

Accelerator-Based Radiation Technology: Innovations, Challenges and Opportunities Ahead

Bumsoo Han

bshan@eri.or.kr

Korean Association for Radiation Application (KARA)

D. M. Youn

Korean Association for Radiation Application (KARA)

C. H. Park

Korean Association for Radiation Application (KARA)

J. G. Park

Korean Association for Radiation Application (KARA)

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Abstract

Accelerator-based radiation technology has evolved from a niche area of nuclear physics into a mature industrial discipline. Ninety years after the founding inventions, more than 35 000 accelerators operate worldwide, supporting an equipment market of approximately USD 5 billion per year and underpinning goods valued at some USD 100 billion treated annually. This paper reviews the evolution of the field across five technological eras; the three principal modalities – electron beam (EB), X-ray (Bremsstrahlung) and ion beam – and their industrial characteristics; and the key application sectors of medical device sterilization, polymer crosslinking and radiation curing, food safety and environmental remediation. The sustainability advantages over ethylene oxide (EtO) sterilization are assessed, and a once-in-a-generation modality shift from gamma and EtO towards EB and X-ray processing is quantified. Three persistent barriers – capital intensity, regulatory complexity and industrial inertia – are examined alongside opportunities in advanced accelerator designs, digitalization and artificial intelligence (AI), and expanding geographic markets, including the progression towards autonomous irradiation facilities. A technology outlook to 2035 and a six-point call to action are presented.

1. Introduction

At any given moment, somewhere in the world, a proton beam is treating a cancer patient, a cyclotron is producing a diagnostic radioisotope, and an electron beam is sterilizing a medical device, strengthening a cable, preserving food, cleaning wastewater or creating a material that did not previously exist. Accelerator-based radiation technology is, in this sense, both invisible and indispensable.

The scale of the field is not widely appreciated. More than 35 000 particle accelerators are in operation worldwide; annual sales of accelerator equipment amount to approximately USD 5 billion, while the value of goods treated annually is of the order of USD 100 billion – a market roughly twenty times the size of the equipment industry serving it [1]. From a handful of research machines in the 1950s, the field has grown into critical industrial infrastructure across the medical, manufacturing, agricultural and environmental sectors: it is no longer an emerging technology, but mature, scaled and growing.

High-energy ionizing radiation also belongs to the family of Advanced Oxidation Processes and offers a viable route for eliminating recalcitrant micropollutants [2]. In water, radiolysis generates highly reactive species – principally the hydroxyl radical ($\cdot\text{OH}$), the hydrated electron and the hydrogen atom – which attack organic molecules without added reagents and without secondary waste streams [2]. This paper reviews the historical evolution of the field, the three principal accelerator modalities, the key application sectors and their regulatory frameworks, the sustainability case against EtO sterilization, the structural barriers to wider adoption, and the opportunities arising from advanced accelerator designs, digitalization and expanding geographic markets.

2. Evolution of Accelerator-Based Radiation Technology

The trajectory of the field spans five eras, and this history explains both the strengths of the present industry and the constraints under which it operates. In the founding era, three machines invented within five years defined the subsequent century. In 1932 at Cambridge, Cockcroft and Walton achieved the first nuclear disintegration using artificially accelerated particles; their voltage-multiplier circuit, operating up to 800 keV direct current, is the direct ancestor of today’s DC industrial accelerators. Also in 1932, at Berkeley, Lawrence demonstrated the cyclotron, the first machine to exceed 1 MeV and the foundation of medical isotope production. In 1933 at MIT, Van de Graaff developed the belt-driven electrostatic generator, reaching several megavolts at industrial scale. All three inventors became Nobel laureates, and all three architectures became workhorses of industrial radiation processing [3].

Industrialization was compressed into the two following decades: the first commercial industrial EB machine (1953), the first commercial Co-60 sterilization facility (1956), the founding of Raychem and its EB-crosslinked heat-shrink products (1957), the first industrial linacs (1958), commercialization of the Dynamitron for cable crosslinking (1962) and the emergence of the contract sterilization business model (1968). Sterilization, crosslinking and food irradiation all took root in this period. Through the 1970s industrial linacs then scaled from 1 to 10 MeV and began displacing radioisotope sources, as X-ray converters and beam scanning enabled uniform dose delivery; crosslinked polyethylene cable came to dominate EB use, and manufacturing capability spread from the United States to Japan, Europe and the Soviet Union [3]. The population of industrial EB facilities grew from approximately 30 in 1980 to some 150 by 1990 – the fastest expansion in the industry’s history – driven by Co-60 supply volatility, higher-reliability linacs, formalization of EB validation within ISO frameworks and the growth of single-use medical devices [4].

