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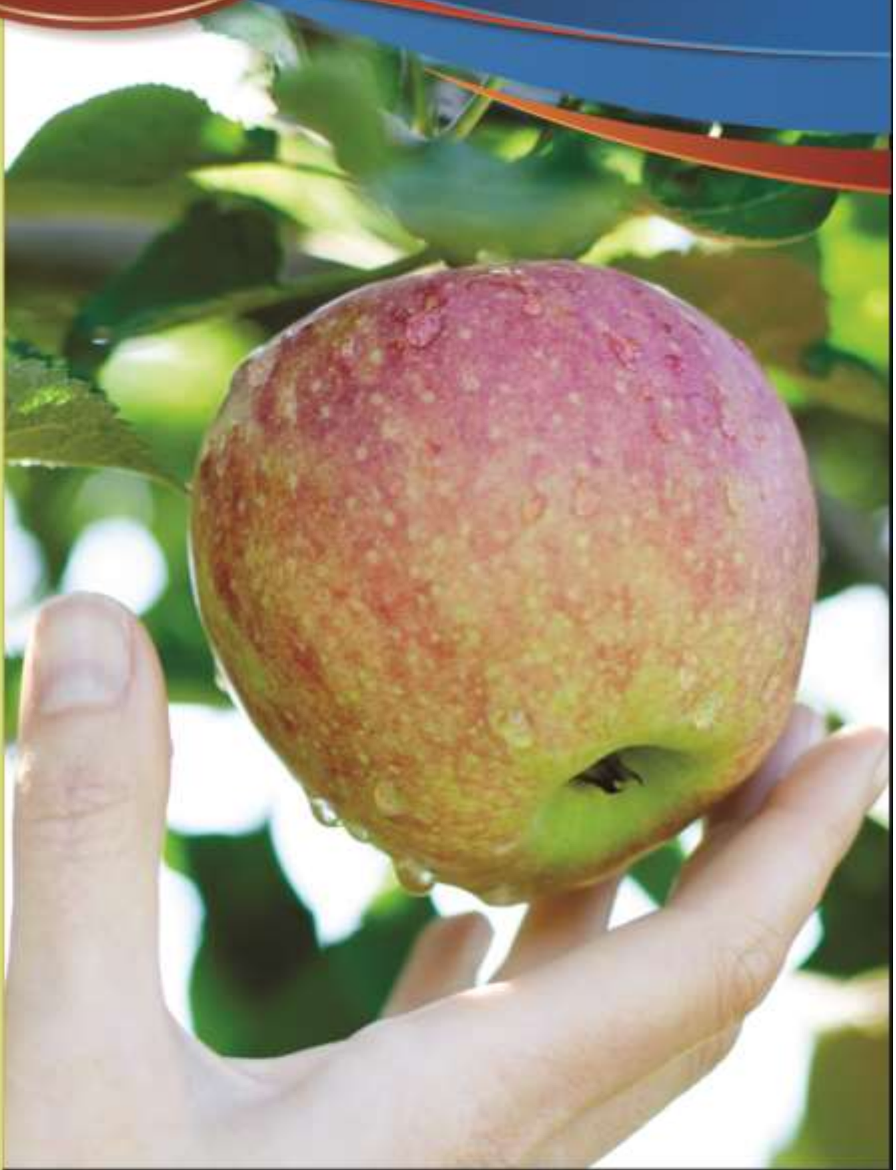

XVI International Scientific Agriculture Symposium

"Agrosym 2025"

Jahorina, October 2-5, 2025

agrosym 2025

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XVI International Scientific Agriculture Symposium
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Jahorina, October 2 - 5, 2025

Impressum

XVI International Scientific Agriculture Symposium „AGROSYM 2025“

Book of Proceedings Published by

Faculty of Agriculture, University of East Sarajevo, Republic of Srpska, Bosnia and Herzegovina
Faculty of Agriculture,University of Belgrade, Serbia
Mediterranean Agronomic Institute of Bari (CIHEAM - Bari) Italy
International Society of Environment and Rural Development, Japan
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Website:
http://agrosym.ues.rs.ba

CIP - Каталогизација у публикацији
Народна и универзитетска библиотека
Републике Српске, Бања Лука

631(082)(0.034.2)

INTERNATIONAL Scientific Agriculture Symposium "AGROSYM" (16 ; 2025 ; Jahorina)
Book of Proceedings [Електронски извор] / XVI International Scientific Agriculture Symposium "AGROSYM 2025", Jahorina, October 2- 5, 2025 ; [editor in chief Hamid El Bilali]. - Onlajn izd. - El. zbornik. - East Sarajevo : Faculty of Agriculture, 2025

Системски захтјеви: Нису наведени. - Način pristupa (URL): Način pristupa (URL): https://agrosym.ues.rs.ba/article/showpdf/BOOK_OF_PROCEEDINGS_2025_FINAL.pdf. - Ел. публикација у ПДФ формату опсега 1121 стр. - Насл. са насловног екрана. - Опис извора дана 20.11.2025. - Библиографија уз сваки рад. - Регистар.

