Introduction :

Food irradiation has been around the globe for centuries now, with the original patent for X-ray treatment of foods issued in early 1905, 20 years after W.C. Roentgen discovered X-ray in 1885. It was then the most extensively studied and developed food treatment technology in the history of mankind. Food irradiation was not a popular concept until it was scientifically established and proven to be beneficial and safe for food treatment processing for the past 50 to 70 years. In the 1950s, research programmes for food irradiation were initiated across Western Europe, while the International Food Irradiation Project (IPFI) was launched in 1970 to investigate and validate the overall effects of radiation on food. A joint committee formed by the International Atomic Energy Agency (IAEA), Food and Agriculture Organisation (FAO), and World Health Organisation (WHO) was named to examine the findings of the project .However, until today, it has been considered as the most misunderstood technology since the food was irradiated with ionizing radiation, which could break the chemical bond of the food. This understanding always leads to public concern about the safety and quality of the irradiated food even though our food is constantly irradiated by non-ionizing radiation called microwave.

A regulation governs the treatment of foods by ionization. It is the **Framework Directive 1999/2/EC of the European Parliament** on food and food ingredients treated with ionization and the **Implementing Directive 1999/3/EC of the European Parliament and of the Council**, which establishes a Community list of foods and food ingredients that may be treated with ionization. These directives require the **labeling of irradiated products**.

The following symbol identifies these products: **the Radura symbol**.

International symbol identifying an irradiated food.

1.Ionization doses and fields of application

Gamma photons emitted by the radioisotopes such as ^{60}Co (cobalt-60), ^{137}Cs (cesium-137) as well as X-rays which also known as Bremsstrahlung, generated by a machine with a maximum of 5 MeV, or accelerated electrons beam with a maximum of 10 MeV kinetic energy are the common types of radiation used for food irradiation. In 1997, an investigation of high dose irradiation (25 – 60 kGy) on food by FAO, IAEA, and WHO has proven that these radiation types on food irradiation were safe to consume and nutritionally adequate

- **Units of measurement of the irradiation dose**

- **Energy associated with electrons: electron volt (eV).**
  $\mathbf{1\ eV = 1.6 \times 10^{-12}}$**erg.**
- **Unit of radionuclide activity: the SI unit is the becquerel (Bq).**
  The former unit is the curie (Ci).
  $\mathbf{1\ Ci = 3.7 \times 10^{10}\ Bq.}$
- **The Gray (Gy): corresponds to the absorption of an energy of 1 joule per kilogram of irradiated food.**
  The former unit is the radium $(\mathbf{1\ rad = 10^{-2}\ J/kg})$.

-Fields of application

Three terms are used to characterize the different possible applications:

- **Radurization**: ionizing doses that allow the reduction of the microbial load of the product in order to slightly extend its shelf life (doses ≤ 5 kGy).
- **Radicidation**: irradiation doses sufficient to reduce the number of non-spore-forming pathogenic microorganisms (doses ≤ 10 kGy).

This treatment is equivalent to pasteurization (radiopasteurization).

- **Radappertization**: application of high irradiation doses (20 to 50 kGy) sufficient to reduce the number of living microorganisms and spores (radiosterilization).

2/ Nature of the radiations used

Two main types of radiation have been applied in the food field:

- **a) Gamma radiation:**
  These are **electromagnetic radiations** of the same nature as light but with a **higher frequency**. They originate from the **disintegration of Cobalt-60 or Cesium-137**. The high energy of these radiations (**about 1.3 MeV**) gives them a **strong penetrating power** (several tens of centimeters).
- The **lifetime of a cobalt source rod** is about **5 years** (a **12% replenishment per year** is necessary).

$$^{137}_{55}\mathrm{Cs} + 1\mathrm{n} \longrightarrow {}^{137}_{56}\mathrm{Ba} + e + \gamma \qquad {}^{60}_{27}\mathrm{Co} + 1\mathrm{n} \longrightarrow {}^{60}_{28}\mathrm{Ni} + e + \gamma$$

b) Accelerated electrons:
The equipment consists of an **electron production system**, an **acceleration system**, and **focusing and scanning systems**.
The **energy of the electron beam** is limited to **10 MeV**. Accelerated electrons allow **rapid and flexible use** by directing the beam toward the product.
However, the use of accelerated electrons is **limited to surface treatments or thin products** because of their **low penetration power**.

