الجمهوريــــة الجزائريــة الديمقراطيـــة الشعبيـــة
People's Democratic Republic of Algeria

وزارة التعليم العالي والبحث العلمي
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Preservation technology

Course Handout

Master's Year 1 Agri-Food and Quality Control

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2025/2026

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Abbreviations list

Abbreviation	Full Term
AAB	Acetic acid bacteria
AW	Water activity
BBE	Best before end date
D	Decimal reduction time
DNA	Desoxyribonucleic acid
E-beam	Electron Beam
EMP	Embden–Meyerhof–Parnas
Gy	Gray
HPP	High Pressure Processing
NaCl	Sodium chloride
RNA	Ribonuleic acid
UBD	Used before date
UHT	Ultra High Temperature
UV	Ultraviolet
UHT	Ultra High Temperature
γ	Gamma rays

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The food industry plays a strategic role in meeting the nutritional needs of populations. However, foods are perishable biological products whose quality can be altered by various physical, chemical, enzymatic, and microbiological factors. Therefore, mastering food preservation is a major challenge to ensure food safety, maintain the nutritional and sensory qualities of products, reduce food losses, and extend shelf life.

Food preservation technology encompasses all processes and techniques used to limit or delay the deterioration of food products. Over time, traditional preservation methods have evolved into more efficient technologies that incorporate scientific and technological advances. These processes are based on various principles, such as the application of heat or cold, the reduction of water activity, pH modification, the use of food additives, irradiation, membrane processing technologies, high-pressure processing, and modified atmosphere preservation.

In addition to preservation techniques, food packaging plays an essential role in protecting foods throughout their life cycle. It acts as a barrier against external hazards, facilitates handling, storage, and distribution, and provides consumers with important information through food labeling. Recent innovations have also led to the development of active and intelligent packaging systems capable of interacting with food products or providing information about their preservation status.

This course aims to provide students with fundamental knowledge of the main food preservation and packaging technologies. It covers the mechanisms of action, advantages, limitations, and application areas of each process, with particular emphasis on their effects on food quality, safety, and stability. The acquisition of this knowledge will enable future specialists in food science and technology and quality control to select, evaluate, and optimize the most appropriate preservation methods for different categories of food products.

1.Preservation techniques

This chapter presents the different food preservation techniques used to extend shelf life and ensure the sanitary and nutritional quality of foods. It first discusses preservation methods based on heat, such as pasteurization, sterilization, appertization, and ultra-high temperature (UHT) treatment, followed by preservation techniques based on cold, including refrigeration, freezing, and deep freezing. The chapter also deals with processes based on water separation or removal, such as concentration, drying, freeze-drying, smoking, salting, and sugar preservation. Techniques involving food additives as well as fermentation will also be discussed, in addition to modern methods such as ionization and irradiation.

1.1. History of food preservation

The practice of preserving food began in the prehistoric age when ancient humans hunted animals and ate fresh animal meat. Acquired foods were sometimes stored to prevent famine and different food preservation methods for improving food quality were attempted. For example, grains were sun-dried to extend their storage period and fresh food were stored in cool, dry caves. About 400,000 years ago, Peking Man (*Homo erectus pekinensis*) may have utilized cooking methods using fire, such as grilling food over a fire to improve its flavor (table 1).

Table 1. Historic events in food preservation (Noh et al. (2009).

Year	Summary
Before 1500	Natural drying agents, such as fire, wind, sun, seawater, and halite were used for preservation, along with cooking, grilling, roasting, and curing with salt or sugar; and natural cool storage, such as caves, were mostly used. In 1492, American Indians were using fire for drying pemmican.
1600s	A low-heat air-drying room for using the hot air artificial drying method was developed.
1780	In the UK, preconditioning with hot water for drying vegetables was performed.
1795	In France, hot air was used for drying vegetables.
1800s	In 1804, Nicolas Appert (France) invented a canning method using wide-mouth bottles. In 1810, Peter Durand (UK) discovered the tin can. In 1819, Thomas Kensett (UK) started to can shrimp, salmon, and oysters.
1875	Carl von Linde invented a compression refrigerating machine using ammonia for making ice.
1900s	Canning was more developed in this period.
1916	Rudolph Planck proposed a theoretical quick-freezing technique.
1922	Franklin Kidd and Cyril West (England) began studying methods of gas storage.
1929	Clarence Birdseye (USA) invented a quick-freezing system and began to make frozen food.
1942	During WWII, freezing, cooling, drying, canning, and bottling processing techniques were further developed.
1950	Vacuum concentration of liquid food and lyophilization of dehydrated food became available.
1953	In the US, studies into the application of radiation to food began.
After 1960	Until 1950, processing techniques and equipment were being improved side-by-side, and through the incorporation of food chemicals and additives, the quality of processed food similarly improved. Also, through the development of petro-chemistry, many types of plastic products were developed for use as packaging materials or containers. Electronic engineering, such as microwave ovens, thermoelectric cooling, supersonic machining, etc. are applied to food processing.

1.2. Food categories

Foods are generally classified into two categories: perishable foods and non-perishable foods.

- **Perishable foods**: Are products that deteriorate rapidly under the action of various factors such as insects, fungi, microbial germs, certain chemical reactions like oxidation in air, or simply the effect of time. These deteriorations lead to changes in texture, color, and taste, which may render the food unfit for consumption. Therefore, these foods often require appropriate preservation methods, particularly refrigeration or freezing.

- **Non-perishable foods**: Are durable products that do not require specific preservation methods or refrigeration. Due to their low moisture content or the preservation processes applied to them, they can be stored for long periods without significant quality deterioration. Examples of these foods include rice, pasta, cereals, flour, oils, crackers, biscuits, canned foods, condiments, sugar, potatoes, and onions

1.3. Definition and principles of food preservation

Food preservation is the set of techniques and processes used to protect foods against microbiological, chemical, and physical deterioration, in order to maintain their quality, nutritional value, and safety for a longer period of time.

Two important concepts should be mentioned:

- **Use-By Date (UBD)**: Is applied to "highly perishable food products which are likely, after a short period, to present an immediate danger to human health." The UBD indicates a strict limit beyond which the product must be discarded because it is considered unsafe.

It is preceded by the words "use by …………………". This statement is followed by a description of the storage conditions that must be respected.

- **Best Before End Date (BBE):** Is indicated on the product instead of the Use-By Date (UBD) when the food is not considered "highly perishable from a microbiological point of view." These are generally microbiologically stable products, particularly with regard to pathogenic microorganisms. A microbiologically stable food slows down or inhibits microbial growth or toxin production due to its physicochemical composition (particularly pH and water activity, Aw), the presence of inhibitory compounds, or the storage temperature.

The BBE is preceded by the words "best before ………" when the date includes the day, or "best before end ………" in other cases. Beyond the BBE, the food is not dangerous to health and may still be consumed, but it may lose some of its sensory and/or nutritional qualities. For example, there may be changes in taste, color, or even odor

There are two main principles by which food preservation is achieved:

- **Controlling microorganisms:** Microbial contamination may cause change that renders food unfit for human consumption. Primary sources of contamination are irrigation water, air, soil, animals, feed, and food processing equipments. Foods may be contaminated by bacteria yeasts or molds at any stages of pre-harvest to post-harvest continuum.
- **Controlling enzymes:** Enzymes play important role in living tissues of food. But it catalyzes spoilage reactions following harvest or slaughter of plant or animal-based foods. In case of plant foods, certain enzymes remain active in the tissue cells of fruits and vegetables following harvest and may continue to catalyze the biochemical processes of ripening of these foods which may eventually lead to rotting, as can be observed in many fruits. Oxidative enzymes in produce such as banana or other fruits may continue to maintain cellular respiration by metabolizing sugar with oxygen for energy and may shorten the shelf life of fresh fruits leading to spoilage. Respiration may be controlled by refrigerated storage or modified-atmosphere packaging.

1.4. Heat preservation techniques

Thermal processing is an effective method of food preservation because the vast majority of pathogenic or spoilage microorganisms are destroyed at temperatures close to the boiling point of water. For a long time, food heating has played an essential role in the food industry. Its effectiveness mainly depends on the time/temperature combination: in general, the higher the applied temperature and the longer the treatment time, the greater the effect on microbial destruction and enzyme inactivation.

Thermal processing is used for several purposes:

- It helps destroy microorganisms responsible for food spoilage or foodborne diseases, as well as inactivate endogenous enzymes involved in food deterioration.
- It also contributes to stabilizing the structure of certain products, especially those rich in proteins and lipids, such as UHT milk.
- In addition, thermal processing improves the organoleptic qualities of foods by enhancing their texture, color, and flavor, particularly through Maillard reactions that produce aromatic compounds responsible for flavor development.

However, a major challenge is to apply these thermal technologies effectively while preserving the desired sensory, functional, and nutritional qualities of foods.

1.4.1. Cooking

Cooking is the process of subjecting food to heat for direct consumption. This method is not considered a true food preservation technique since it does not involve long-term preservation. However, it contributes to the microbiological stabilization of the product.

Various types of cooking are possible:

- Direct water cooking (boiling) or indirect water cooking (double boiler/Bain-Marie).
- In a fatty substance (frying).
- Over an open flame (grilling and roasting),
- In a closed container (stewing).
- Steaming.

1.4.2. Sterilization

Sterilization is a food preservation process that consists of applying an intense heat treatment, generally at a temperature above 100°C, for a specific period of time in order to destroy or inactivate all microorganisms, including resistant spore-forming microorganisms, as well as enzymes responsible for food spoilage. This process ensures a long shelf life of the product at room temperature.

The control of sterilization relies on several important thermal parameters, particularly the D, Z, and F values:

- **D-value (decimal reduction time):**

It is the time required, at a given temperature, to destroy 90% (or reduce by a factor of 10) of the microbial population present (figure 1).

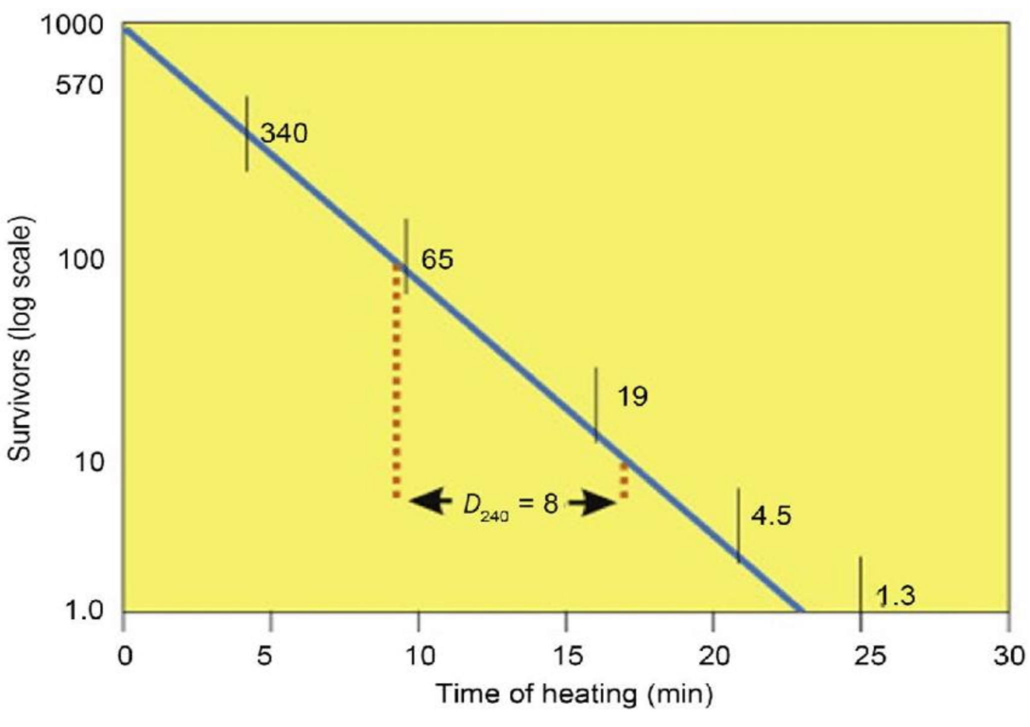


Figure 1. Thermal inactivation curve for a microorganism (Ghernaout and Elboughdiri, 2020).

The D value is the period re- quested for demobilization of 90% of the microorganisms at a specific temperature. In this case, it needed 8 min to neutralize 90% of the microorganisms at 240˚F (115˚C) or D 240 = 8 min

The number of surviving germs decreases exponentially over time according to the following formula:

$$Log\frac{No}{N} = k \bullet t$$

N_0: initial population,

N: final population,

t: time,

k: constant, which varies depending on the type of microorganism and the sterilization temperature.

- **Z-value:**

The Z-value corresponds to the temperature increase required to reduce the D-value by a factor of 10. It reflects the thermal resistance of microorganisms to temperature changes.

- **F-value:**

The F-value represents the time required to achieve a given level of microbial destruction at a defined temperature. The most commonly used value in the food industry is F_0, expressed at 121.1°C, particularly for canned foods.

These parameters make it possible to determine the optimal sterilization conditions in order to ensure the microbiological safety of foods while preserving as much as possible their nutritional and organoleptic qualities.

1.4.2.1. Sterilization of acid foods

The composition of the product subjected to heat treatment strongly influences the heat resistance of microorganisms (table 2). Among the various factors, pH is one of the most important. According to their pH, foods are generally classified into three categories: low-acid, acidic, and highly acidic foods.

In the case of acidic foods, a relatively moderate heat treatment is sufficient to ensure their sterilization. Indeed, microorganisms become more sensitive to heat when the pH is low. Furthermore, heat-resistant spore-forming bacteria, as well as the majority of non-spore-forming bacteria, are unable to grow in acidic environments. Therefore, the main microorganisms that need to be eliminated are primarily yeasts and molds.

Heating for a few minutes at a temperature between 85 and 90°C is generally sufficient to destroy them. In some cases, higher temperatures are applied either to inactivate certain enzymes or to shorten the duration of the heat treatment in order to better preserve the organoleptic qualities of foods.