ISBN 978-99976-070-5-8

COBISS.RS-ID 14353894

SCIENTIFIC AND REGULATORY PERSPECTIVES ON IRRADIATED FOOD: DETECTION STANDARDS AND SAFETY EVALUATION

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Abstract

Food irradiation is a scientifically validated and internationally endorsed technology that applies ionizing radiation to improve the microbiological safety and shelf life of food products. By effectively inactivating pathogens, parasites, and pests without significantly compromising nutritional or sensory quality, irradiation serves as a potent alternative to conventional decontamination methods. This review provides a comprehensive analysis of the scientific principles underlying irradiation, detailing the mechanisms of action, microbiological efficacy, toxicological safety, and minimal impact on nutritional value. These findings are supported by extensive evaluations from authoritative bodies, including the World Health Organization (WHO), the Food and Agriculture Organization (FAO), the International Atomic Energy Agency (IAEA), the European Food Safety Authority (EFSA), and the U.S. Food and Drug Administration (FDA). The paper also explores the regulatory landscape surrounding food irradiation, with particular focus on the European Union's limited list of approved irradiated food categories under Directives 1999/2/EC and 1999/3/EC. The implications of regulatory fragmentation within the EU and the contrasts with countries such as the United States, Canada, India, and Thailand are assessed. Key applications, such as pathogen reduction in meat and poultry, insect control in spices and grains, and phytosanitary treatment for exportable fruits are discussed alongside economic and logistical benefits. Consumer perception remains a major barrier to widespread acceptance, often shaped by misconceptions and negative associations with the term "irradiation." Strategies for effective communication, labeling transparency, and public education are examined. The review further assesses CEN (the European Committee for Standardization)-standardized and emerging detection methodologies critical for regulatory enforcement and traceability. Finally, it highlights the role of irradiation in advancing climate-resilient food systems, reducing post-harvest losses, and supporting global food security, while calling for harmonized regulation and greater international cooperation.

Keywords: *food irradiation, ionizing radiation, EU legislation, detection methods, consumer perception.*

Introduction

Food irradiation is a well-established technology that employs ionizing radiation to improve food safety and prolong shelf life by eliminating or reducing microorganisms, parasites, and insect pests. It operates by exposing food to controlled amounts of ionizing radiation—gamma rays, X-rays, or electron beams—to achieve effects similar to conventional preservation methods such as pasteurization, refrigeration, or chemical treatment, but often with fewer adverse impacts on food quality and nutritional content (Diehl, 2002; Farkas, 2006). Sensory and nutritional properties such as taste, texture, and overall appearance are largely preserved, while minor losses in heat-sensitive vitamins, like thiamine and vitamin C, are typically within acceptable limits.

The concept of using radiation to preserve food was first explored in the early 20th century, but meaningful development began in the 1950s, followed by the first commercial approvals in the 1960s. As of 2024, more than 60 countries permit the use of food irradiation for specific categories of food, including dried spices, fresh fruits, vegetables, meats, seafood, and ready-to-eat products (IAEA, 2025; Loaharanu & Thomas, 2020). The primary objectives of food irradiation are to ensure microbial safety, reduce spoilage, and enable compliance with sanitary and phytosanitary requirements in international trade (Morehouse & Komolprasert, 2004; Arvanitoyannis, 2010).

Despite decades of scientific consensus on its safety, food irradiation remains controversial among consumers and some stakeholders in the food industry. The skepticism largely arises from associations with nuclear technologies, such as fear of radioactive contamination, and concerns about the generation of unknown chemical compounds, nutritional degradation, or long-term health risks. Studies have shown that consumers frequently misunderstand the nature of ionizing radiation and conflate irradiated food with radioactive contamination (Frewer et al., 2004; Orynbekov et al., 2025). These misconceptions highlight the need for clear communication, transparent labeling, and evidence-based public education to foster informed consumer choices and improve market acceptance (D'Souza et al., 2021; EFSA, 2011).