.3/ Ionization Installation

These are installations that require **specific engineering to ensure the safety of operators**. They are **relatively expensive** and are generally located in **agro-food production areas** that use this technique, which often requires **costly transportation of food products**.

For both ionization techniques, the entire installation includes:

- A **concrete shielding chamber** (1.8 to 2 m thick) **(a)** ensuring **personnel protection**;
- A **radiation source system** producing **gamma rays** or a system for the **production and acceleration of electrons (b)**;
- A **control and automation system (c)**;
- A **ventilation system** that removes **heat and ozone formed as a result of air ionization**;
- A **conveyor system** that transports the products to the **accelerator**, moves them through the **radiation beam**, and removes them after treatment **(d)** (Figure.1).

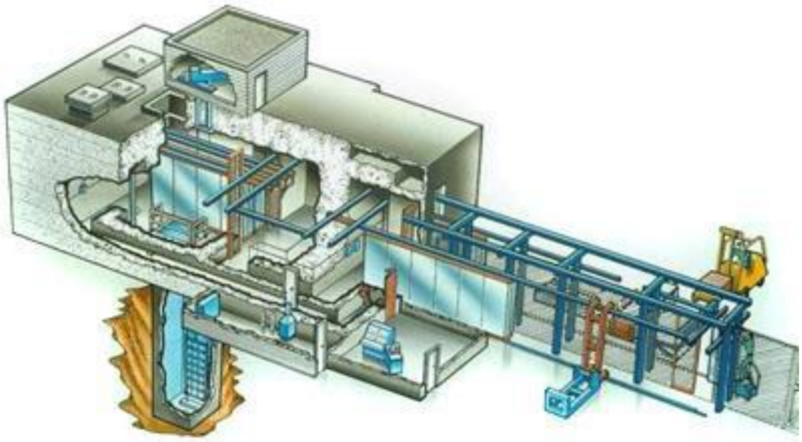


Figure.1 : Ionisation Installation

.4 / Mechanisms of action of radiation

During the application of **ionizing treatments** for the **sanitation and preservation of food products**, radiation is used that has **sufficient energy to remove an orbital electron from the irradiated biological media**, thus converting these atoms into **positive ions** and generating **ionization** in the exposed substance.

Radiation modifies the **medium through which it passes**. The energy supplied by the **photon** may simply be **absorbed by the atom**, which is then called **excitation**. If this energy is too high to be absorbed, **secondary electrons are ejected**; this phenomenon is known as the **Compton effect** (FigureIV.2).

Note: The energies of these radiations are sufficient to **remove an electron from the atoms of the encountered matter**, but they remain **below the activation threshold**. This means that it is **impossible to induce radioactivity in the treated food**.