The high-power era followed. The first Rhodotron prototype was operated in 1989; recirculating the beam through a single radiofrequency cavity in continuous-wave operation, successive models scaled from 35 kW to 700 kW at wall-plug efficiencies of 35–45% [5]. Pallet-scale penetration became routine, the 7.5 MeV food and medical energy limit was codified in 2003 [6], and the first commercial X-ray sterilization facility entered service in the same year.

3. Three Pillar Technologies

Industrial radiation processing rests upon three complementary modalities, summarized in Table I.

TABLE I: COMPARATIVE OVERVIEW OF THE THREE PRINCIPAL RADIATION PROCESSING MODALITIES

PARAMETER	ELECTRON BEAM (EB)	X-RAY (BREMSSTRAHLUNG)	ION BEAM
Energy range	80 keV – 10 MeV	≤ 7.5 MeV (regulatory limit)	keV – GeV per nucleon
Dose rate	~ 10 ⁵ kGy·h ⁻¹	~ 10 ² kGy·h ⁻¹	Variable
Penetration	~ 3–4 cm per MeV in water	Up to ~ 480 mm water-equiv.	Bragg peak – precise
Conversion	Direct	8–16% (EB → X-ray)	Direct
Installed base	~ 3 000 + facilities	Growing rapidly	> 15 000 implanters
Key advantage	High dose rate; on/off control	Bulk product penetration	Precise depth control
<i>Note: Values are indicative; performance varies with machine type and product density. Source: Refs [1, 3].</i>			

3.1. Electron Beam Irradiation

Electron beam irradiation directs electrons accelerated to relativistic energies at a target. Industrial systems operate between 80 keV and 10 MeV at very high dose rates, making them among the most productive radiation processing tools available [3]. Penetration in water is approximately 3–4 cm per MeV, limiting EB to thin or low-density products while providing excellent near-surface dose uniformity. More than 3 000 industrial EB facilities operate worldwide.

Three machine families are distinguished. Direct-current accelerators (0.08–5 MeV) are robust, deliver very high beam current and are cost-effective for coatings and surface curing, at the cost of limited energy. Radiofrequency linacs (1–10 MeV) are compact for their energy and therefore well suited to X-ray conversion; solid-state amplifiers now permit 100 kW units within a shipping container, with significant implications for distributed sterilization capacity. Recirculating machines (5–10 MeV) deliver up to 700 kW of continuous-wave power at the highest specific output and wall-plug efficiency in the industry [5]. The instantaneous on/off capability of all EB systems, in contrast to Co-60 sources, provides a significant operational and safety advantage and eliminates source-transport logistics.

Available beam power has risen approximately seventyfold since the 1970s, from about 10 kW to 700 kW today. The consequences are economic: higher dose rates raise throughput, pallet-scale processing becomes routine, X-ray conversion becomes economically viable, and bulk environmental applications become feasible. Wall-plug cost per kGy·tonne has fallen by roughly an order of magnitude since 1990 [7].

3.2. X-Ray (Bremsstrahlung) Irradiation

X-ray irradiation is generated by directing an EB at a high-atomic-number converter, typically tantalum or gold. Modern systems achieve beam-to-X-ray conversion efficiencies of 8–16%, and the resulting

photons penetrate to a depth equivalent to approximately 480 mm of water, making the modality suitable for pallet-scale processing [3]. Regulatory energy limits are grounded in the physics of photonuclear reactions. The Codex Alimentarius standard restricts energy to 5 MeV for food irradiation, extendable to 7.5 MeV with tantalum or gold targets, and industry consensus limits medical sterilization to 7.5 MeV [6]. Below this threshold no measurable induced radioactivity arises, because the (γ, n) thresholds for carbon-12 (18.7 MeV), oxygen-16 (15.7 MeV) and nitrogen-14 (10.6 MeV) all lie well above the permitted range [5, 6]. X-ray systems are the fastest-growing modality, driven by Co-60 supply constraints and regulatory pressure on EtO [8].

3.3. Ion Beam Processing

Ion beam processing is the most technically diverse pillar. What distinguishes heavy charged particles is the Bragg peak: whereas electrons and photons deposit energy broadly continuously along their path, ions deposit most of their energy at the end of their range, at a depth determined precisely by initial energy. This underpins both proton therapy and controlled-depth semiconductor doping [1]. Four machine families serve distinct applications: ion implanters (1–500 keV), cyclotrons (10–250 MeV), synchrotrons (70 MeV/u to 5 GeV/u) and radiofrequency quadrupoles and ion linacs of variable energy.