This review aims to explore the scientific basis of food irradiation, assess its regulatory landscape, particularly within the European Union, evaluate current detection standards, and examine public perception and consumer acceptance. By analyzing these interrelated dimensions, the paper highlights the need for harmonized international regulations, improved transparency, and public education to support the safe and effective implementation of food irradiation technology.

Scientific basis and safety evaluation

Irradiation involves the controlled application of ionizing radiation—typically gamma rays (from cobalt-60 or cesium-137), X-rays, or high-energy electron beams—to destroy pathogens, delay ripening, and inhibit sprouting. These rays penetrate the food and interact with molecular structures, particularly the DNA of microorganisms. Ionizing radiation induces strand breaks and cross-linking in microbial DNA, disrupting replication and cellular processes, ultimately leading to the death or inactivation of the organisms (Farkas, 2006; Diehl, 2002).

Scientific assessments by the World Health Organization (WHO), the Food and Agriculture Organization (FAO), and the International Atomic Energy Agency (IAEA) have consistently concluded that irradiation is safe for human consumption when applied within regulated dose ranges. These typically range from low doses (up to 1 kGy) for inhibition of sprouting and insect disinfestation, to medium (1–10 kGy) for reduction of spoilage organisms and pathogens. High doses (above 10 kGy) are used for sterilization of foods, though these applications are limited (Ravindran & Jaiswal, 2019).

The European Food Safety Authority (EFSA) and the US Food and Drug Administration (FDA) have similarly affirmed the safety of irradiated foods. Toxicological studies, including long-term feeding experiments, have demonstrated that irradiated foods do not present increased carcinogenic or mutagenic risks compared to their non-irradiated counterparts.

Nutritional studies show that macronutrients remain largely unaffected. There may be modest losses in heat-sensitive vitamins, such as thiamine (vitamin B1), vitamin C, and vitamin A. For instance, irradiation might reduce thiamine levels in pork or vitamin C in strawberries, but these reductions are similar to or lower than those caused by cooking or drying, making them nutritionally insignificant in most cases (Morehouse & Komolprasert, 2004; Arvanitoyannis, 2010).

Microbiological evaluations confirm the efficacy of irradiation in reducing foodborne pathogens, including *Salmonella* spp., *Listeria monocytogenes*, *Escherichia coli* O157:H7, and *Campylobacter jejuni*. The reduction depends on the dose and food matrix, but it can achieve several log reductions in microbial populations. Irradiation is also effective in inactivating parasites such as *Trichinella spiralis* and controlling insects in stored products, making it especially valuable in global trade and phytosanitary applications (Molins et al., 2001; IAEA, 2025).

European legislative framework

Globally, food irradiation is governed by the Codex Alimentarius General Standard for Irradiated Foods (CODEX STAN 106-1983), which establishes international guidelines on maximum dose levels, labeling requirements, and hygienic production standards. These standards serve as the foundation for national legislation and facilitate international trade by promoting regulatory convergence.

In the European Union, the regulatory framework for irradiated food is primarily built on two key directives:

- Directive 1999/2/EC: Establishes general provisions for irradiated food, including production, labeling, and import conditions.
- Directive 1999/3/EC: Provides a Community list of foods authorized for irradiation. Currently, this list includes only dried aromatic herbs, spices, and vegetable seasonings.

In addition, Regulation (EU) No 1169/2011 requires irradiated food products to be clearly labeled, ensuring consumer transparency. Only food irradiated in EU-approved facilities, whether within the Union or in third countries, may legally enter the EU market.

Despite the global consensus on the safety of irradiation, the EU maintains a conservative stance with its narrow list of authorized products. This restrictiveness may be attributed to factors such as strong consumer protection and environmental advocacy groups, historical aversion to nuclear technologies, and heightened sensitivity to perceived health risks among European consumers.

The consequences of this fragmented regulatory landscape extend beyond trade barriers. It hampers innovation in food processing technologies, discourages investment in irradiation facilities, and ultimately limits consumer access to microbiologically safer food options. Several EU Member States permit irradiation of other food products, such as frog legs, poultry, or herbs (EC, 2023), but these products cannot circulate freely across the single market due to the lack of harmonized approval.

By contrast, other jurisdictions such as the United States (FDA), Health Canada, Australia, India, and Thailand have adopted broader regulatory frameworks that authorize a wider array of irradiated food products. These frameworks allow the application of irradiation to fresh produce, meats, seafood, and ready-to-eat meals, often without impeding intra-national trade.