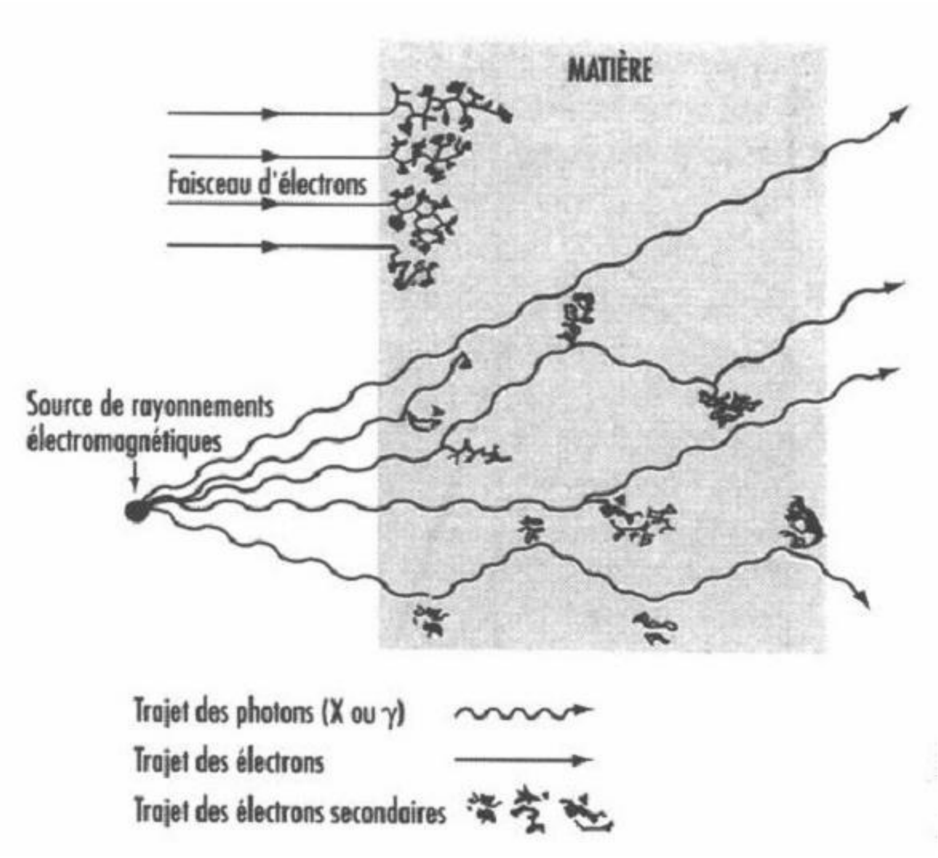


Figure.2: Interaction of ionizing radiation with matter.

.5/ Effect of radiation on the medium

Electrons and **γ (gamma) radiation** have the ability to **penetrate different materials**, to which they transfer their energy, thereby **causing ionization of the medium they pass through**.

When penetrating a food product, **accelerated electrons** or those produced from **electromagnetic radiation (X or γ)** lose their energy by **interacting with the electrons of the atoms** in the medium they cross.

This process continues until the **residual energy of the electrons** becomes **comparable to the energy required to break covalent bonds**. At this stage, **radiolysis products appear**, known as the **"cage effect."**

5.1 / Chemical effects

Molecular ions and **free radicals** will have different effects depending on the **rigidity of the medium**.

- In a **solid medium** (where high viscosity prevents ions from migrating), **molecular interactions remain relatively limited**. Only a **direct effect of radiation** occurs.
- In an **aqueous medium**, where **recombination reactions occur due to the diffusive properties of the medium**, an **indirect effect called "water radiolysis"** is added to the **direct effect**.

Pour l'ionisation

$$AB \rightarrow AB^{+} + e^{-}$$

$$\begin{array}{l} AB^{+} \rightarrow A^{+} + B^{\bullet} \\ \hline AB \rightarrow \underset{\text{ion}}{A^{+}} + \underset{\text{Radical libre}}{B^{\bullet}} + \underset{\text{électron}}{e^{-}} \end{array}$$

Pour l'excitation

$$AB \rightarrow AB^{*}$$

$$AB^{*} \rightarrow A^{\bullet} + B^{\bullet}$$

✓ Direct effect: Mechanism of hydrolysis reactions

The processes of **ionization and excitation** lead to the **breaking of chemical bonds** that connect the atoms of a molecule and to the **formation of molecular fragments**

$$H_2O \rightarrow OH^{\bullet},\, e^{-}_{aqueux},\, H^{\bullet}$$

These fragments are **endowed with a strong oxidizing power** and are called **free radicals** (denoted **X•**).

✓ Indirect effect: Radiolysis of water and aqueous media

The **ionization of a water molecule** causes the formation of **highly reactive free radicals**, whose **unpaired electron** seeks to pair with that of another radical.

Radiolysis products such as **H_2 and H_2O_2** are formed through the **recombination of free radicals** with each other or with **solutes**.

It should be noted that **oxygen plays a particularly important role as a solute**, because this **biradical molecule** is highly reactive with **free radicals and unsaturated molecules**. It forms, with radiolysis products, **peroxide bridges**, which are notably responsible for the **rancidity of fats** when reacting with **unsaturated lipids**.

These **radiolysis products** are a consequence of **irradiation**, but they are **similar in nature to those produced by heat treatment**, although **in smaller quantities**.

.5.2 / Biological effects

Ionization induces an effect on **spoilage agents** (bacteria, viruses, yeasts, and molds) through a **direct effect on DNA and RNA**, causing **chemical modifications** such as **hydration of cytosine, breakage of chains, and rupture of hydrogen bonds**.