The semiconductor industry alone operates more ion beam units than all other radiation processing combined: more than 15 000 implanters perform in excess of 100 billion doping steps annually in support of a global market exceeding USD 650 billion. Further applications include surface modification for hardness and wear resistance; materials analysis by particle-induced X-ray emission and Rutherford backscattering; and track-etch membranes, in which heavy-ion irradiation followed by chemical etching yields filters of uniform pore size unobtainable by other means.

Medical applications represent the highest-value segment. Approximately 125 proton therapy centres operate globally in 2026, together with some 14 carbon-ion facilities, and more than 300 000 patients have been treated with particle therapy. Compact superconducting cyclotrons have reduced proton facility costs from approximately USD 200 million in 2015 to USD 40–80 million today, while carbon-ion therapy near 400 MeV/u offers roughly three times the relative biological effectiveness of protons and suits radio-resistant tumours. Cyclotron-produced fluorine-18 supports approximately 12 million positron emission tomography examinations annually, and theranostic radionuclides are a rapidly expanding frontier. For Member States, medical isotope production is the most accessible entry point and where technical cooperation programmes achieve their highest impact per unit of investment.

4. Key Industrial Applications and the Sustainability Case

Electron beam processing is deployed across nine industrial domains with mature commercial operation, spanning medical device sterilization (25 kGy), wire and cable crosslinking (100–300 kGy), tyre and rubber pre-vulcanization, polymer foam crosslinking, heat-shrink tubing, surface curing of inks and coatings (80–300 keV), food and agriculture (0.1–10 kGy), gemstone colour enhancement (10–50 MGy) and wood and paper composites. The dose range spans nine orders of magnitude and the energy

range two, so no single machine serves it and the industry has segmented into specialist technologies [1, 3].

4.1. Medical Device Sterilization

Medical device sterilization is the largest application by volume, accounting for more than 40% of all sterilized single-use devices globally and some 12 billion products annually [8]. The process is validated in accordance with ISO 11137 [9] at a reference dose of 25 kGy, and offers three advantages: penetration of sealed packaging, enabling terminal sterilization; absence of chemical residues; and continuous-flow operation supporting scalable throughput.

A once-in-a-generation modality transition is underway, quantified in Table II. Concerns over Co-60 supply security and public perception are accelerating the shift from gamma to X-ray and EB. Simultaneously, the United States Environmental Protection Agency emission standards revision of 2024 [10], with restrictions under the European Union REACH framework, is displacing EtO – classified by the International Agency for Research on Cancer as a Group 1 human carcinogen – from its long-held dominance for heat-sensitive devices. On current projections X-ray processing becomes the largest single modality by 2035.

TABLE II: STERILIZATION MODALITY SHIFT, 2015–2035 (SHARE OF TREATED VOLUME)

MODALITY	2015	2026	2035 (PROJ.)	TRAJECTORY
Gamma (Co-60)	45%	35%	20%	Declining – supply, perception
Ethylene oxide (EtO)	45%	38%	20%	Declining – US EPA, EU REACH
Electron beam (EB)	8%	15%	25%	Growing rapidly
X-ray (Bremsstrahlung)	2%	12%	35%	Fastest-growing
<i>Note: Indicative shares synthesized from industry disclosures and analyst forecasts [8, 10]. Projections to 2035 are subject to regulatory and capacity assumptions.</i>				

4.2. Polymer Crosslinking and Radiation Curing

Wire and cable crosslinking is the largest single EB application by tonnage and installed power, accounting for more than 60% of global industrial EB power and supporting production of over 5 million kilometres of treated cable annually. Radiation crosslinking elevates continuous operating temperature from approximately 90°C to 150°C, improves mechanical strength by 30–50%, confers chemical resistance and supports service lives exceeding 30 years, while imparting the shape-memory effect exploited in heat-shrink products [3]. Solar photovoltaic and electric vehicle charging cable are the current surge markets.

Radiation curing employs low-energy EB (80–300 keV) to initiate polymerization in 100% solids formulations of coatings, inks and adhesives: solvent-free, zero volatile organic compound emissions, effectively instantaneous cure and 25–50% less energy than thermal curing. An emerging circular-economy application is EB-assisted recycling of polytetrafluoroethylene, where high-dose irradiation (300–600 kGy) degrades long-chain structures to a low-molecular-weight micro-powder reusable as a lubricant additive [11].