Harmonizing international and intra-EU irradiation policies could provide multiple benefits: increased consumer trust through unified standards, improved efficiency in cross-border trade, and enhanced adoption of irradiation as a complementary food safety tool. A comprehensive policy revision, informed by scientific evidence and public dialogue, could significantly support the role of irradiation in strengthening sustainable and resilient food systems.

Regulation (EU) No 1169/2011 addresses labeling obligations, ensuring consumer transparency. Only irradiated food from approved facilities, within or outside the EU, may be legally marketed in EU countries. Despite the proven safety, the narrow list of approved food categories and inconsistent implementation across Member States hinder broader adoption.

Applications, benefits and labeling of irradiated foods

Food irradiation has diverse applications across multiple food categories. It is commonly used for:

- Spices and dried herbs: to eliminate microbial contamination and insect pests, often reducing microbial loads by up to 5–6 log cycles (Farkas, 2006).
- Meats and poultry: to reduce foodborne pathogens such as *Salmonella* and *Listeria*. Studies show that irradiation at doses of 1–1.5 kGy can reduce these two pathogens in meat and poultry products (Kudra et al., 2011; Kudra et al., 2012).
- Fruits and vegetables: to delay ripening, inhibit sprouting, and provide phytosanitary treatment. For example, mangoes irradiated in India for export to the U.S. bypass chemical fumigation and comply with U.S. import regulations (Morehouse & Komolprasert, 2004).

The benefits of irradiation include:

- Improved microbiological safety and shelf life,
- Reduced use of chemical preservatives and fumigants,
- Lowered risk of cross-border pest transmission,
- Enhanced trade compliance with phytosanitary standards (Arapcheska, 2020).

Labeling remains a sensitive and often controversial issue. In the EU, irradiated food must carry a label stating "treated with ionizing radiation" in accordance with Regulation (EU) No 1169/2011. Similar requirements apply in the United States, where the FDA mandates both the statement and the inclusion of the international Radura symbol (FDA, 2019). In Canada, irradiated foods must be clearly labeled and identified by both a statement and the symbol under the Food and Drug Regulations (Health Canada, 2025).

The term "cold pasteurization" has been proposed as an alternative descriptor to alleviate consumer fears associated with the word "radiation". This term emphasizes that the process is conducted without heat and aims to convey functional similarities with thermal pasteurization—namely, microbial reduction without compromising food integrity (Bruhn, 1998).

Globally, labeling requirements vary in detail and enforcement. While countries like the U.S., EU, and Canada enforce mandatory labeling, others—particularly in Asia and Latin America—may only require labeling for products sold directly to consumers, with more lenient rules for bulk or food service items (Codex Alimentarius Commission, 2003; Arvanitoyannis, 2010).

Clear and standardized labeling policies are essential not only for regulatory compliance but also for building consumer trust and enabling informed purchasing decisions. Educational campaigns can further improve public understanding and acceptance of this safe and effective technology.

Public perception and consumer acceptance

Numerous studies show mixed consumer attitudes toward irradiated foods. Acceptance increases when consumers are informed of its safety and benefits, particularly in relation to food safety and the reduction of chemical preservatives (D’Souza et al., 2021; Castell-Perez & Moreira, 2021). However, widespread misunderstandings persist. For example, many consumers incorrectly believe that irradiated foods are radioactive or that the process significantly depletes nutrients, despite clear scientific evidence to the contrary (Frewer et al., 2004).

Language plays a critical role in shaping perception. The term "irradiated" often triggers negative associations with nuclear energy, contamination, and toxicity. Cultural beliefs and media representations can amplify these fears. Media coverage, particularly when sensationalized or poorly contextualized, can significantly sway public opinion either positively—by highlighting safety benefits—or negatively—by reinforcing misconceptions and alarmist narratives (Arvanitoyannis, 2010).

To improve acceptance, educational outreach should be complemented with targeted communication strategies. These may include:

- Using analogies: Comparing irradiation to commonly accepted technologies like milk pasteurization or fruit preservation by freezing.
- Addressing specific concerns: Clearly explaining the difference between radiation exposure and radioactive contamination.
- Engaging trusted voices: Involving healthcare professionals, scientists, and consumer advocacy groups in public discussions.
- Transparent labeling and demonstration: Showing real-world examples where irradiated foods are safely consumed, such as spices or imported produce.

Campaigns integrated into school curricula, public health programs, and food literacy initiatives can also promote long-term understanding. Countries that have successfully introduced irradiation programs—like the U.S., India, and Thailand—often combine regulatory transparency with sustained public engagement (Maherani et al., 2016).