Table 2. Effect of the pH of the medium (phosphate buffer) on the heat resistance (115°C) of *Clostridium sporogenes* spores (10^4 spores/mL) (Karel and Lund, 2003).

pH	Maximum heating duration allowing survival (minutes)
5.0	9
5.7	12
6.0	15
6.6	21
7.0	25
7.5	20
8.2	15

1.4.2.2. Sterilization of non-acid foods

Sterilization of non-acid or low-acid products is an essential method of food preservation. Since these products have a pH higher than 4.5, they are particularly susceptible to the growth of heat-resistant microorganisms. To ensure their complete destruction, the heat treatment must be carried out at temperatures above 100°C, generally between 115°C and 130°C, under pressure. This process makes it possible to eliminate spore-forming bacteria and to guarantee the microbiological stability of foods during long periods of storage. Sterilization is widely used for canned vegetables, meat, fish, and other low-acid food products.

1.4.3. Pasteurization

Pasteurization is a mild heat treatment carried out at temperatures below 100°C, allowing the destruction of heat-sensitive microorganisms and a large number of spoilage microorganisms, including:

- Vegetative forms of pathogenic microorganisms.
- Yeasts and molds.
- Gram-negative bacteria.

Three types of pasteurization are applied according to the time/temperature combinations:

- Low-temperature pasteurization (15–30 min / 60–65°C).
- High-temperature pasteurization (15–40 sec / 70–75°C).
- Flash pasteurization (1–2 sec / 85–95°C)

Pasteurization preserves the safety of foods without altering the nutrients they contain.

From a technological point of view, pasteurization can be carried out either on previously packaged products (glass bottles, heat-resistant plastic packaging) or on bulk products (often liquids) (figure 2). Pasteurization is a limited preservation process. It must therefore be combined with:

- Hermetically sealed packaging,
- A modified atmosphere or vacuum packaging,
- Refrigeration between 4°C and 6°C,
- Chemical preservatives (acid, sugar, salt, ascorbic acid, nitrates or nitrites, etc.),
- Packaging labeled with a “use-by date” (UBD) ranging from 7 to 24 days.

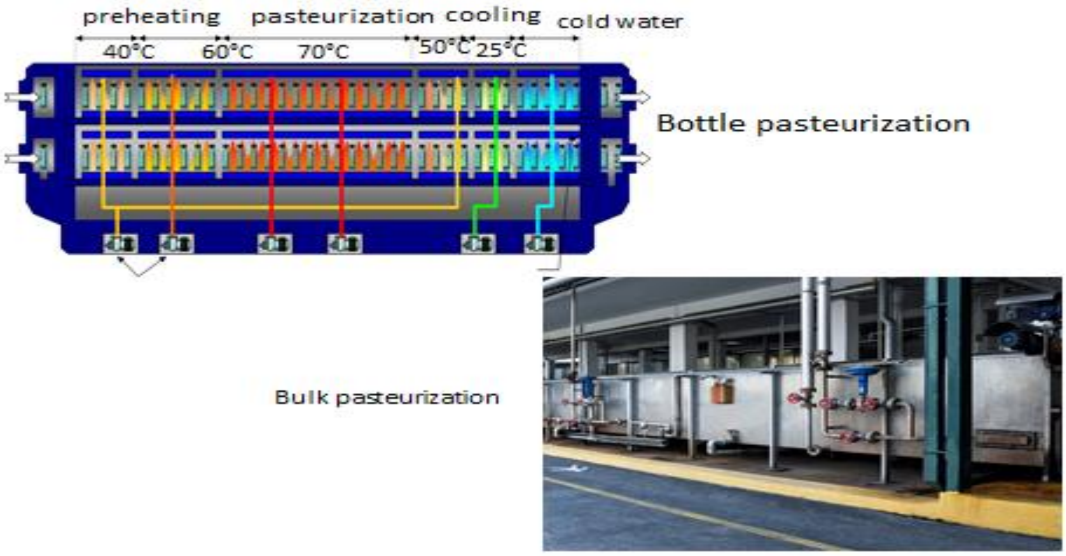


Figure 2. Bottle and bulk pasteurization (Ayers, 2015).

1.4.4. Appertization

It is a preservation method consisting of sealing perishable food products of animal or plant origin in a hermetically sealed container and subjecting them to heat treatment to ensure the destruction or inactivation of enzymes, toxins, and microorganisms, whether pathogenic or non-pathogenic, capable of proliferating in food at normal storage and distribution temperatures without refrigeration.

Appertization involves several successive steps (figure 3):

- **Harvesting, slaughtering, and fishing**

The first step of appertization begins with the harvesting, slaughtering, or fishing of raw materials. Product freshness is an essential condition for ensuring the quality of canned foods and limiting the risks of microbiological spoilage. Foods intended for appertization must therefore be rapidly handled and processed after collection. For example, peas are generally appertized within two to three hours after harvesting in order to preserve their nutritional, organoleptic, and microbiological qualities.

- **Préparation**

This step varies depending on the product to be preserved. For example, for fruits and vegetables, it consists of cleaning, trimming, removing impurities, peeling, and grading.

- **Blanching / pre-cooking**

Blanching or pre-cooking is a rapid heat treatment consisting of immersing the food for one to two minutes in boiling water or steam, followed by rapid cooling. This operation has several technological and microbiological objectives. It helps destroy certain enzymes responsible for color changes and food degradation, such as polyphenol oxidases, isomerases, and proteases. Blanching also helps remove air trapped in the tissues in order to limit oxidation phenomena during cooking or sterilization. In addition, it softens the tissues, reduces the apparent volume of the food, and adjusts its water content before canning. Finally, this step contributes to reducing the number of bacteria present on the surface of foods as well as partially eliminating pesticide residues used in agriculture.

- **Canning / filling**

This step must be precise, meaning that the drained net weight measured when opening the can must correspond to the value indicated on the label. The accuracy largely depends on the shape and size of the food product being canned.

- **Addition of covering liquid**

The covering liquid is added to the can, such as juice or sauce. This liquid facilitates heat transfer during sterilization and ensures the homogeneous incorporation of salt, sugar, spices, and additives. It also helps protect the product against shocks.

- **Seaming / sealing**

Very rapidly after the addition of the covering liquid, the containers must be sealed while removing as much air as possible. This operation is called seaming for metal cans and capping for glass jars.

- **Autoclaving / heat treatment**

This is the sterilization step (or pasteurization if the product is acidic or intended to be stored under refrigeration, such as semi-preserved foods). Heating is used both to cook the canned foods and to destroy microorganisms as well as bacterial spores. Precise sterilization schedules are established for each type of food, for each can model, and are specific to a given autoclave.

- **Cooling**

Cooling is the final step. It stops the heat treatment in order to prevent overcooking phenomena and must be carried out rapidly. Cooling takes place directly inside the autoclave under pressure. After this step, the canned products are ready to be stored and transported.

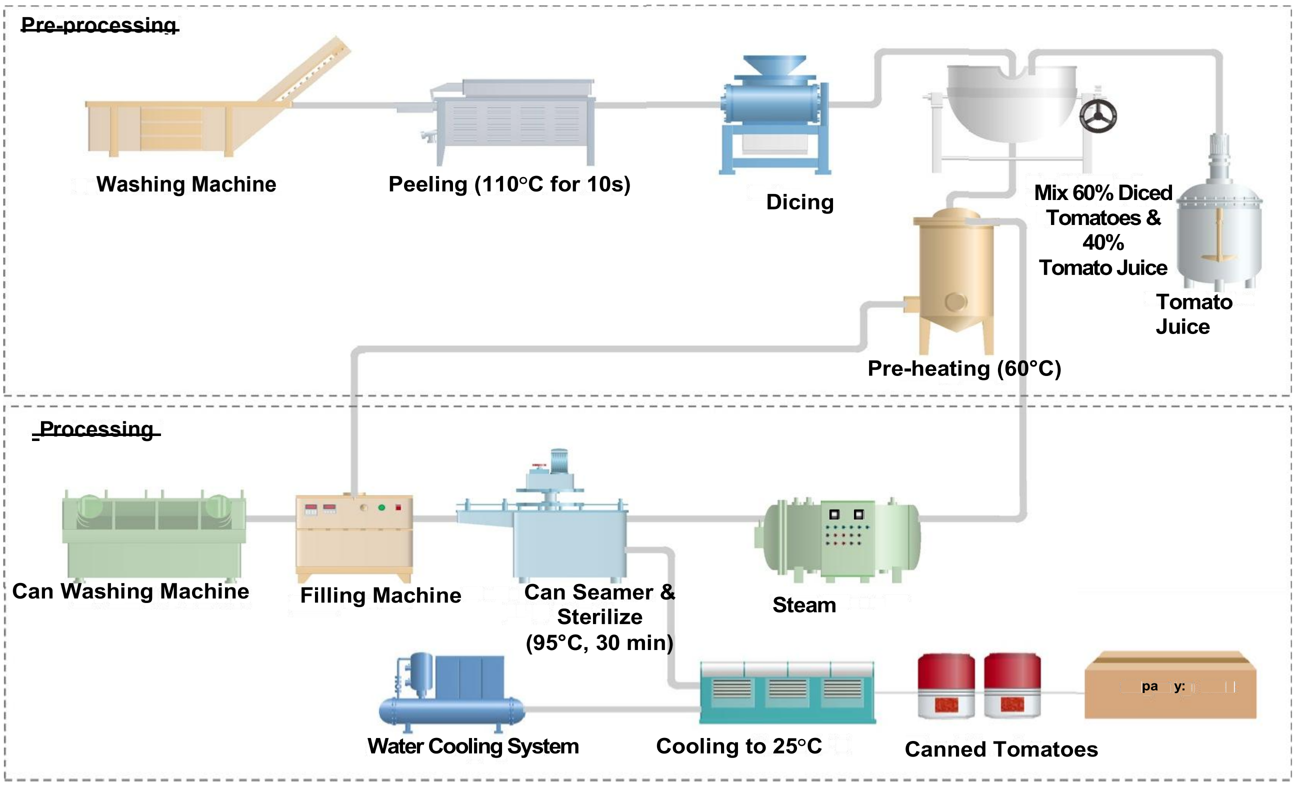


Figure 3. Appertization including pre-processing, canning, sterilization and cooling (Ghnimi et al., 2021).

1.4.4.1. Heat transfer in canned foods

Heat transfer in canned foods corresponds to the propagation of heat from the heating medium of the autoclave to the food contained in the can during sterilization. This heat transfer is essential to ensure the destruction of microorganisms and guarantee the microbiological safety of the product. Heat first passes through the metal wall of the can by conduction, then spreads inside the food either by conduction or convection, depending on the nature of the product (figure 4).

- **In liquid or low-viscosity foods:** Heat is mainly transferred by convection through liquid movements that promote rapid and uniform temperature distribution.
- **In solid or highly viscous foods:** Such as pâtés or certain purées, heat transfer occurs mainly by conduction, a slower mechanism in which heat progresses gradually through the product. The rate and efficiency of heat transfer depend on several factors, including the size and shape of the can, the composition of the food, its viscosity, and the temperature applied during the heat treatment.

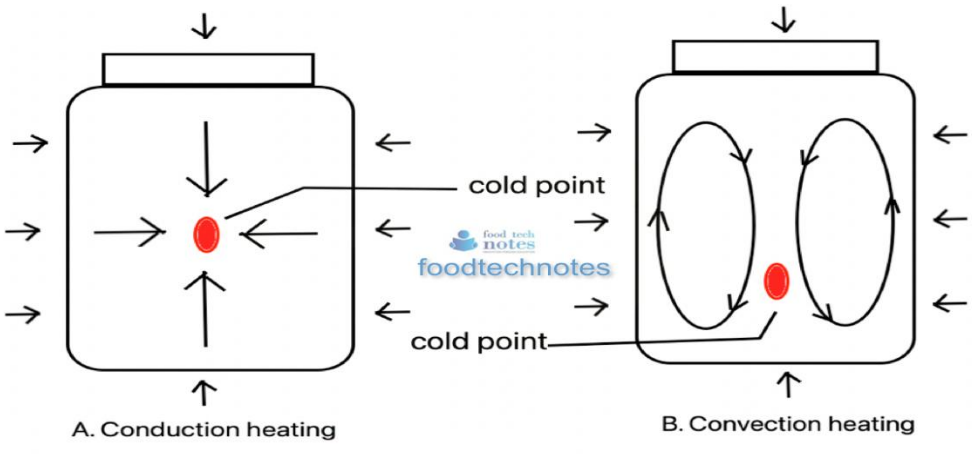


Figure 4. Method of heat penetration during thermal processing (Pratiksha Shrestha, 2023).

1.4.5. Ultra high temperature (UHT) treatment

The UHT (Ultra High Temperature) sterilization is a preservation technique mainly used for liquid foods such as milk, juices, soups, and sauces. It consists of heating the product to a very high temperature, generally between 135°C and 150°C, for a short time of 2 to 10 seconds in order to destroy microorganisms, spores, and enzymes responsible for food spoilage. After heating, the product is rapidly cooled to prevent overcooking and to preserve its nutritional and sensory qualities as much as possible. Packaging is then carried out in sterile containers under aseptic conditions to avoid any recontamination. This method ensures a long shelf life at room temperature as well as excellent microbiological safety while preserving the nutritional and sensory qualities of the products.

UHT treatment can be performed by either direct or indirect heating.

- **In direct heating:** The product is brought into direct contact with hot steam either by steam injection into the product or by steam infusion, where the product is introduced into a chamber containing steam. The most important advantage of direct heating technology is very fast heating and, in this way, minimizing the rate of chemical changes. It takes just a few tenths of a second to reach the sterilizing temperature. This is the main reason why direct systems are used to ensure superior product quality. A flow chart of the TetraTherm Aseptic VTIS® UHT plant (Tetra Pak, Lund, Sweden) based on both direct heating technologies steam injection and steam infusion is shown in figure 5.