4.3. Food Safety and Environmental Remediation

Food irradiation is approved in more than 60 countries for spices and dried herbs (6–30 kGy), fresh fruit for phytosanitary treatment (0.15–1.0 kGy) and meat for pathogen reduction (1.5–4.5 kGy) [5, 6]. The Codex General Standard provides the international framework, and joint IAEA, FAO and WHO assessments have affirmed the wholesomeness of appropriately irradiated foods [12]. Growth drivers include phytosanitary requirements replacing methyl bromide fumigation and climate adaptation through reduced post-harvest losses.

Environmental applications are the most rapidly expanding frontier. Wastewater treatment (1–50 kGy) degrades pharmaceuticals, dyes and endocrine-disrupting compounds without added reagents; a pilot plant in Daegu, Republic of Korea, treats of the order of 10 000 t/d of dyeing wastewater [13]. Flue gas cleaning (3–10 kGy) removes NO_x, SO₂ and volatile organic compounds simultaneously, yielding fertilizer by-products; the Pomorzany power plant in Poland has operated commercially since 2005 [13]. Fluoropolymer and plastics valorisation (300–600 kGy) offers a treatment route for PFAS-contaminated water, supported by IAEA project RAS1034 over 2024–2027 [14], and sludge sanitization (2–10 kGy) inactivates pathogens including helminth ova, enabling reuse as agricultural biosolid.

4.4. The Sustainability Case for EtO Replacement

Table III compares radiation processing with EtO sterilization. Radiation-based alternatives require no chemical inputs, produce no gaseous emissions and consume energy that decarbonizes proportionally with the electricity grid. Life-cycle analyses indicate significantly lower carbon footprints on a per-product basis [8], an advantage that grows as renewable shares increase. Healthcare manufacturers increasingly specify lower-carbon sterilization in supplier requirements, adding commercial impetus to regulatory pressure.

TABLE III: COMPARATIVE ASSESSMENT OF ETO STERILIZATION VERSUS ACCELERATOR-BASED RADIATION

ATTRIBUTE	ETHYLENE OXIDE (ETO)	EB / X-RAY RADIATION
Carcinogenicity	IARC Group 1 human carcinogen	None — no chemical agent
Environmental impact	Hazardous air pollutant (EPA listed)	No emissions; electricity only
Process cycle time	2–3 days (aeration required)	Minutes to hours
Chemical residues	Require testing (ISO 10993-7)	None
Worker exposure risk	Significant; TLV 1 ppm (ACGIH)	Shielded; no chemical exposure
Carbon footprint	High (chemical + aeration energy)	Grid-dependent; declining
Regulatory trend	Tightening limits (US EPA 2024)	Favourable; growing acceptance
<i>Note: EtO classification per IARC Monograph Vol. 100F (2012); carbon footprint per industry life-cycle assessment studies, 2020–2024.</i>		

5. Barriers to Wider Adoption

Three persistent structural barriers constrain adoption, particularly in low- and middle-income countries. None is a deficiency of the technology itself; all three are organizational and institutional, and are therefore amenable to policy and coordination measures.

Capital intensity. Industrial irradiation facilities require investment of USD 5–25 million depending on modality, power and throughput. Payback extends to 6–10 years, commissioning typically requires 12–24 months, and vendor concentration limits competitive pressure on pricing. Few financial institutions possess underwriting expertise specific to irradiation economics, making green bonds, blended-finance instruments and tailored lending programmes priority requirements [14].

Regulatory complexity. Facilities are subject to two parallel frameworks — radiation safety, and sector-specific food or medical regulation. Licensing typically requires 12–24 months and involves multiple competent authorities. A critical structural gap is the absence of mutual recognition of sterilization validation: a product validated in one jurisdiction frequently requires revalidation for another, and revalidation is likewise required when switching modality — materially slowing the transition away from EtO. Harmonization among the IAEA, ISO and Codex Alimentarius is the highest-leverage policy intervention available to the field.

Industrial inertia. EtO, methyl bromide fumigation and steam sterilization are deeply embedded in practice. Switching costs include revalidation, supply chain redesign and requalification of downstream customers; healthcare procurement is conservative by design, and buyer acceptance consistently lags technical capability by 5–10 years.