Radiation may also cause **oxidation of membrane lipoproteins**, which **blocks cell division**.

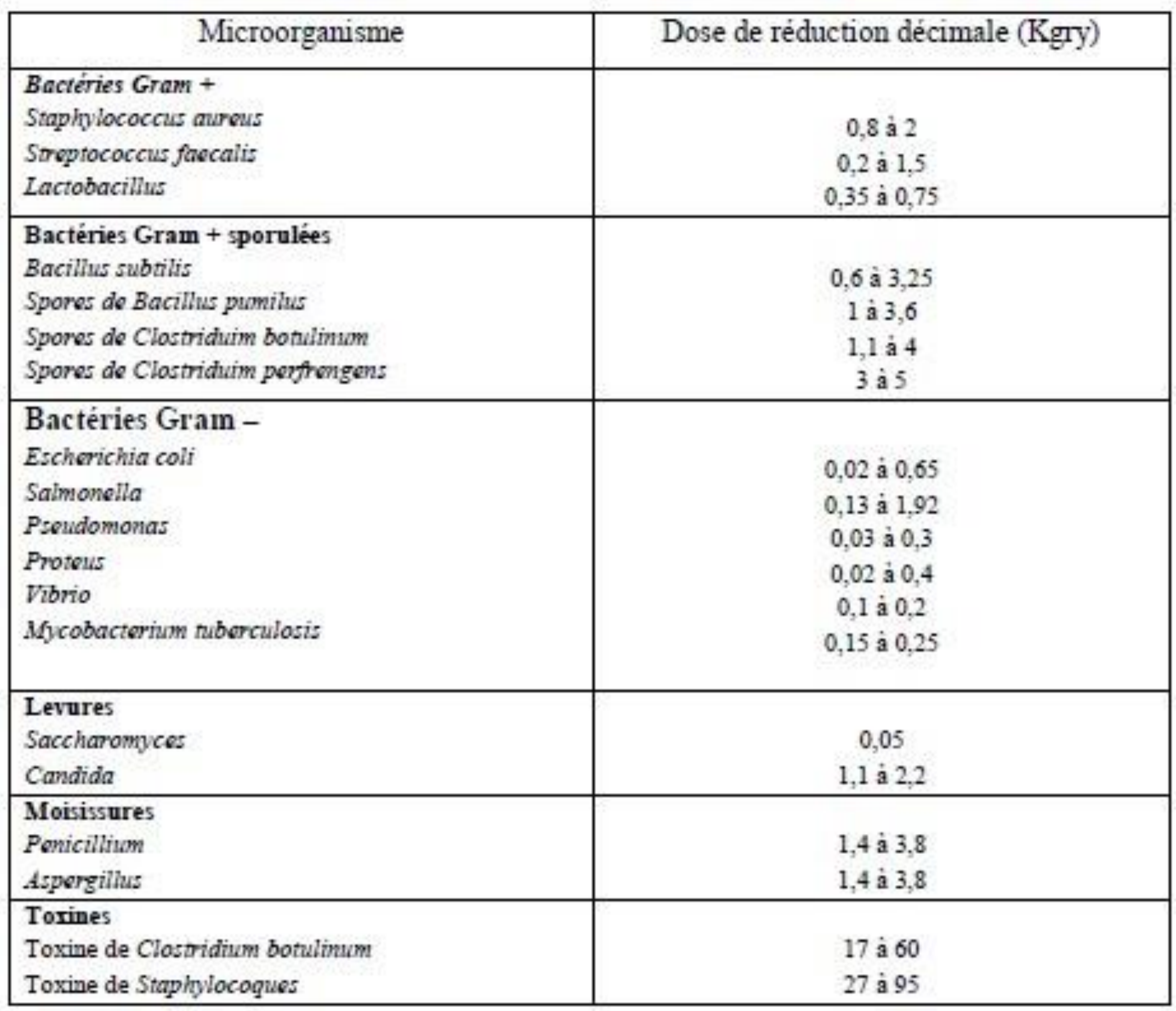
The **sensitivity of microorganisms to ionization** varies depending on:

- **The species**: **spore-forming organisms are more resistant**.
- **Temperature**: an **increase in temperature decreases radioresistance**.
- **Presence of oxygen**: **oxygen increases the radiosensitivity of microorganisms** (through oxidation of lipids).