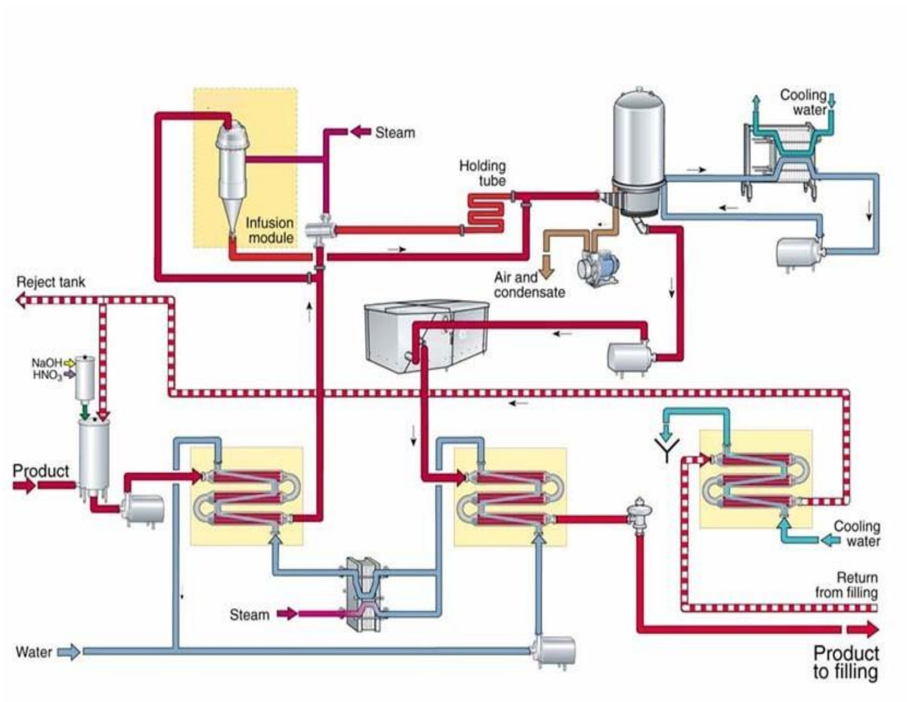
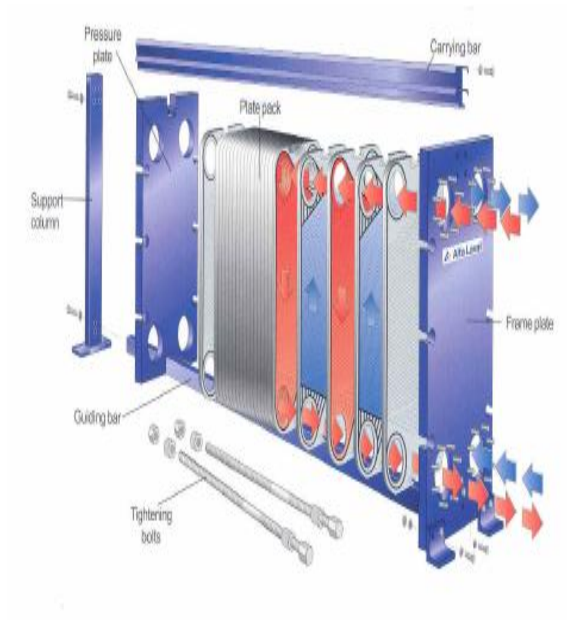


Figure 5. Flow diagram of TetraTherm Aseptic VTIS® UHT direct system plant equipped with direct steam injection and steam infusion technology for the final heating (Malmgren, 2007).

➢ **In indirect heating:** Heat is transferred to the product through a metallic surface using heat exchangers such as plate or tubular exchangers (figure 6 and 7), without direct contact between the product and the heat source.



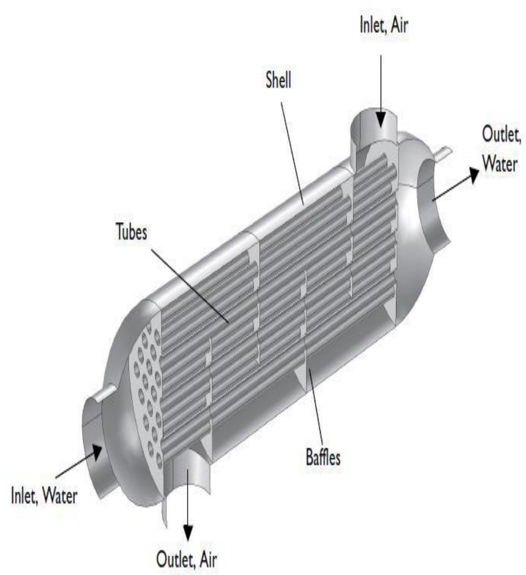


Figure 6. Set-up of a plate heat exchanger (Mokheimer and Said, 2023).

Figure 7. Typical shell and tube heat (Martínez-Vázquez et al., 2022).

The comparisons of time-temperature curves characteristic for treatment of milk in direct and indirect systems are shown in figure 8.

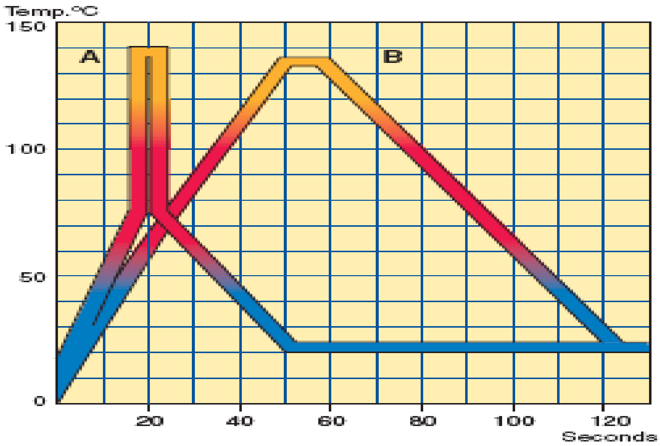


Figure 8. Time temperature curve for processing of milk in a direct system (A) and indirect system (B) (Malmgren, 2007).

1.4.6. Thermization

Thermization is a mild heat treatment mainly applied to raw milk in order to reduce the microbial load and extend its shelf life before further processing. It consists of heating the milk to a temperature generally between 57°C and 68°C for about 15 seconds, followed by rapid cooling. Unlike pasteurization, thermization does not ensure the complete destruction of pathogenic microorganisms, but it reduces the number of bacteria, particularly psychrotrophic bacteria responsible for milk spoilage during refrigerated storage (table 3). This process is often used before cheese production or before temporary storage of raw milk in order to preserve its nutritional and sensory qualities as much as possible.

Table 3. Effect of thermization temperature and quality of raw milk on microbial quality of milk after thermization and storage (Nefasa et al., 2023).

Initial count (CFU/ml)	Thermization Temperature (°C)	Holding time (s)	Count After thermization (CFU/ml)	After thermization and storage for 3 days _C
				At 7⁰C
80 x 10^3	59.5	15	14 x 10^3	20 x 10^3
	64	15	8 x 10^3	6 x 10^3
1500 x 10^3	60	12.5	560 x 10^3	1400 x 10^3
	64	12.5	14 x 10^3	13 x 10^3
				At 4–5⁰C
170 x 10^3	55	60	17 x 10^3	1100 x 10^3
	65	15	1.7 x 10^3	3.4 x 10^3
				At 6 ⁰C
199 x 10^3	65	15	No data	63 x 10^3
18 x 10^3	65	15	No data	1.6 x 10^3

1.4.7. Blanching

Blanching is a heat treatment commonly applied to plant products before preservation processes such as freezing, drying, or canning. Its objectives vary depending on the subsequent treatment. When used prior to freezing or dehydration, its main purpose is to inactivate enzymes responsible for food deterioration. Without blanching, frozen or dried products undergo more rapid changes in color, flavor, and nutritional value due to enzymatic activity.

Among the most heat-resistant and widely distributed enzymes in plant tissues are peroxidase and catalase. The inactivation of these enzymes is generally used to evaluate the effectiveness of blanching, since their destruction indicates that other important enzymes have also been inactivated. The heating time required depends on several factors, including the type of fruit or vegetable, the heating method used, the size of the product, and the temperature of the heating medium. Industrial blanching is often carried out at about 100°C for varying durations depending on the product (table 4). Different heating media may be used, such as hot water, steam, hot air, or microwaves.

Vegetables are generally blanched in hot water or steam, whereas fruits may be blanched in calcium solutions in order to improve their firmness through the formation of calcium pectates. Colloidal thickeners such as pectin, carboxymethyl cellulose, and alginates may also be added to help maintain fruit texture after blanching.

Table 4. Blanching times for vegetables prior freezing (Karel and Lund, 2003).

Vegetable in water at 1008C	Blanching time (min)
Asparagus	
,5/16 in. per butt	2
5/16–9/16 in. per butt	3
.10/16 in. per butt	4
Beans, green and wax	
Small	1–12
Medium	2–3
Large	3–4
Beets	
Small, whole	3–5
Diced	3
Broccoli	2–3
Corn	2–3
Peas	1–12
Spinach	12

1.4.8.Tyndallization

Tyndallization is a fractional sterilization method used to destroy microorganisms present in certain foods that are sensitive to high temperatures. This process is based on several successive heating cycles separated by resting periods in order to eliminate both the vegetative forms of bacteria and heat-resistant spores.

In the food industry, tyndallization generally consists of heating the product to a temperature between 60°C and 100°C for a specific period, followed by a resting phase at a temperature favorable for the development of surviving spores. During this period, the spores germinate and transform into vegetative forms that are more sensitive to heat. The heating process is then repeated several times, often over three consecutive cycles, to ensure a more complete destruction of microorganisms.

This technique is mainly used for delicate food products that could be damaged by conventional high-temperature sterilization. It helps preserve certain nutritional and sensory qualities of foods more effectively. However, tyndallization is less commonly used in the modern food industry because of its long duration and the greater efficiency of industrial sterilization processes such as UHT treatment or canning.

1.5. Cold preservation techniques

The use of cold (temperature reduction “positive” or “negative” cold) for food preservation is the most widely used technique.

Cold preservation techniques are partly based on a reduction in the water activity (Aw) of foods. Indeed, the water activity of ice decreases as temperature decreases. Thus, Aw is equal to 1 at room temperature, reaches approximately 0.95 at –5°C, and decreases to 0.82 at –20°C.

It is well known that there are three fundamental rules to follow in the application of cold preservation:

- Cold must be applied to food that is initially wholesome and safe;
- Cooling must be carried out as early as possible;
- Cold conditions must be maintained continuously throughout the distribution chain: the cold chain must not be interrupted.

1.5.1. Refrigeration

Storage of foods at temperatures above freezing and below 15^0C (59^0F) is known as refrigerated or chilling storage. Chilling storage is widely used because it generally results in effective short-term preservation by retarding the following:

- **Slowing down microbial growth**

Lower temperatures reduce the activity and multiplication of microorganisms such as bacteria, yeasts, and molds. At low temperatures, their metabolism becomes slower, which limits food spoilage and extends shelf life.

- **Reduction of enzymatic activity**

Enzymes naturally present in foods remain active after harvesting or slaughtering. Cooling slows enzymatic reactions responsible for browning, softening, and changes in flavor, odor, and color.

- **Reduction of chemical reactions**

Chemical reactions such as lipid oxidation, vitamin degradation, and non-enzymatic browning are slowed when temperature decreases.

- **Slowing down respiration in plant tissues**

Fruits and vegetables continue to respire after harvest. Cooling reduces their respiration rate (table 5), thereby slowing ripening, aging, and senescence of plant tissues.

- **Reduction of available water activity**

At very low temperatures, part of the water may turn into ice, reducing the amount of water available for biological reactions and microbial growth.

However, cooling does not destroy microorganisms; it only slows down their activity. Therefore, any break in the cold chain may lead to a rapid resumption of microbial growth.

Table 5. Respiration rates of fruits and vegetables based on evolution of heat (Karel and Lund, 2003).

Rapid (>11,600 kJ)	Moderately rapid (5,800–11,600 kJ)	Moderately slow (< 2,300–5,800 kJ)	Slow (< 2,300 kJ)
Asparagus Beans (green) Broccoli Corn, sweet Okra Peas (green)	Beans, lime Brussels sprouts Lettuce, leaf Raspberries Spinach Strawberries	Apples (yellow transparent) Beets (topped) Carrots (topped) Cauliflower Celery Cherries (sour) Lettuce, head Potatoes, sweet Turnips	Apples Cabbage Cranberries Grapefruit Grapes Lemons Onions, mature Oranges Peaches

1.5.2. Freezing

The main objective of food preservation by freezing is to maintain the optimal organoleptic characteristics and nutritional value of foods while ensuring the absence of microbial growth. The great advantage of freezing as a preservation method lies in its ability to ensure food stability without altering its initial quality.

Freezing achieves these preservation objectives through the combination of two key factors:

- **Concentration of solutes**

The crystallization of water into ice leads to a concentration of solutes in the unfrozen phase, which increases the osmotic pressure of this concentrated solution and thereby prevents microbial growth. The high viscosity of the concentrated solution reduces the mobility of reactants and may contribute to maintaining quality by minimizing the rate of deteriorative reactions.

- **Maintenance of low storage temperature**

Maintaining a low storage temperature is the most important factor in controlling the biochemical and chemical reactions responsible for quality deterioration. Low temperature also contributes to preventing the growth of microorganisms.

1.5.2.1. Freezing kinetics

Freezing kinetics refers to the study of the rate and mechanisms of heat transfer during food freezing. It describes the evolution of the product temperature over time until the frozen state is reached. Food freezing generally occurs in three main phases (figure 9):

- **Pre-cooling phase**

The temperature of the food gradually decreases from its initial temperature to its freezing point. During this stage, only sensible heat is removed, with no ice formation.

- **Phase change (crystallization) phase**

When the freezing point is reached, the water contained in the food begins to transform into ice. During this phase, the temperature remains nearly constant because the extracted energy is mainly used to remove the latent heat of fusion.
The freezing rate strongly influences the size of ice crystals:

- slow freezing produces large crystals that may damage cells;
- rapid freezing forms small and more uniformly distributed crystals, which better preserve food texture and quality.