Several challenges remain. These include limited EU-wide approval, institutional hesitancy to expand authorized food categories, and the lack of a unified infrastructure for labeling and detection. Consumer skepticism, fueled by a lack of accessible, trustworthy information, continues to be a major barrier to broader adoption.

Detection methods and standardization

Reliable detection methods are essential for enforcing labeling laws and monitoring compliance. The EU, through the European Committee for Standardization (CEN), has developed a suite of standardized detection methods categorized into three primary groups based on their underlying scientific principles:

- Chemical methods: These identify specific chemical compounds formed uniquely during irradiation. For example, EN 1784 and EN 1785 detect hydrocarbons and 2-alkylcyclobutanones in fatty foods, which are by-products of lipid radiolysis (Campaniello et al., 2020). These methods are particularly effective for high-fat products like meat, cheese, or poultry.
- Physical methods: These rely on structural or mineralogical changes in food matrices due to radiation exposure. Electron spin resonance (ESR) spectroscopy (EN 1786 and EN 1787) is commonly used for bone-containing foods like poultry or fish, as it detects unpaired electrons created by irradiation. Thermoluminescence (EN 1788) and photostimulated luminescence (EN 13751) are especially effective for dried foods containing silicate minerals, such as herbs and spices (EN 13708 for crystalline sugar) (Stevenson, 1994; Delincee, 2002).
- Biological methods: These assess irradiation-induced effects on microorganisms or cellular structures. For instance, EN 13783 and EN 13784 use techniques such as the DEFT/APC (Direct Epifluorescent Filter Technique/Aerobic Plate Count) and the DNA comet assay, respectively. These are more applicable to fresh or low-fat foods where chemical markers are less stable (Marchioni, 2012).

These methods vary in sensitivity, specificity, and suitability depending on the type of food product being analyzed. Screening methods offer a quick preliminary indication but must be supported by confirmatory methods to comply with regulatory standards.

Recent advances in analytical chemistry and data science have enabled exploration of new detection platforms, including near-infrared (NIR) spectroscopy, metabolomics and proteomics

profiling, and machine learning-enhanced image recognition. While these techniques promise broader applicability and automation, their implementation in routine testing is currently limited by cost, technical complexity, and the need for method validation and harmonization across laboratories (IFST, 2025).
Despite these challenges, ongoing interlaboratory validation studies and efforts by CEN, ISO, and national reference laboratories continue to improve method robustness, making detection more accessible. Greater adoption will depend on funding, capacity building, and the integration of newer methods into existing regulatory frameworks.

Conclusion

Looking forward, food irradiation could play a crucial role in achieving global food security, reducing food waste, and ensuring safe food trade—especially under increasing climate stress. Rising global temperatures can exacerbate the prevalence of foodborne pathogens, increase spoilage rates, and extend the distances food must travel from producers to consumers. In this context, irradiation offers a reliable method to mitigate microbial risks and extend shelf life without the need for excessive chemical use or refrigeration (Indiarto et al., 2023).
Future strategies for food processing are likely to involve the integration of irradiation with other technologies, such as high-pressure processing (HPP) or pulsed light treatment. These combinations could enhance microbial inactivation while preserving nutritional and sensory qualities. For example, HPP can disrupt microbial cell membranes, while irradiation targets DNA, providing a multi-hurdle approach that reduces resistance and broadens application potential (Knorr et al., 2011; Aaaliya et al., 2021). Similarly, coupling irradiation with cold plasma or ozone could allow for reduced radiation doses while maintaining safety efficacy.
From a policy and sustainability perspective, food irradiation aligns well with the United Nations Sustainable Development Goals (SDGs), particularly those addressing food security (SDG 2), health and well-being (SDG 3), responsible consumption and production (SDG 12), and climate action (SDG 13). Reducing post-harvest losses and limiting foodborne illnesses are essential components of sustainable food systems.
However, realizing the full potential of irradiation requires a coordinated global effort. Governments and regulatory bodies must harmonize legislation to facilitate safe and transparent trade. Researchers and scientists must continue to investigate novel applications and synergistic technologies. Industry stakeholders should invest in scalable solutions and infrastructure, and consumer-facing organizations must lead the charge in education and advocacy.
A unified call to action is needed to transform irradiation from a niche intervention into a mainstream food safety and sustainability tool. Only through collaboration between researchers, regulators, industry leaders, and consumers can irradiation fulfill its promise in supporting resilient, safe, and sustainable food systems.

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