- **Dry matter content**: an **increase in dry matter content increases radioresistance**.
- **The presence of water and salts increases the radiosensitivity of microorganisms.**

Table.1 presents the **decimal reduction doses of the most common microorganisms in the agri-food sector.**

Table.1: Decimal reduction doses of some microorganisms.



Microorganisme	Dose de réduction décimale (Kgry)
Bactéries Gram +	
Staphylococcus aureus	0,8 à 2
Streptococcus faecalis	0,2 à 1,5
Lactobacillus	0,35 à 0,75
Bactéries Gram + sporulées	
Bacillus subtilis	0,6 à 3,25
Spores de Bacillus pumilus	1 à 3,6
Spores de Clostriduim botulinum	1,1 à 4
Spores de Clostriduim perfrengens	3 à 5
Bactéries Gram –	
Escherichia coli	0,02 à 0,65
Salmonella	0,13 à 1,92
Pseudomonas	0,03 à 0,3
Proteus	0,02 à 0,4
Vibrio	0,1 à 0,2
Mycobacterium tuberculosis	0,15 à 0,25
Levures	
Saccharomyces	0,05
Candida	1,1 à 2,2
Moisissures	
Penicillium	1,4 à 3,8
Aspergillus	1,4 à 3,8
Toxines	
Toxine de *Clostridium botulinum*	17 à 60
Toxine de *Staphylocoques*	27 à 95

.6/ Effect of Ionization on Food Quality

.6.1/ Effects on Organoleptic Quality

The modifications induced by ionizing radiation may lead to an alteration of the **organoleptic quality** of food products. The extent of these changes depends on the **absorbed dose** and the **chemical composition of the food**.

These organoleptic modifications result from the **radiolysis of food constituents**. Although this does **not present any risk to the consumer**, it may make the **commercialization of the treated products impossible**.

The main alteration is the development of the **"irradiated" flavor**, mainly due to the action of radiation on **lipids and proteins**, which increases the level of **peroxides and hydroperoxides** (in foods rich in unsaturated fatty acids). This leads to the production of **aldehydes and ketones**, responsible for unpleasant odors.

Proteins are also responsible for the appearance of **undesirable odors**, mainly due to the production of **hydrogen sulfide**.

Research has shown that it is possible to reduce the occurrence of these modifications by:

- **Lowering the temperature** during ionization;
- **Ionizing in the absence of oxygen**;
- **Optimizing the irradiation dose**;
- **Proper storage and cooking** of irradiated products.

However, for some foods, these phenomena may still require a **restriction of the field of application**.

.6.2/ Effects on Nutritional Quality

The irradiation doses used cause only **slight changes in the nutritional quality** of food products and produce **very small amounts of radiolysis products** (about **0.1 to 0.2 ppm of each product**). The action of radiation is **negligible on proteins and carbohydrates**.

However, **oxidation reactions** may occur in **unsaturated lipids**, leading to the formation of **peroxides**, which are responsible for the **rancidity** of products.

The **vitamins most sensitive to ionization** are **K, E, B1, C, and A**. However, studies have shown that these vitamins are **better preserved by ionization than by thermal treatment**.

Note: Some types of **plastic packaging** may release **polymeric fragments** under the effect of radiation. Therefore, it is recommended to use **polyethylene** and **polystyrene**, which are the **most radio-resistant materials**.

For meat:
The doses applied generally range between **1 and 5 kGy**. An **unpleasant odor similar to "wet dog"** and **changes in meat color** may appear if the applied dose is too high. This dose limit depends on the **type of meat** and the **processing conditions** (packaging and atmosphere).

It is possible to increase this limit by performing **ionization in an inert atmosphere** or by **lowering the temperature during irradiation**.

Exposure at low temperature (−20 °C) can help reduce these effects. In addition, the **texture of meat may be modified**, often resulting in **increased tenderness in irradiated meat**.

For seafood products:

For **exposure doses higher than 3 kGy**, unpleasant odors may appear, along with **fading of the pink color of salmon** and **hardening of lobster texture**. Therefore, the doses used for seafood generally **do not exceed 2 kGy**.