- **Post-freezing cooling phase**

After most of the water has solidified, the temperature continues to decrease until the desired storage temperature is reached. During this stage, the remaining water may continue to freeze gradually.

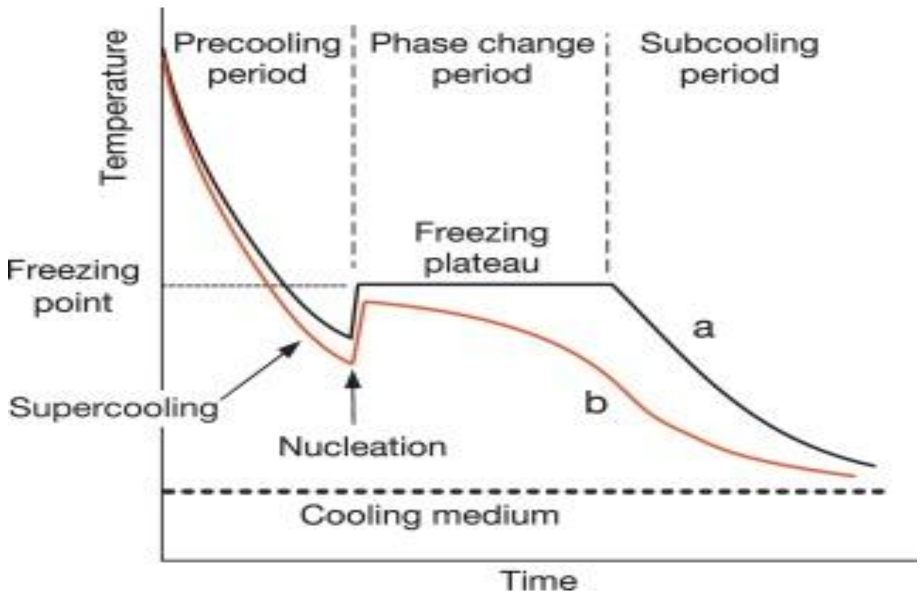


Figure 9. Phases of freezing kinetics (Caballero et al., 2015).

Freezing kinetics depends on several factors:

- the temperature of the refrigerating medium;
- the circulation rate of air or refrigerating fluid;
- the size, shape, and thickness of the product;
- the composition of the food (water, sugars, lipids, and salt content);
- the thermal conductivity of the product and its packaging.

According to the freezing rate of foods, the following types can be distinguished:

A. Slow freezing:

It causes progressive crystallization within tissues affecting only the extracellular water and is responsible for the formation of a small number of large ice crystals. The sharp ice crystal needles may pierce and rupture the walls of fragile cells and promote a certain amount of drip loss during thawing.

B. Rapid freezing (quick freezing):

This rapid freezing process includes several fundamental elements: the use of very low temperatures ranging from –30°C to –50°C, and rapid cooling that allows the product to pass quickly through the zone of maximum crystallization temperature. The objective is to bring the "core" of the food as quickly as possible to a temperature of –18°C. This cooling technique is used for small, fresh, and wholesome products. The product is subjected to a lower temperature than in slow freezing, approximately –40°C, so that the core of the product rapidly reaches and maintains the temperature of –18°C. This technique allows the formation of numerous small ice crystals that do not damage the food. As a result, only a small amount of drip loss is produced during thawing.

Rapid freezing is generally preferred in the food industry because it limits cellular damage, reduces drip losses after thawing, and improves the final quality of the product.

Quick freezing can be applied to a wide variety of foods such as vegetables and fruits.

Owing to the cellular structure of fruits and vegetables, fine ice crystals distributed uniformly in both intra and extracellular regions are desirable, as they result in minimum damage to the cells and maintain the overall product quality upon thawing. Therefore, the quality and microstructure of fruits and vegetables subjected to freezing are influenced by the process involving ice formation (Figure 10), thereby making it essential to control the freezing process to obtain small and evenly distributed ice crystals that are desired for maintaining cell wall integrity in fruits and vegetables. Figure 11 summarizes various factors affecting the quality of fruits and vegetables during freezing. Nonetheless, the ramifications associated with freezing and thawing pose a serious problem to the quality of frozen products.

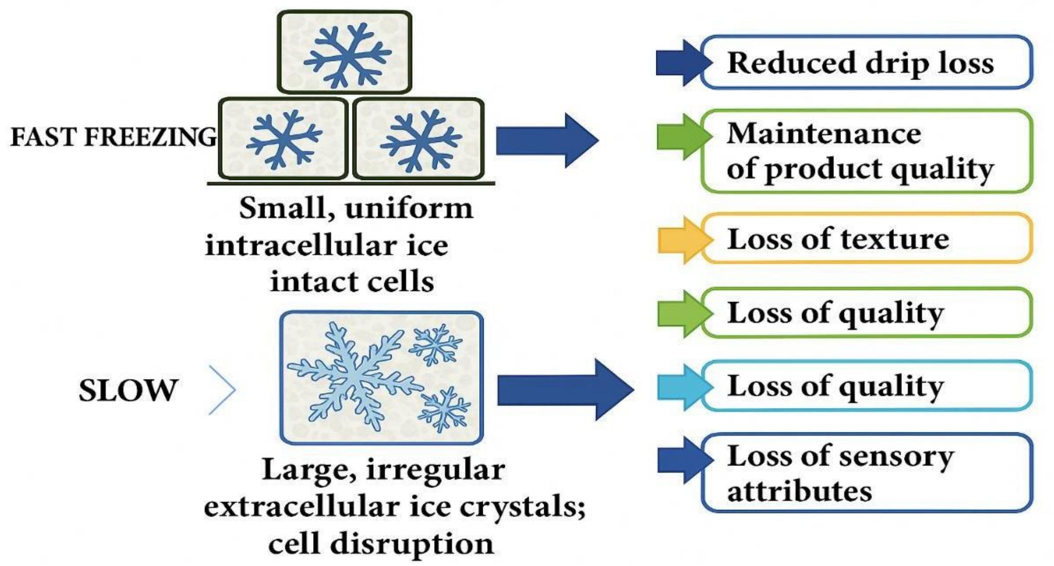


Figure 10. Effect of freezing rate on the cellular structure and quality of fruits and vegetables (Grover and Negi, 2023).

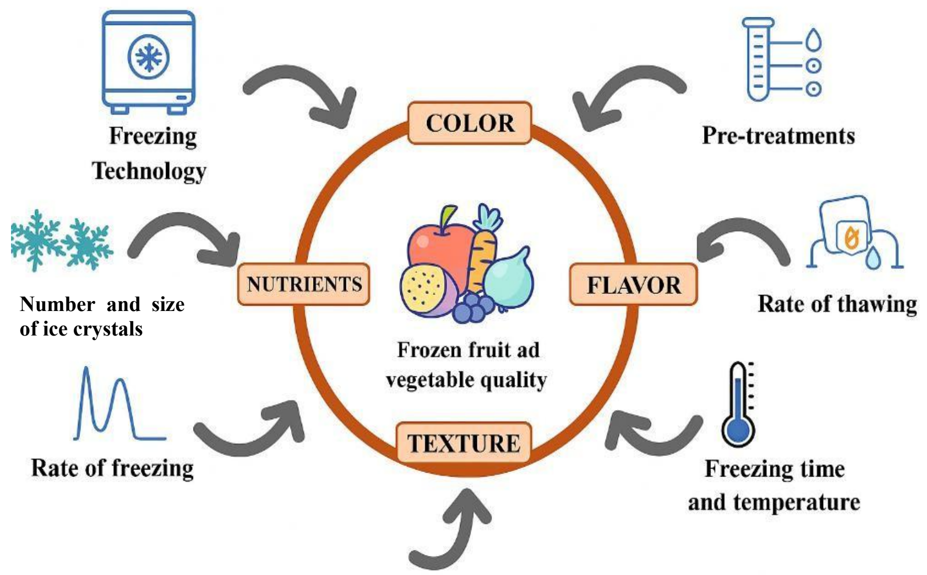


Figure 11. Factors affecting quality of frozen fruits & vegetables (Grover and Negi, 2023).

1.5.2.2. Freezing techniques

The freezing of food products uses several techniques:

- **Tunnel freezers**: They use forced air as an intermediate refrigerating fluid. The air is cooled through the evaporator of the refrigeration system, blown over the product by a fan, and then recirculated to be cooled again. This system exists in both continuous and batch modes. The advantage of tunnel freezers lies in their flexibility of use. They are recommended when different types of products, with varying shapes and sizes, need to be frozen.

- **Plate freezers**: The product is cooled by contact with the surface of the plates (figure 12) inside which the refrigerating fluid circulates. This type of freezer may have horizontal or vertical plates depending on whether the plates are arranged horizontally (like shelves) or vertically. Their main advantage lies in their energy efficiency. However, they can only be used for products with a regular geometric shape, either before or after packaging.

Figure 12. Plate freezers (Butcher and Copy, 2000).

- **Cryogenic freezing (or direct)**: cryogenic freezing consists of placing the product in direct contact with a cooling source (figure 13) by spraying a liquid such as liquid nitrogen or liquid carbon dioxide (CO_2), which evaporates upon contact with the product. In this case, the refrigeration effect is provided by the latent heat of evaporation of the liquid in contact with the product (liquid nitrogen evaporates at –196°C and liquid CO_2 evaporates at –54°C). This freezing system is relatively expensive and can therefore only be used for food products with high commercial value

Figure 13. Immersion freezers use a bath of liquid nitrogen (Butcher and Copy, 2000).

1.6. Water removal and separation preservation techniques

Water removal and separation preservation techniques are based on the reduction of water activity (Aw) in foods. Since microorganisms and many chemical and enzymatic reactions require available water to develop, decreasing Aw helps slow down spoilage and extend shelf life. These preservation methods involve either the removal of water from the food or the separation of part of its water content, thereby limiting microbial growth and deteriorative reactions.

Living organisms contain between 50 and 70% water in their tissues, although this water content varies depending on the type of tissue. In foods, water exists in two forms: bound water and free water.

- **Bound water**: Is an integral part of the structure of living cells, just like proteins and carbohydrates, and cannot be used by microorganisms.
- **Free water**: Present inside but mainly outside the cells, is essential for bacterial growth and biological reactions. Therefore, the measurement of available water in a food, expressed as water activity (Aw), can be used to predict microbial development and the types of bacteria likely to proliferate.

The availability of water in food can be determined using the following formula: $Aw=P/P_0$.

P_0 corresponds to the water vapor pressure above pure water, whereas P is the water vapor pressure above the food product (figure 14).

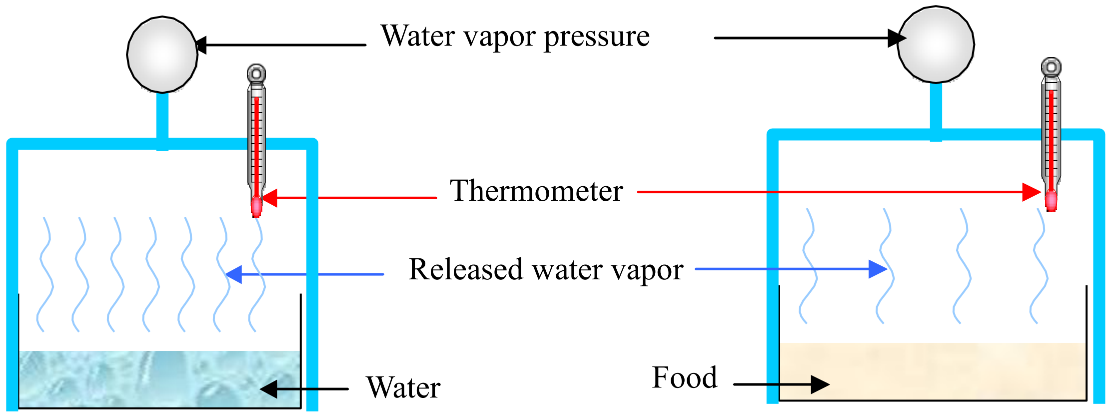


Figure 14. Experimental setup for measuring water activity (Source: author).

The reduction of water activity (Aw) in foods can be achieved through two approaches. The first, known as

- **The direct method**: Consists of removing part of the water contained in the food by dehydration processes such as drying or freeze-drying. The second, referred to as
- **The indirect method**: Involves reducing water availability by adding substances that bind water, known as water activity depressants.

1.6.1. Reduction of water activity by dehydration

Dehydration is a physical food preservation technique that consists of partially or completely removing the water contained in food products. This reduction in water content lowers the water activity (Aw), often to values below 0.60, a level at which the growth of most microorganisms is strongly inhibited.

The main dehydration methods include:

- Concentration;
- Drying;
- Lyophilization;
- Smoking.

This process offers two major advantages:

- **Reduction of water activity**: which limits or prevents the growth of microorganisms and slows down or stops the enzymatic reactions responsible for food spoilage.
- **Reduction of product weight and volume**: resulting in significant savings in packaging, transportation, and storage costs.

1.6.1.1. Concentration

Concentration is a food preservation method that consists of removing part of the water contained in a product in order to increase its dry matter content. This reduction in the amount of available water leads to a decrease in water activity, thereby limiting microbial growth and slowing the enzymatic and chemical reactions responsible for food spoilage. The process generally relies on the partial evaporation of water through the application of heat and is often carried out under vacuum to lower the boiling point and better preserve the nutritional and sensory qualities of the product. Concentration is widely used in the production of concentrated fruit juices, sweetened or unsweetened condensed milk, tomato concentrates, syrups, and molasses. This technique offers several advantages, including the reduction of water activity, inhibition of microbial spoilage, lower transportation and storage costs due to the reduced weight and volume of products, and better retention of flavors compared with some intensive drying processes. However, concentration alone does not always ensure long-term preservation and is often combined with other preservation methods such as refrigeration, pasteurization, or sugar addition. Furthermore, the use of high temperatures may cause changes in color, flavor, and certain heat-sensitive vitamins.

1.6.1.2. Drying

Drying is one of the oldest methods of food preservation. It consists of removing a large portion of the water contained in food through evaporation, using either natural or artificial heat. This reduction in water content decreases water activity (Aw), which is the amount of water available for biological reactions and the growth of microorganisms.

