe food for all inhabitants with proven safety and increased longevity will induce higher demands for the irradiation services.

- Trade and transportation routes from the distance countries require additional time and initiate need for the extended shelf life of the packaged foodstuff.
- Reducing quantities of the food waste will generate new value and improve environmental status enabling sustainable development and minimizing global malnutrition across the world-wide.
- Increasing number of the irradiation facilities in the world with more efficient process should reduce commercial irradiation cost thus expanding range of the clients which can afford this service based on the cost/benefit analysis.

6. Challenges in the food irradiation process

Food irradiation presents growing market since nowadays there is increase of society's need for safe food and waste reduction agenda. The food supply chains benefit from irradiation technologies which enables safety of the packaged foodstuff and prolong shelf life which are necessary for the efficient worldwide distribution. The rise of consumption of the clean-label and organic foods directs food manufacturers to use irradiation technology since it provides a substitution for artificial chemical preservatives. So, role players in this industry will meet severe challenges such as:

- Public perception of the term radiation is major reason for lower acceptance since irradiation is commonly mixed with term radioactive which has dangerous connotation,
- Legislation approval is based on concise scientific confirmation of the irradiation process so additional research of the application on the other types of the foodstuff and new packaging materials through analysis of the radiolytic byproducts and their effects on the food and human health must be conducted as well as properly funded,
- Distribution of the irradiation facilities is not uniform in the world thus limiting producers in some parts of the world to provide safe food for domestic consumption and export,
- Growing demands for the irradiation services due to global increase in the food production and longer transportation routes with provided food safeness must be followed with proper capacities of the irradiation services,
- Structural technological changes from gamma radiation facilities to E-beam and X-Ray facilities due to improving radiation protection and reducing impact on the environment must be realized without losses in the installed capacities,
- Food irradiation is not fully adopted in all countries which can complicate trade agreements. International trade agreements must properly address to this issue,
- Competitive processes such as ozone treatment or cold plasma can decelerate the development and research in field of the irradiation due to lesser safety and security issues.

7. Conclusion

Ionizing radiation can be applied on a number of agricultural products and foodstuff in order to provide safe food. This activities include sprout inhibition, disinfestation, reduction or elimination of food borne pathogens and delayed ripening of fruits. The process involves application of the strictly determined radiation dose which is clearly confirmed through proper scientific research. The quality and safety of irradiated food at the defined and approved dose level for commercial use can be properly described and confirmed if it is compared with food preserved using other methods of preservation which are already accepted. Scientific community should actively participate in the promotion of the irradiation treatments in all segments of the human activities including foodstuff, medical consumables, waste etc. Increased knowledge regarding food irradiation can change public perception regarding application of the ionizing radiation in the human activities and improve public acceptance of the process itself.

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