6. Opportunities on the Horizon

6.1. Advanced Accelerator Designs

Four platforms at differing maturity are reducing capital cost and operational complexity. Compact linacs with solid-state radiofrequency amplifiers are commercially available in 100 kW container-scale configurations, enabling distributed and on-site sterilization particularly suited to emerging markets. High-power recirculating machines deliver up to 700 kW at 7 MeV with the highest wall-plug efficiency in the industry, and are the enabling platform for economic Bremsstrahlung conversion. Superconducting radiofrequency technology is transitioning from research to industry, offering ultra-low losses and the high average currents required for bulk processing; it represents the principal route to megawatt-class industrial EB. Dielectric wall accelerators, at research stage, employ ultra-fast pulsed acceleration at high gradient for compact and potentially field-deployable configurations, on a 5–10 year horizon.

6.2. Digitalization and Artificial Intelligence

Radiation processing facilities are data-rich but historically analytics-poor, and artificial intelligence is changing this without requiring new capital equipment. Three capabilities are already deployed at leading facilities: reinforcement learning controllers have replaced manual beam tuning, stabilizing beam position to better than 0.1 mm and cutting operator tuning workload by 60–80%; autoencoder networks trained on operational telemetry identify deviations 4–48 hours before they would cause downtime, with production accuracy above 90%; and component-level predictive maintenance reduces unplanned downtime by 30–50%.

In process modelling the gains are larger still. Neural network surrogates trained on Monte Carlo databases predict three-dimensional dose distributions in under one second, against hours for full simulation, within 1–3% of the simulated ground truth, enabling real-time control and on-the-fly recipe adjustment. Digital twins maintain a live physics-and-control model alongside the facility: divergence between predicted and measured dose gives early indication of drift, and new recipes can be evaluated in silico, reducing validation effort five- to tenfold. For pilot plants in developing countries this is particularly consequential, as modelling that previously required substantial computing infrastructure can now be performed on a laptop.

These capabilities are converging on a three-stage transformation of facility operation. Today (2026), operation is AI-assisted, with operators in the loop and human review of every batch release. In the near term (2028–2030), semi-autonomous facilities are expected, in which AI runs routine processing end-to-end while humans handle exceptions and validation. Beyond 2030, fully autonomous lights-out operation with remote oversight becomes feasible. Technical feasibility of the intermediate stage is largely established; regulatory acceptance is the gating factor, as validation and audit frameworks were designed for human-operated systems. The operator's role shifts from manual tuning towards oversight of automated systems, and university curricula will need to incorporate data science and model validation alongside radiation physics.

6.3. Emerging Geographic Markets

The geographic distribution of irradiation capacity remains heavily skewed. Indicative facility counts for 2024 are approximately 320 in North America, 280 in Europe and 210 in East Asia, against some 95 in South and South-East Asia, 65 in Latin America, 30 in the Middle East and 18 in Africa. Regions with the greatest unmet need thus account for a small fraction of installed capacity despite substantial post-harvest losses and growing medical device manufacture. Principal growth drivers differ by region – EtO replacement and food safety in North America, polymer processing in Europe, medical devices and food exports in East Asia, pharmaceutical sterilization and phytosanitary treatment in South and South-East Asia – but the imbalance represents the largest single growth opportunity in the field.

7. International Initiatives

Several coordinated international efforts support the field. The National Academies of Sciences, Engineering, and Medicine of the United States has undertaken a study, Expanded U.S. Electron Beam Usage in Sterilization and Irradiation Applications [15], motivated by reducing hazards from radiological dispersal devices and harmful chemical releases; its scope covers lifecycle assessment of EB against other commercial technologies, identification of new applications, and public–private case studies addressing the laboratory-to-commercial transition. The IAEA maintains two relevant databases: cyclotrons used for radionuclide production, developed in 1983 and updated in 1998 and 2006, currently covering approximately 1 280 machines worldwide [16]; and a worldwide database of irradiation facilities and their applications, in development [17]. Such resources underpin international collaboration, encourage technology transfer and provide a strategic planning tool for governments and enterprises.

8. Technology Outlook and Call to Action

The period to 2035 will be defined by four concurrent developments: completion of the sterilization modality shift, with X-ray becoming the largest single modality; maturation of environmental applications from demonstration to commercial deployment; transition of facility operation from AI-assisted to semi-autonomous; and geographic rebalancing of capacity. None is technologically speculative; each depends principally on financing, regulatory and workforce conditions. Realizing this potential requires coordinated action on six fronts: capital instruments (green bonds, blended finance and lending tailored to irradiation project economics); regulatory harmonization (IAEA, ISO and Codex coordination on mutual recognition of sterilization validation and streamlined licensing); the workforce pipeline (university curricula, IAEA training schools and apprenticeships); market education (engagement with end-users, regulators and the public, recognizing that the communication gap rather than the evidence base is the binding constraint); open standards and data (shared dosimetry datasets and open-source simulation codes); and public–private dialogue on coordinated technology roadmaps for the 2030s. Individually none is sufficient; together they are mutually reinforcing.