Fruits and vegetables:

For **ionization doses exceeding 2 kGy**, a **texture alteration of fruits (softening)** can be observed. This phenomenon can be avoided by **calcium fertilization in the field**, particularly for **strawberries**.
The problem is less significant for **vegetables**, which are generally **cooked**, and a **reduction in cooking time** is even observed.

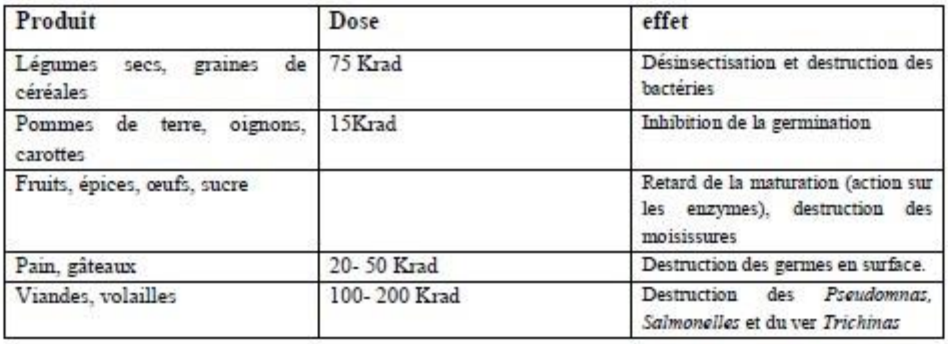
Potatoes and onions:

These foods are irradiated to **inhibit the germination process**. Since the exposure doses are **low (about 0.1 kGy)**, **very few organoleptic changes** are observed.
For **potatoes**, a **slight increase in sweet taste** may occur during prolonged storage.
For **onions**, a **decrease in their tear-producing effect** and **astringent properties** has sometimes been observed after treatment.

Milk and dairy products:

These products may develop **unpleasant odors after ionizing treatment**, even at **very low doses (around 0.05 kGy)**. This phenomenon explains the **limited interest in using ionization for this type of product**.

Table.2 summarizes the **effects of radiation on different food products**.



Produit	Dose	effet
Légumes secs, graines de céréales	75 Krad	Désinsectisation et destruction des bactéries
Pommes de terre, oignons, carottes	15Krad	Inhibition de la germination
Fruits, épices, œufs, sucre		Retard de la maturation (action sur les enzymes), destruction des moisissures
Pain, gâteaux	20- 50 Krad	Destruction des germes en surface.
Viandes, volailles	100- 200 Krad	Destruction des *Pseudomnas*, *Salmonelles* et du ver *Trichinas*

.7/ Detection of Irradiated Foods

It is necessary to have methods that allow the **detection of irradiated foods**. Demonstrating that a product has been irradiated makes it possible to **verify the labeling of treated products** and helps in the **fight against fraud**.

Because the **radiolysis products are not specific**, detection was previously difficult. However,in recent years, several **effective methods** have been developed to detect **radiation-induced modifications**.

.7.1 / Screening Method (DNA Comet Assay)

This method is based on **micro-gel electrophoresis of single cells or nuclei** to detect possible **DNA fragmentation** resulting from ionization.

Fragments of **damaged DNA migrate toward the anode**, forming a tail that gives the appearance of a **comet**.

This method is effective for **products of animal or plant origin**.

.7.2 / Thermoluminescence

This method is applied to **spices and dehydrated vegetables**. It is based on the **measurement of light emitted during the thermal de-excitation of secondary electrons**.

The **intensity of thermoluminescence** depends on the **irradiation dose**, **storage time**, and **heating temperature**.

.7.3 / Electron Paramagnetic Resonance (EPR)

EPR is based on the **magnetic properties of unpaired electrons**, especially when the irradiation dose is **higher than 1 kGy**.

This method can be applied to **bones of meat, fish bones, eggs, and shellfish**.

.7.4 / Chemical Methods

These methods involve the **analysis of the chromatographic profile of fatty acids by gas chromatography (GC)** and the **detection of radiolysis products** directly related to the original product.

Cyclobutanones (**volatile hydrocarbons**) are also formed from **lipids**, and their structure is linked to the original lipid.

Therefore, this method is mainly used for **products rich in triglycerides**, such as **oils and meat**.