➢ Since microorganisms require free water for their growth and multiplication, lowering water activity creates an environment that is unfavorable for their development.

- Most bacteria can no longer multiply when the Aw falls below 0.90,
- while yeasts are generally inhibited below an Aw of 0.85.
- Molds are more resistant, and some species can grow at Aw values as low as 0.60.

When water activity is reduced to values close to or below 0.60, the growth of virtually all microorganisms is inhibited. However, drying does not necessarily destroy the microorganisms present; some may survive in a dormant state and become active again if the food reabsorbs moisture.

➢ Drying also affects the enzymes naturally present in foods, which are responsible for various deteriorative reactions. The reduction in available water greatly slows down enzymatic activity, while the heat applied during drying may partially or completely inactivate certain enzymes. When drying is carried out at low temperatures, such as during freeze-drying, many enzymes remain active, but their activity is significantly reduced because of the limited availability of water. Nevertheless, some residual enzymatic reactions may continue during storage and cause changes in color, texture, flavor, and nutritional quality. For this reason, blanching is often applied before drying fruits and vegetables to inactivate the enzymes responsible for these undesirable changes. As a result, drying effectively extends the shelf life of foods by limiting microbial growth and reducing enzymatic activity while also decreasing product weight and volume, thereby facilitating storage and transportation.

A. Drying technologies

a. Traditional sun-drying methods

The principle is based on exposing food products to solar energy. The heat generated by solar radiation causes the evaporation of the water contained in the product, while air circulation removes the resulting moisture to the outside. Drying can be carried out either directly under the sun or in a solar dryer, where the food is placed inside a transparent enclosure. In this case, solar radiation passes through the transparent cover and heats the air inside. Owing to the greenhouse effect, the temperature within the dryer increases, accelerating water evaporation and improving the efficiency of the drying process (figure 15).

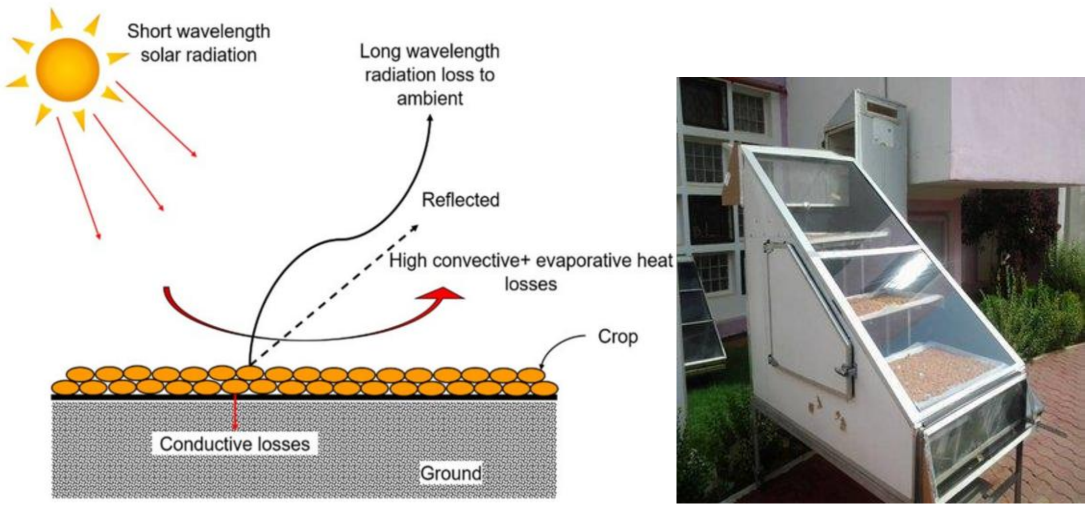


Figure 15. Open-air drying and passive solar dryers
(Gorjian et al., 2021).

In the open-sun-drying process, substantial losses occur because of numerous factors including birds, rodents, insects, and micro-organisms, while unpredicted storms or rain worsen the condition. Further, excess/insufficient drying; impurities due to external contaminants such as dirt, dust, insects, and micro-organisms; and color fading by ultra-violet (UV) radiation are characteristics of open-sun-drying. Additionally, open-sun-drying is a sluggish

process that can lead to significantly huge losses. Products dried under open-sun-drying usually fail to meet international standard quality.
Sun drying can also be carried out using an indirect mode. In this process, the air is first heated by a solar collector and then directed into the drying chamber containing the product, which is protected from direct solar radiation. Heat transfer between the warm air and the product promotes water evaporation, resulting in faster and more uniform drying while better preserving the quality of the product (figure 16).

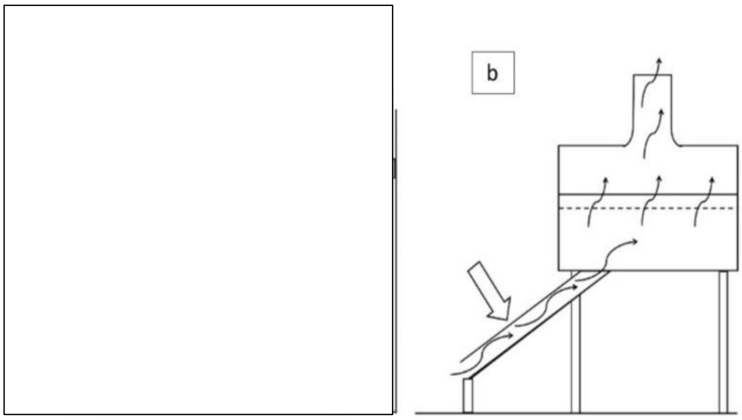


Figure 16. Indirect sun drying (Gorjian et al., 2021).

B. Modern or artificial drying methods

a. Hybrid dryers

Hybrid dryers primarily rely on indirect solar energy and an auxiliary heating source fueled by gas or diesel. This backup system operates during nighttime periods and when solar radiation is insufficient due to cloudy weather conditions (figure 17). L'énergie solaire est cueillie par des collecteurs installés sur le toit et acheminée vers et répartie dans les compartiments de l'enceinte du séchoir par des tubes souples en polyéthylène. Un système de ventilation alimenté par des cellules solaires permet de propulser l'air chaud dans les différentes parties du séchoir. La source d'énergie d'appoint est constituée par un moteur muni d'un brûleur marchant au gaz ou au diesel et qui se déclenche automatiquement dès que la température descend au-delà du minimum requis pour éviter la réhydratation des produits.

a b

Figure 17. Energy sources of a hybrid dryer: (a) photovoltaic panels and (b) auxiliary diesel-powered energy source (Ouaouich and Chimi, 2005).

b. Osmotic dehydration

In fruit processing, osmotic dehydration is a technique used to reduce water content by immersing whole fruits or fruit pieces in hypertonic sugar solutions. This process induces a simultaneous mass transfer: water diffuses from the fruit into the osmotic solution, while soluble solids from the syrup are transferred into the fruit. Concurrently, certain endogenous fruit components, especially organic acids and mineral salts, diffuse from the fruit into the surrounding sugar solution.

c. Microwave drying

Microwave drying is a fast and efficient drying technique that provides more uniform heating and lower energy consumption compared with conventional hot-air drying methods. Microwaves belong to the electromagnetic spectrum and operate at frequencies ranging from 300 to 300,000 MHz, corresponding to wavelengths between 1,000 and 1 mm. During the process, microwave energy selectively heats the free water contained within the food matrix, promoting its evaporation and removal as water vapor. Owing to its uniform and selective heating characteristics, microwave drying has become an increasingly attractive technology in the food processing industry.

1.6.1.3. Lyophilization

Lyophilization is a food preservation technique that consists of removing water from a frozen product through sublimation, that is, the direct transition of ice into vapor without passing through the liquid state. The process generally involves three main stages (figure 18):

- **Product freezing**: the food is first frozen at low temperatures to convert its water content into ice.

- **Primary drying (sublimation)**: under high vacuum conditions, the ice is removed directly as water vapor through the controlled application of heat.
- **Secondary drying (desorption)**: residual water bound to the product constituents is removed to achieve a very low moisture content.

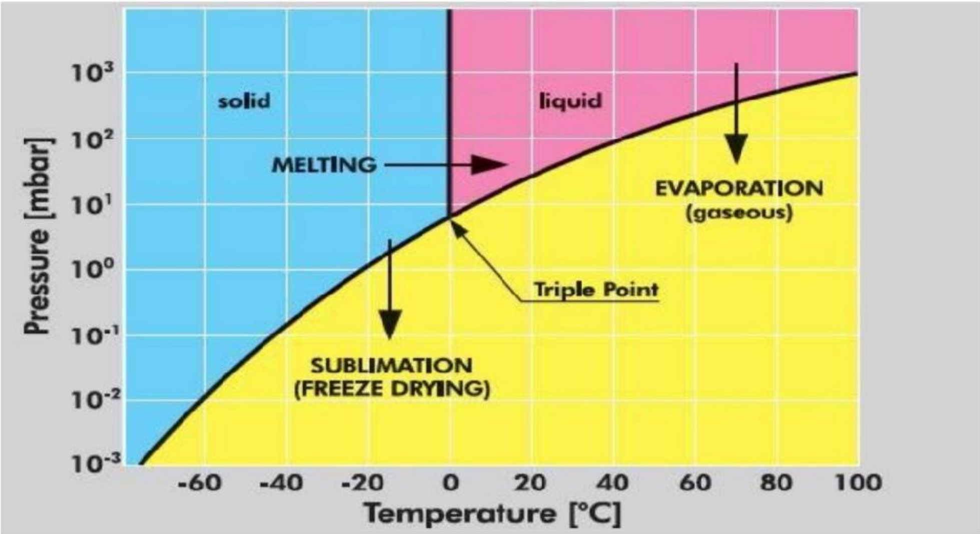


Figure 18. Freeze drying process (Gaidhani et al., 2015).

This technique effectively preserves the structure, color, aroma, flavor, and nutritional value of foods. Freeze-dried products also exhibit a long shelf life, low weight, and excellent rehydration capacity. Freeze-drying is widely used for fruits, vegetables, coffee, dairy products, astronaut foods, and various pharmaceutical products.

However, despite its numerous advantages, freeze-drying remains an expensive process because of its high energy requirements and the sophisticated equipment needed for its operation.

A. Freeze dryer design

A freeze dryer is a device designed to remove water from a frozen product through sublimation under vacuum. Its design is based on several essential components that allow the control of temperature, pressure, and heat transfer throughout the process (figure 19).

- Freeze-drying chamber

The freeze-drying chamber is the enclosure where the products to be treated are placed. It must be perfectly airtight to maintain the low pressures required for sublimation. The products are generally arranged on heated shelves that provide the energy necessary for drying.

- Freezing system

Before drying, the product is frozen at a sufficiently low temperature to convert all free water into ice. Some freeze dryers incorporate a refrigeration system that allows freezing to be carried out directly inside the processing chamber.

- Heating system

During primary drying, a controlled amount of heat is supplied to the product to provide the energy required for ice sublimation. Heating may be achieved by conduction through the shelves, by radiation, or by circulation of a heat-transfer fluid.

- Vacuum Pump

The vacuum pump reduces the pressure inside the chamber to values below the triple point of water. This low pressure promotes the sublimation of ice without passing through the liquid phase.

- Condenser or ice trap

The water vapor generated during sublimation is captured by a condenser maintained at a very low temperature (typically between –40 and –80 °C). The vapor refreezes there as ice, preventing its return to the product and protecting the vacuum pump.

- Control and instrumentation system

Temperature, pressure, and humidity sensors are used to monitor and control the different stages of the process. Modern systems employ programmable controllers to optimize freeze-drying cycles.

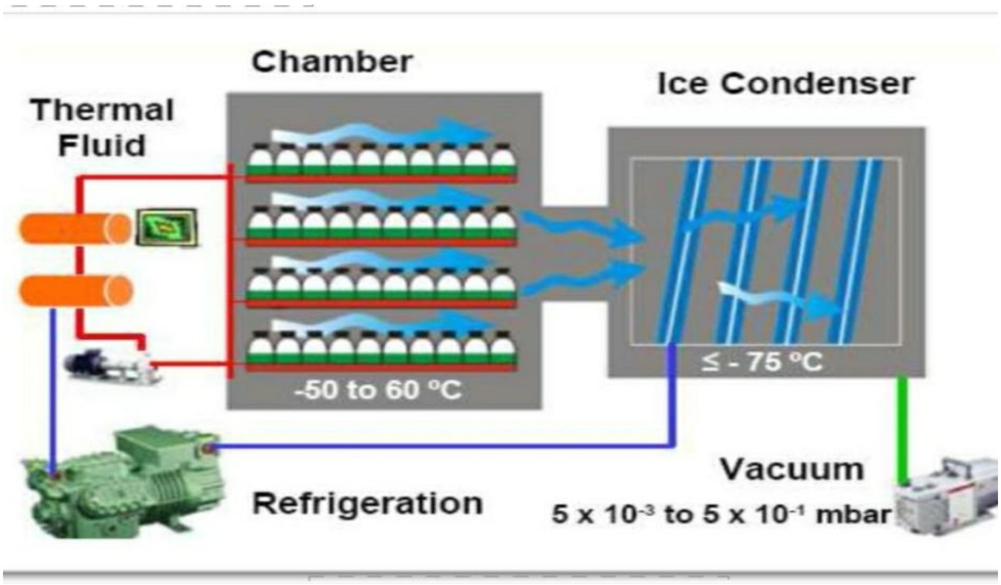


Figure 19. Lyophilizer design (Gaidhani et al., 2015).

1.6.1.4. Smoking

Smoking is a preservation technique and, in some cases, a cooking method that involves exposing food to aromatic smoke generated by the controlled combustion of wood, wood chips, hay, or other dried plant materials. To improve its effectiveness, smoking is often preceded by a salting step aimed at reducing the water content of the food, inhibiting microbial growth, and extending its shelf life.

This method is mainly applied to meat (figure 20) and fish products. The combination of drying and smoking helps preserve meat and fish through the combined effects of dehydration and the antiseptic compounds present in the smoke. In addition, smoking imparts distinctive sensory characteristics to foods, particularly in terms of flavor, aroma, and color.