9. Conclusions

Ninety years after the founding inventions of Cockcroft and Walton, Lawrence, and Van de Graaff, three principal modalities — electron beam, X-ray and ion beam — together support an industrial market of the order of USD 100 billion annually in treated goods, delivered by more than 35 000 accelerators worldwide. The technology is demonstrably superior to EtO sterilization on worker safety, environmental and carbon-footprint dimensions, and its advantages grow as electricity grids decarbonize.

Key application sectors are individually mature and collectively expanding, and a once-in-a-generation modality shift is transferring a large share of sterilization volume from gamma and EtO to EB and X-ray over 2020–2035, with environmental applications the most rapidly growing frontier. Structural barriers — capital intensity, regulatory complexity and industrial inertia — are real but tractable, and institutional rather than technological in character. Advanced accelerator designs, AI-driven optimization and expanding geographic markets offer concrete near-term opportunities, but the workforce and regulatory frameworks needed to support them require attention now, ahead of the technology itself. The principal task for the international community is to remove the friction — financial, regulatory and social — holding this proven, scalable and sustainability-aligned technology back from its full potential.

Declarations

Author Contribution

Author 1 wrote the main manuscript text and Authors 2,3, and 4 reviewed the manuscript.

References

1. INTERNATIONAL ATOMIC ENERGY AGENCY, Industrial Radiation Processing with Electron Beams and X-rays, IAEA, Vienna (2011).
2. WANG, J., CHU, L., WOJNÁROVITS, L., TAKÁCS, E., Occurrence and fate of antibiotics and antibiotic resistant genes in municipal wastewater treatment plants, *Sci. Total Environ.* 744 (2020) 140997.
3. CLELAND, M.R., “Industrial applications of electron accelerators”, CERN Accelerator School Proceedings, CERN, Geneva (2006).
4. BEREJKA, A.J., CLELAND, M.R. (Eds.), Industrial Radiation Processing with Electron Beams and X-rays, IAEA, Vienna (2010).
5. CLELAND, M.R., STICHELBAUT, F., Radiation processing with high-energy X-rays, *Radiat. Phys. Chem.* 84 (2013) 91–99.
6. CODEX ALIMENTARIUS COMMISSION, General Standard for Irradiated Foods, CXS 106–1983 (Rev. 2003), FAO/WHO, Rome (2003).
7. CHMIELEWSKI, A.G., Electron accelerators for environmental protection, *Radiat. Phys. Chem.* 144 (2018) 19–27.
8. INTERNATIONAL ATOMIC ENERGY AGENCY, Trends in Radiation Sterilization of Health Care Products, STI/PUB/1313, IAEA, Vienna (2008).

9. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Sterilization of Health Care Products – Radiation, ISO 11137-1/-2/-3, ISO, Geneva (current edition).
10. UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, National Emission Standards for Hazardous Air Pollutants: Ethylene Oxide, 40 CFR Part 63, US EPA, Washington, DC (2024).
11. KOREA ATOMIC ENERGY RESEARCH INSTITUTE, PTFE Recycling and PFAS Treatment R&D Programme, KAERI, Daejeon (2023).
12. WORLD HEALTH ORGANIZATION, High-Dose Irradiation: Wholesomeness of Food Irradiated with Doses above 10 kGy, TRS No. 890, WHO, Geneva (1999).
13. INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Treatment of Wastewater and Flue Gas, IAEA, Vienna (2018).
14. INTERNATIONAL ATOMIC ENERGY AGENCY, TC Project RAS1034: Pilot Plants for Plastic Waste Recycling, IAEA, Vienna (2024).
15. NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE, Expanded U.S. Electron Beam Usage in Sterilization and Irradiation Applications, National Academies Press, Washington, DC (2025).
16. INTERNATIONAL ATOMIC ENERGY AGENCY, Cyclotrons Used for Radionuclide Production (database), IAEA, Vienna, <https://nucleus.iaea.org/sites/accelerators> (2026).
17. INTERNATIONAL ATOMIC ENERGY AGENCY, Worldwide Database of Irradiation Facilities, IAEA, Vienna (in development).