Figure 20. Smoking process of meat to remove moisture (Ariyamuthu et al., 2022).

A. Hot smoking and cold smoking.

- **Hot smoking** is a technique that both cooks food and imparts a characteristic smoky flavor. The smoking temperature is relatively high, generally ranging from 55 to 100°C. As a result, the process requires a much shorter time than cold smoking, usually between 20 minutes and 1 hour. Products subjected to hot smoking typically have a firmer texture than those produced by cold smoking. This method is commonly used for certain fish species, such as mackerel.
- **Cold Smoking** is carried out at temperatures that generally do not exceed 25 to 30°C. The process is longer and may last for several hours or even several days. Unlike hot smoking, the food is not cooked; however, after a preliminary drying stage, exposure to smoke helps inhibit the growth of bacteria and molds, thereby improving preservation. This technique is traditionally used for products such as smoked salmon.

B. Action of smoke on foods

From a physicochemical point of view, smoke consists of liquid and solid particles suspended in a gaseous phase of variable composition. These volatile particles are absorbed at the surface of the food and then migrate into its interior; their penetration may continue for several days

- **Color**

The color developed during smoking is mainly due to carbonyl compounds, which participate in Maillard-type reactions. The intensity of coloration increases with the tar content of the smoke and is also proportional to the concentration of phenolic compounds present in the smoke.

- **Preservation**

Certain phenolic compounds exhibit a bacteriostatic effect, inhibiting the growth of microorganisms. However, in the case of hot smoking, the antibacterial action is mainly attributed to the high processing temperature. Smoking also contributes to extending shelf life by reducing microbial activity and slowing spoilage reactions.

- **Aroma and flavor**

The characteristic aroma of smoked foods is primarily due to phenolic compounds. The type of wood used for smoke generation has a significant influence on the flavor profile of the final product, producing distinct sensory characteristics depending on the wood species employed.

1.6.2.Reduction of water activity through the addition of humectants

The most commonly used water activity (aw) depressants in the food industry are salts, particularly sodium chloride (NaCl), and carbohydrates, especially monosaccharides and disaccharides. The addition of salts and carbohydrates represents one of the simplest and most cost-effective methods for lowering the water activity (aw) of foods, thereby enhancing their shelf life. Nevertheless, this technique is generally limited to products in which salt or sugar contributes significantly to the sensory properties of the food. Typical examples include salted anchovies, capers preserved in salt, syrups, and confectionery products.

1.6.2.1. Salting

Salting is one of the oldest food preservation techniques, having been used since ancient times to extend the shelf life of food products. This method consists of subjecting food to the action of salt, either

- by directly applying salt to the surface of the product (dry salting) or
- by immersing the food in a saline solution (brining).

In both cases, the objective is to create an environment with a high solute concentration. The concentration difference between the interior of the food and its surroundings causes water to move from the cells to the outside through osmosis.

The resulting water loss leads to a reduction in water activity (aw), thereby decreasing the amount of water available for biological reactions and microbial growth. By lowering water activity, salting slows down the biochemical and enzymatic reactions responsible for food spoilage and inhibits the growth of many microorganisms. Consequently, it improves the stability and extends the shelf life of food products.

This technique is widely used in the food industry, particularly in cheesemaking for the production and ripening of various cheeses, in the meat-processing industry for the preservation of meats and cured products, and in the preservation of certain fish species such as herring and salmon. In addition to preserving food, salting also contributes to the development of sensory characteristics, particularly flavor and texture.

1.6.2.2. Sugaring

Sugaring is a traditional food preservation method that is still widely used for certain products. Its effectiveness is based on the addition of large amounts of sugar, creating a hypertonic environment that reduces the product's water activity (aw). Under these conditions, water contained within microbial cells moves to the surrounding medium by osmosis, causing cell dehydration and thereby limiting microbial growth and activity.

This technique is particularly used for the preservation of fruits, which may be stored in honey or in highly concentrated sugar solutions. It is also employed in the production of products such as jams, jellies, and candied fruits, where the high sugar content contributes to microbiological stability and extends shelf life. In addition, sugaring is used in the preparation of certain soft drink concentrates and syrups, whose preservation largely depends on their high sugar concentration.

1.6.2.3.Other depressing agents

In addition to salts and carbohydrates, other substances such as proteins and their derivatives can be used to reduce the water activity (aw) of a food product, although their depressant effect is limited. Moreover, the cost of these products is relatively high. Their use is therefore more often considered for improving the nutritional value of a food product or enhancing its flavor.

1.7. Food preservation techniques using food additives

Food additives are substances intentionally added to foods in small amounts to improve, preserve, or maintain their technological, nutritional, sensory, or microbiological properties. They are not normally consumed as food by themselves but are incorporated during the manufacture, processing, packaging, transportation, or storage of food products.

According to the Codex Alimentarius, a food additive is any substance that, when used for a technological purpose, becomes a component of the food or modifies its characteristics.

1.7.1. Functions of food additives

Food additives perform several important functions in the food industry. They help extend the shelf life of foods by limiting the growth of microorganisms responsible for spoilage, improve product stability during storage and distribution, maintain or enhance sensory qualities such as color, flavor, aroma, and texture, and prevent oxidation reactions that cause rancidity and quality deterioration.

1.7.2. Main categories of food additives

- **Preservatives** prevent or slow the growth of bacteria, yeasts, and molds. Common examples include benzoic acid, potassium sorbate, and sodium nitrite.
- **Antioxidants**: Protect foods against oxidation processes that may affect lipids, pigments, and certain vitamins. Ascorbic acid and tocopherols are among the most commonly used antioxidants.
- **Colorants** : Are used to impart, enhance, or restore the color of food products. Curcumin and carotenoids are widely used examples.
- **Sweeteners**: Provide a sweet taste while reducing or eliminating the caloric contribution of sugar. Aspartame and sucralose are among the best-known sweeteners.
- **Emulsifiers, stabilizers, and thickeners**: These additives improve the texture, consistency, and stability of food products. Common examples include lecithin, xanthan gum, and pectin.
- **Flavor enhancers**: Strengthen or intensify the natural flavors of foods. Monosodium glutamate is one of the most widely used flavor enhancers.

1.7.3. Classification of food additives

Authorized food additives are identified by a code consisting of the letter E followed by three digits. This classification system allows different categories of additives to be distinguished according to their primary function:

- E100–E199: Colorants
- E200–E299: Preservatives
- E300–E399: Antioxidants and acidity regulators
- E400–E499: Emulsifiers, stabilizers, thickeners, and gelling agents
- E500–E599: Acidity regulators and raising agents
- E600–E699: Flavor enhancers

In general, the first digit of the E-number indicates the functional category of the additive: 1 for colorants, 2 for preservatives, and 3 for antioxidants. This coding system facilitates the identification and regulation of additives used in food products.

1.7.4. Food preservatives

Food preservatives are additives used to extend the shelf life of foods by limiting the growth of microorganisms responsible for spoilage or those that may pose a risk to consumer health. They contribute to ensuring the microbiological safety of foods by inhibiting the growth of pathogenic microorganisms capable of causing foodborne illnesses or producing toxins. They also help maintain the organoleptic quality of food products by preserving their color, odor, flavor, and texture through the inhibition of spoilage microorganisms.

The action of preservatives is based on various mechanisms, including the disruption of microbial metabolism, inhibition of enzymatic activity, alteration of membrane permeability, and reduction in the availability of certain nutrients essential for microbial growth. These effects help slow down microbial proliferation and thereby enhance the stability and shelf life of food products.

However, preservatives cannot restore the quality of a food product that has already deteriorated, nor can they sanitize a contaminated product before treatment. Their role is limited to delaying spoilage processes and preserving the original characteristics of the product for as long as possible. Their effectiveness therefore depends on the initial quality of the food as well as the conditions of processing, storage, and distribution.

1.7.4.1. Conditions for the effectiveness of food preservatives

The effectiveness of food preservatives depends on several factors related to the nature of the preservative, the characteristics of the food, and storage conditions. To fully exert their antimicrobial activity, preservatives must be used under appropriate conditions.

- The concentration of the preservative must be sufficient to inhibit the growth of target microorganisms without exceeding the regulatory limits. A concentration that is too low may be ineffective, whereas an excessive dose may alter the sensory properties of the food or pose toxicological risks.
- The pH of the medium also plays a crucial role. Many preservatives, particularly organic acids such as benzoic acid and sorbic acid, are more effective in acidic environments, where their undissociated form can more easily penetrate microbial cells.
- Water activity (aw) strongly influences the effectiveness of preservatives. A low water activity naturally limits microbial growth and can enhance the action of preservatives.
- The nature and initial microbial load of the food are also important factors. The higher the initial contamination, the more difficult it is for the preservative to control microbial growth.
- Storage temperature is another essential factor. Preservatives are generally more

effective when foods are stored at low temperatures, as refrigeration acts synergistically with their antimicrobial activity.

- The composition of the food, particularly its lipid, protein, and carbohydrate content, may also affect preservative efficacy by influencing its availability or its interaction with microorganisms.

Preservatives cannot compensate for poor initial microbiological quality; their role is only to slow down spoilage processes and extend the shelf life of food products.

1.7.4.2. Types of food preservatives

Food preservatives are generally classified into several categories:

A. **Organic preservatives**: Are mainly composed of organic acids and their salts. They are widely used in the food industry to inhibit the growth of bacteria, yeasts, and molds. Among the most common are benzoic acid, sorbic acid, and their derivatives. Their effectiveness is generally greater in acidic foods with a low pH.

B. **Mineral preservatives**: Are compounds of mineral origin used for their antimicrobial and antioxidant properties. Nitrates and nitrites are the main representatives of this group. They are particularly used in meat products to limit the growth of pathogenic microorganisms, especially *Clostridium botulinum*, while also contributing to the stabilization of meat color.

Table 6 summarizes the main synthetic preservatives commonly used in the food industry, highlighting their applications and the potential adverse effects associated with their us.

Table 6. Commonly used synthetic preservatives (Antony and Narayanaswamy, 2026).

Preservatives	Mode of action	Effective against	ADI (mg/kg body weight/day)	Adverse Effects	Food application
Sorbic acid and sorbates INS 200–203	Antimicrobial	Yeasts, molds and some bacteria (effective against fungi)	25 mg/kg (JECFA)	Generally well tolerated, rare skin allergies, and contact dermatitis in sensitive individuals	Cheese, wine, baked goods, dried fruits, margarine, fruit juices, processed meats, and pickles.
Benzoic acid and benzoates INS 210–213	Antimicrobial	Yeast, molds, and bacteria (broad-spectrum antibiotic, effective against yeast)	5 mg/kg (JECFA)	Possible benzene ring with ascorbic acid (carcinogen); allergic reactions; hyperactivity in children; asthma in sensitive individuals	Soft drinks, fruit juices, pickles, jams, sauces, salad dressings, carbonated beverages, and fruit cordials.
Sulphur dioxide and sulphites INS 220–228	Antimicrobial Antioxidant Anti-enzymatic	Bacteria, yeasts, and molds (prevent enzymatic browning and lipid oxidation)	0.7 mg/kg (JECFA)	Major asthma allergen: asthma attacks in 3–10% population; destroys thiamine (Vitamin B_1); sulfite-sensitive reactions	Wine, dried fruits, fruit juices, processed potatoes, dehydrated vegetables, fruit concentrates, glucose syrup
Nitrates and nitrites INS 249–252	Antimicrobial (Specialized)	Clostridium botulinum, other anaerobic spore-forming bacteria	Nitrate: 0.6 mg/kg Nitrite: 3.7 mg/kg	Potential carcinogen, nitrosamine formation; methemoglobinemia in infants, blue baby syndrome	Cured meats, bacon, ham, hot dogs, corned beef, lunch meats, smoked fish, processed meat products.
Acetic acid and acetates INS 260–263	Antimicrobial	Bacteria, yeasts and molds (pH-dependent effectiveness)	Not specified (GRAS)	Generally well tolerated; high concentrations may cause gastrointestinal irritation and tooth enamel erosion.	Pickled vegetables, bread, processed cheese, mayonnaise, sauces, salad dressings, canned foods.
Propionic acid and propionates INS 280–283	Antimicrobial (Antifungal)	Molds, yeasts and spore-forming bacteria (Bacillus species)	Not specified (GRAS)	Generally well tolerated; rare reports of behavioural changes in children, possible migraine triggers	Bread, baked goods, processed cheese, pizza dough, tortillas, flour mixes, animal feed.
Ascorbic acid (Vitamin C) INS 300–303	Antioxidant	Oxidative rancidity, colour deterioration, and nutrient loss	Not specified (essential nutrient)	Generally safe: High concentrations cause gastrointestinal distress and kidney stones in susceptible individuals.	Fruit juices, processed fruits, meat products, breakfast cereals, oils, beverages, canned foods.
BHA INS 320	Antioxidant	Lipid oxidation, rancidity, prevents the formation of flavours and colours	0.5 mg/kg (JECFA)	Possible carcinogen in high doses, allergic reactions in sensitive individuals, and endocrine disruption concerns.	Edible oils, butter, processed foods, snack foods, chewing gum, and cosmetics.
BHT INS 320	Antioxidant	Lipid peroxidation, rancidity, colour changes in fats and oils	0.25 mg/kg (JECFA)	Possible liver toxicity at high doses; allergic reactions; potential endocrine effects; accumulation in adipose tissue.	Edible oils, processed foods, cereals, snack foods, animal feed, rubber, plastics

C. Natural preservatives include substances that occur naturally in certain plants table 7, animals (table 8), or microorganisms such as bacteriocins. Due to the growing consumer demand for more natural products, these preservatives are attracting increasing interest in the food industry.

Table 7. Plant extracts as food preservatives (Antony and Narayanaswamy, 2026).

Plant extracts	Major active components	Applications
Oregano Oil (*Origanum vulgare)*	Carvacrol (50–80%), thymol (3–20%), γ Terpinene, p-Cymene	Meat prod-ucts, dairy, baked goods, and vegetable preservation
Thyme Oil *(Thy-mus vulgaris)*	Thymol (30– 70%), Carvacrol (2–15%), Linalool, p-Cymene	Meat processing, dairy products, essential oil blends
Rosemary Extract (*Rosmarinus oficinalis*	Carnosic acid, Carnosol, Rosmarinic acid, Caffeic acid	Meat products, oils, fats, baked goods, sauces, dressings, pro-cessed foods.
Grape Seed Extract (*Vitis vinifera)*	Proanthocyani-dins, Catechins, Epicatechins, Resveratrol	Meat products, dairy, beverages, oils, bakery prod-ucts, seafood
Green Tea Extract *(Camellia sinensis)*	EGCG, ECG, Catechins, Polyphenols	Meat prod-ucts, seafood, beverages, dairy products, oils, ready-to-eat meals

Table 8. Animal-derived food preservatives (Antony and Narayanaswamy, 2026).

Category	Source	Com-pound/ Product	Mechanism of action
Antimicrobial proteins	Egg white	Lysozyme	Breaks down bacte-rial cell wall
	Milk	Lactofer-rin	Iron binding with antimi-crobial effects
Honey and bee products	Bee honey	Honey	Contains hydrogen peroxide and antimicrobials

1.7.4.3. Side effects of food preservatives

Natural preservatives act through multi-target antimicrobial mechanisms, simultaneously affecting several essential cellular functions of microorganisms (figure 21). Their activity is not limited to bacteria but also extends to yeasts and molds, which are frequently involved in food spoilage. They can disrupt cell membrane integrity, alter membrane permeability, inhibit enzymatic activity, affect energy metabolism, and induce intracellular imbalances. This multifactorial mode of action reduces the ability of microorganisms to adapt and survive, thereby limiting their growth and proliferation. Through these diverse mechanisms, natural preservatives provide long-term efficacy while contributing to the preservation of food quality, stability, and safety.

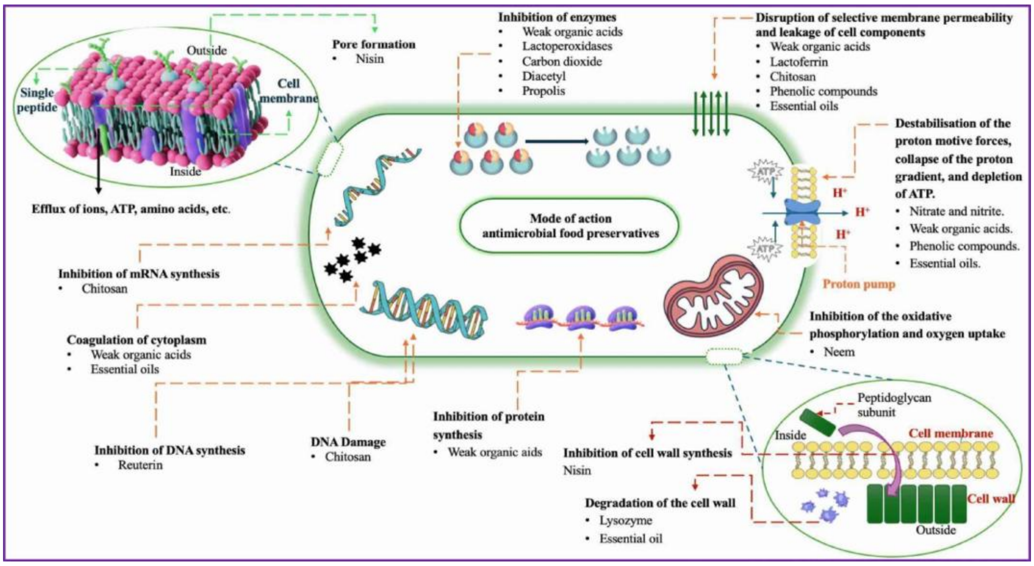


Figure 21. Mode of action of antimicrobial food preservatives (Bensid et al. 2022)

1.8. Food preservation techniques based on pH reduction

pH is one of the most important intrinsic factors influencing food stability. It directly affects microbial growth, enzyme activity, nutrient stability, and the physicochemical properties of foods. Therefore, pH reduction represents an effective preservation method widely used in various food products such as fruits, fermented vegetables, acidified beverages, and canned foods.

1.8.1. pH values of foods

According to the pH values of foods, they are generally classified into four groups:

- **Group 1: Low-acid foods** (pH above 5.3) such as corn, meat, fish, and milk. All types of microorganisms can grow in these foods, particularly bacteria.
- **Group 2: Medium-acid foods** (pH between 5.3 and 4.5) such as bananas, yogurt, and pumpkin. All types of microorganisms can grow in these foods.

- **Group 3: Acid foods** (pH between 4.5 and 3.7) such as tomatoes, orange juice, sugar beet, and grapes. These foods are mainly susceptible to the growth of yeasts and molds, as well as a few types of bacteria. Most pathogenic bacteria cannot grow in these foods.
- **Group 4: High-acid foods** (pH below 3.7) such as apples, grapefruit juice, and limes. These foods are mainly susceptible to the growth of yeasts and molds. Most bacteria, especially pathogenic bacteria, cannot grow in these foods.

The variability of food pH (table 9) directly influences their susceptibility to microbial spoilage, since the growth of microorganisms is restricted to specific pH ranges (table 10).

Table 9. Approximate pH values for the growth of selected microbes in food (Preetha and Narayanan, 2020).

Products	**pH**
Vegetables	
Eggplant	4.5
Potatoes (tubers and sweet)	5.3 to 5.6
Tomatoes (whole)	4.2 to 4.3
Cabbage	5.2-6.3
Spinach	5.1-6.S
Brussels sprouts	6.3-6.6
Beets	4.9-5.S
Asparagus	5.0-6.1
Carrots	4.9 to 6.3
Fruits	
Watermelons	5.2 to 5.6
Bananas	4.5 to 4.7
Limes	1.8 to 2.0
Grapes	3.3-4.5
Cherries	3.2-4.7
Pineapple	3.2-4.1
Strawberries	3.0-4.2
Raspberries	2.9-3.7
Apples	2.9-3.5
Oranges	2.8-4.0
Dairy products	
Milk	6.3 to 6.5
Butter	6.1 to 6.4
Camembert cheese	6.1-7.0
Cottage	4.1-5.4
Gouda	4.7
Meat	
Chicken	6.2 to 6.4
Beef	5.1 to 6.2
Turkey	5.6 - 6.0
Pork	5.3 - 6.4
Dry sausages	4.4 - 5.6
Sea food	
Shrimp	6.8 - 8.2
Crab	6.8 - 8.0
Catfish	6.6 - 7.0

Table 10. Approximate pH values for the growth of selected microbes in food (Preetha and Narayanan, 2020).

Microorganism	Minimum	Optimum	Maximum
Clostridium perfringens	5.5 to 5.8	7.2	8.0 to 9.0
Vibrio vulnificus	5.0	7.8	10.2
Bacillus cereus	4.9	6.0 to 7.0	8.8
Campylobacter spp.	4.9	6.5 to 7.5	9.0
Shigella spp.	4.9	9.3	
Staphylococcus aureus			
Growth	4.0	6.0 to 7.0	10.0
Toxin	4.5	7.0 to 8.0	9.6
Salmonella (most).	4.5 to 5.0	6.0 to 7.5	8.0 to 9.6
Salmonella. typhi	4.0 to 4.5	6.5 to 7.2	8.0 to 9.0
Escherichia coli	4.3-4.4	6.0-8.0	9.0-10.
Lactobacillus. acidophilus	4.0 to 4.6	5.5 to 6.0	7.0
Lactobacillus. plantarum	3.5	5.5 to 6.5	8.0
Clostridium. perfringens	5.0 to 5.5	6.0 to 7.6	8.5 to 9.0
Clostridium botulinum	4.8 to 5.0	6.0 to 8.0	8.5 to 8.8
Propionibacterium	4.7	6.2 to 7.0	7.5
Pseudomonas (most)	5.6	6.6 to 7.0	8.0
Leuconostoc cremoris	5.0	5.5 to 6.0	6.5
Saccharomyces cerevisiae	2.0 to 2.4	4.0 to 5.0	-
Saccharomyces rouxii	1.5	3.5 to 5.5	8.5 to 10.5
Aspergillus niger	1.2	3.0 to 6.0	-
Aspergillus oryzae	1.6 to 1.8	-	9.0 to 9.3
Penicillium	1.9	4.5 to 6.7	9.3

1.8.2. Effects of pH on food components, enzymes, and microorganisms

pH exerts a major influence on the physicochemical properties of food constituents, particularly proteins, polysaccharides, pigments (figure 22), and vitamins. Variations in pH can modify their solubility, stability, reactivity, and molecular interactions, leading to significant changes in the texture, color, flavor, and nutritional value of foods.

Furthermore, the activity of food enzymes is closely dependent on the pH of the surrounding medium. Each enzyme has an optimal pH at which its activity is maximal; any change in this parameter may alter its three-dimensional structure by modifying the ionization state of certain functional groups, resulting in reduced enzymatic activity or even irreversible denaturation. Consequently, acidification helps slow down many enzymatic reactions involved in browning, tissue softening, and nutrient degradation.

pH is also a key factor influencing the growth and survival of microorganisms (figure 23). Its inhibitory effect is mainly due to the action of hydrogen ions (H^+) and undissociated acids, which can readily cross microbial cell membranes. Once inside the cell, these acids dissociate and release H^+ ions, causing acidification of the cytoplasm. This intracellular acidification disrupts the functioning of enzymes, membrane transport processes, ATP synthesis, and various essential metabolic pathways. The accumulation of these disturbances reduces cellular activity and may ultimately lead to the inhibition or complete cessation of microbial growth.

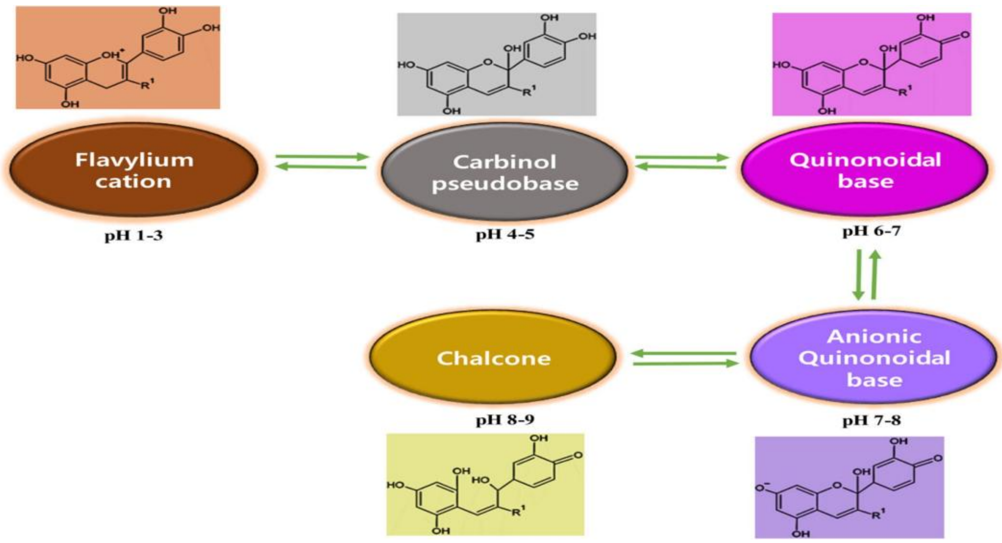


Figure 22. Effect of pH on anthocyanin pigments in foods (Jusnita et al., 2025).

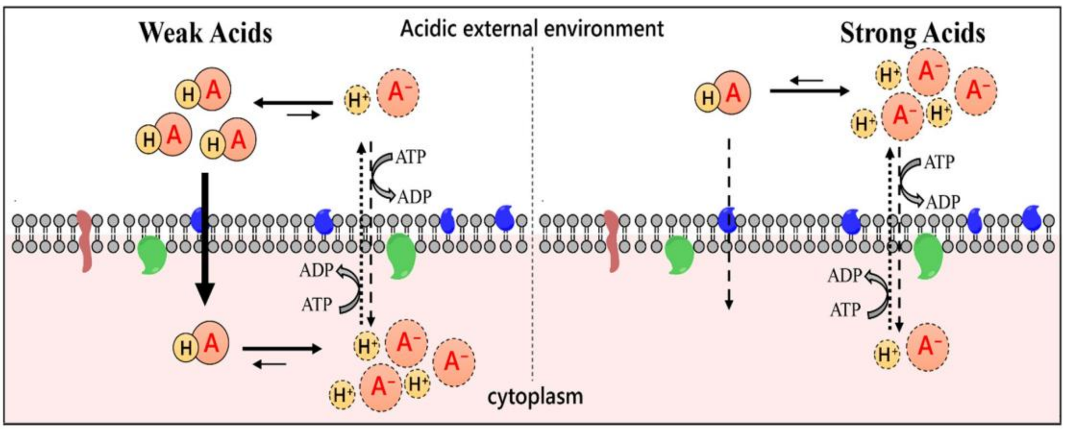


Figure 23. Mechanisms of acidification of bacterial cells by weak and strong acids. A^- anion, H^+ proton, HA acid (Figueira et al., 2022).

1.8.3. Food acidification

Food product acidification can be achieved through two different methods:

- **The first is a direct method** that involves the acidification of the food product by the addition of one or more organic acids.
- **The second is an indirect method** that relies on the use of fermentative microorganisms to produce organic acids and thereby reduce the pH of the food product.

1.8.3.1. Acidification

Acidification is a preservation method that involves the direct addition of one or more organic acids (table 11), such as acetic acid, citric acid, or lactic acid, or naturally acidic ingredients such as lemon juice or vinegar, to a low-acid food. This technique aims to lower the pH of the product to a sufficiently low level to limit or prevent the growth of microorganisms responsible for food spoilage or foodborne illnesses.

The effectiveness of acidification depends on the amount of acid added and the buffering capacity of the food, that is, its resistance to changes in pH. Acidifying agents or acidic ingredients must be incorporated in carefully controlled proportions to ensure that the final product pH remains below 4.5. This value is particularly important in food microbiology because it corresponds approximately to the threshold below which the growth of many pathogenic bacteria is strongly inhibited. In particular, *Clostridium botulinum*, the bacterium responsible for botulism, is unable to produce its toxin when the pH of the medium is below 4.6.

Acidification is widely used in the food industry for the production of numerous products, including pickles, marinated vegetables, sauces, condiments, acidified beverages, and certain vegetable preserves. In addition to its antimicrobial effect, acidification also contributes to improving several organoleptic characteristics of foods, particularly their flavor, aroma, and stability.

Table 11. Commonly used organic acids in the food industry (Bose et al., 2023).

Organic acids	Antimicrobial action
Malic acid	*Listeria monocytogenes*
Phenyllactic acid	*E. cloacae*
Propionic acid	*Escherichia coli* and *Salmonella*
Citric acid	*Shigella. flexneri*
Sorbic acid	*Yeast* and *mold*
Oxalic acid	*Escherichia coli*
Acetic acid	*Shigella*

1.8.3.2. Fermentation

Fermentation is one of the oldest methods of food preservation used by humans. Archaeological evidence indicates that the first fermented beverages were produced more than 7,000 years ago in China. The ancient Egyptians had already mastered the production of leavened bread and beer around 3000 BC.

For a long time, the mechanisms underlying fermentation remained unknown. It was not until the nineteenth century that Louis Pasteur demonstrated that fermentation resulted from the activity of living microorganisms. His pioneering work marked the beginning of modern food microbiology and paved the way for the development of controlled fermentation processes that are widely used in the food industry today (figure 24).

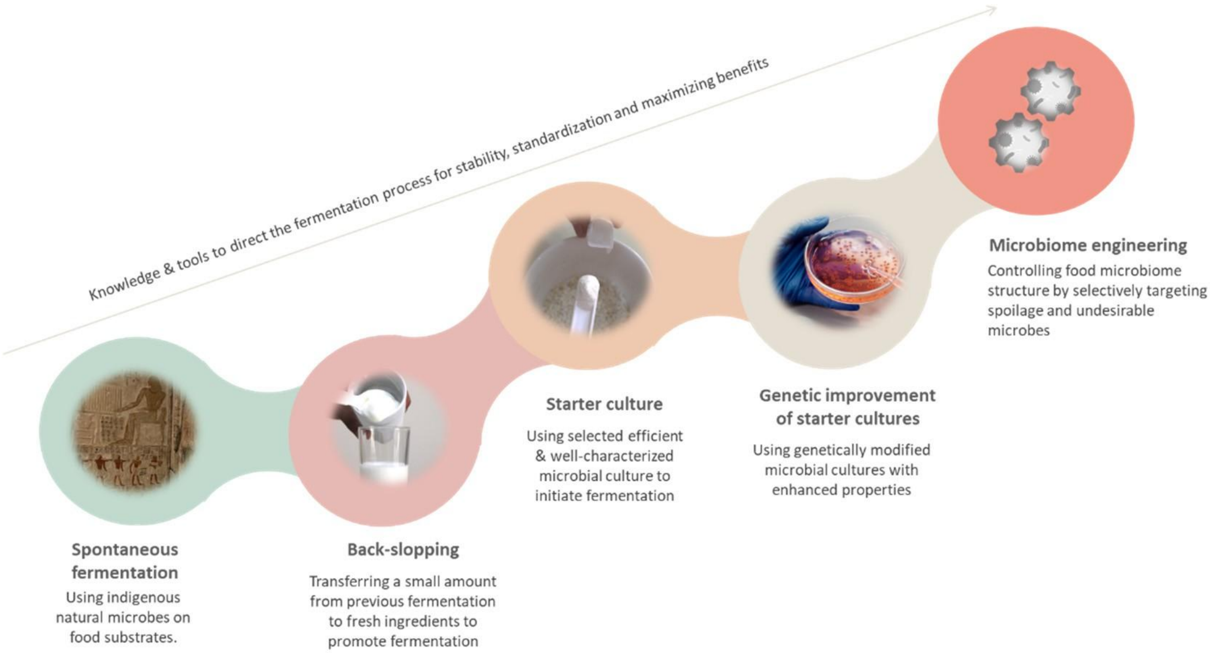


Figure 24. Evolution of the process of fermentation throughout the history (Mannaa et al., 2021).

A. Definition of fermentation

Fermentation is a metabolic process in which certain microorganisms, particularly bacteria, yeasts, and molds, convert carbohydrates and other organic compounds into simpler products, generally in the absence of oxygen. This transformation leads to the production of various metabolites such as organic acids, alcohol, carbon dioxide, and a wide range of aromatic compounds (figure 25).

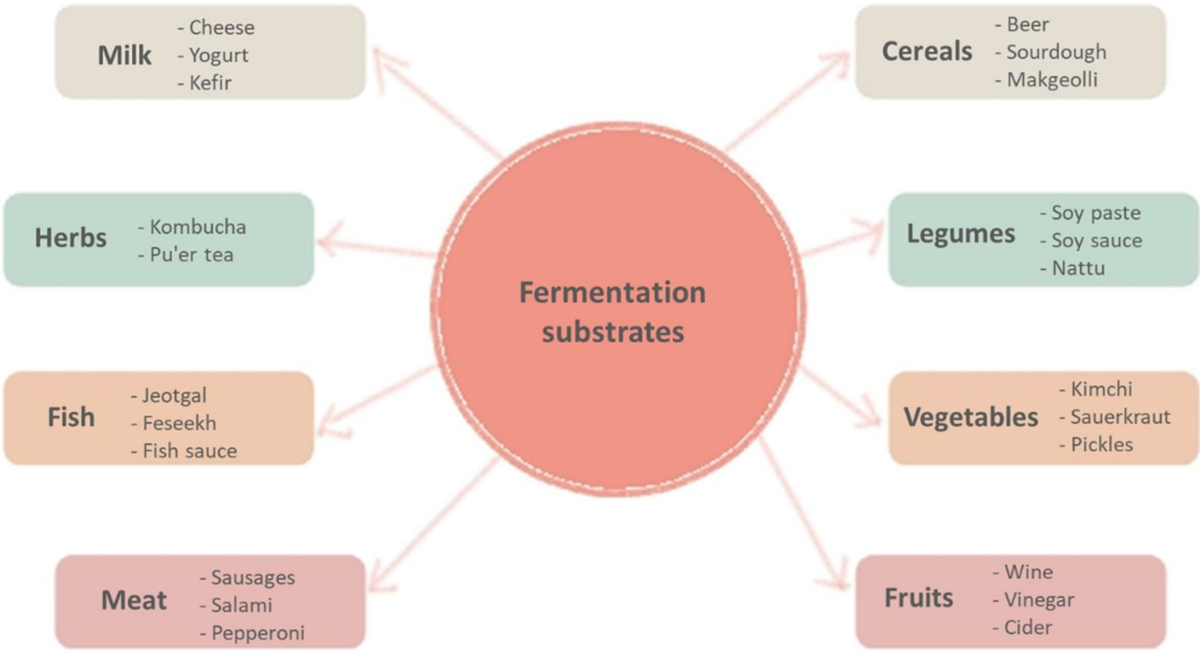


Figure 25. Common fermentation substrates and produced fermented foods and beverages. (Mannaa et al., 2021).

In the food industry, fermentation has been used for thousands of years to improve food preservation, microbiological safety, sensory qualities, and nutritional value.

The successful implementation of fermentation relies

- on the selection of appropriate microorganisms, known as starter cultures, capable of carrying out the desired transformations in the food.
- It also depends on the control of fermentation conditions, including temperature, pH, nutrient availability, and oxygen levels, which promote the growth of beneficial microorganisms while inhibiting undesirable ones. Proper management of these parameters ensures the quality, safety, and stability of the final fermented product.

B.Types of fermentation

Fermentations are generally classified into different types according to the dominant metabolic pathway: alcoholic fermentation, lactic fermentation, acetic fermentation, propionic fermentation… (figure 26).

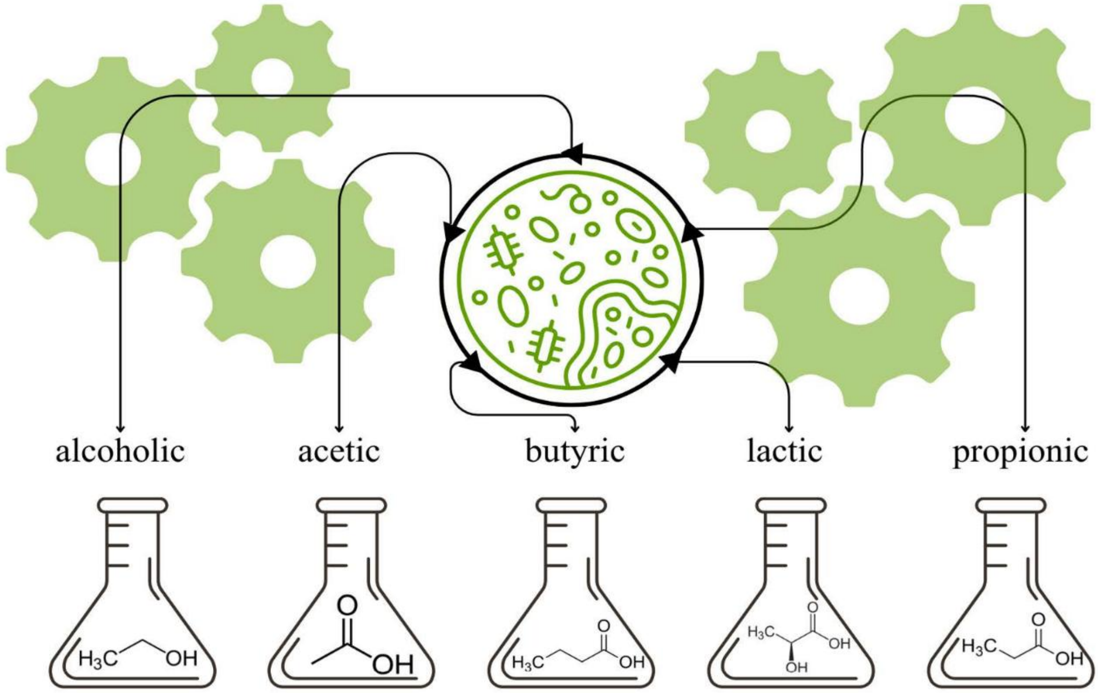


Figure 26. Main types of food fermentation (Rymuszka and Gorczynska, 2026).

a. Alcoholic fermentation

Alcoholic (ethanolic) fermentation is an anaerobic biochemical process in which sugars such as glucose, fructose, and sucrose are converted into ethyl alcohol (ethanol) and carbon dioxide. The most commonly employed microorganism is *Saccharomyces cerevisiae*, which ferments glucose via the classical glycolytic pathway known as the Embden–Meyerhof–Parnas (EMP) pathway.

Considered one of the oldest food processing methods, it forms the basis for the production of numerous fermented and distilled beverages, including wine, beer, cider, mead, whisky, rum, and vodka.

b. Acetic fermentation

Acetic fermentation is a process closely linked to alcoholic fermentation. It occurs under aerobic conditions and involves the oxidation of ethanol into acetic acid by acetic acid bacteria (AAB). This process generally comprises two successive stages: an anaerobic phase during which yeasts, mainly of the genus *Saccharomyces*, convert sugars into ethanol, followed by an aerobic phase in which acetic acid bacteria transform ethanol into acetic acid. This type of fermentation forms the basis of vinegar production.

c. Butyric fermentation

Butyric fermentation is an anaerobic metabolic pathway involved in carbohydrate degradation, in which butyric acid (or butanoic acid), a short-chain volatile fatty acid, is the main end product. This process is primarily carried out by bacteria belonging to the genera *Clostridium*, *Butyrivibrio*, and *Butyribacterium*, although other genera such as *Coprococcus*, *Eubacterium*, *Fusobacterium*, *Megasphaera*, *Roseburia*, and *Sarcina* are also capable of producing butyrate. Among these microorganisms, species of the genus *Clostridium* play a major role due to their high fermentative capacity and their ability to convert a wide range of substrates, including glucose, xylose, lactose, and glycerol, into butyric acid.

d. Lactic fermentation

Lactic acid fermentation is carried out by both homofermentative and heterofermentative lactic acid bacteria.

- Homofermentative lactic acid bacteria metabolize hexoses, mainly glucose, through the Embden–Meyerhof–Parnas (EMP) pathway, producing two molecules of lactate from one molecule of glucose. Representative homofermentative lactic acid bacteria include *Lactobacillus plantarum*, *Pediococcus pentosaceus*, *Lactococcus lactis*, and *Streptococcus thermophilus*.
- In contrast, heterofermentative lactic acid bacteria are capable of fermenting both hexoses and pentoses. The main genera of heterofermentative lactic acid bacteria include *Leuconostoc*, *Oenococcus*, *Levilactobacillus*, and *Limosilactobacillus*.

e. Propionic fermentation

Is carried out by bacteria belonging to the genus *Propionibacterium* and results in the production of propionic acid. It plays an important role in the manufacture of cooked cheeses, to which it imparts a characteristic flavor.

f. Malolactic fermentation

Involves the conversion of malic acid into lactic acid and carbon dioxide (CO_2) by lactic acid bacteria, mainly belonging to the genus *Oenococcus*. This process leads to the deacidification of wine and helps eliminate malic acid, which can impart an undesirable harsh or green character to high-quality wines.

C. Factors affecting food fermentation

Food fermentation is influenced by several intrinsic and extrinsic factors that determine the growth and metabolic activity of microorganisms. Among the main parameters are the chemical composition of the food, particularly its content of carbohydrates, proteins, and other nutrients, as well as pH, water activity, salt concentration, temperature, and oxygen availability. The nature of the resident microflora and the physical structure of the food also play important roles in the fermentation process (figure 27). Controlling these parameters helps direct fermentation, improve food preservation, and enhance the nutritional and organoleptic qualities of the final product.

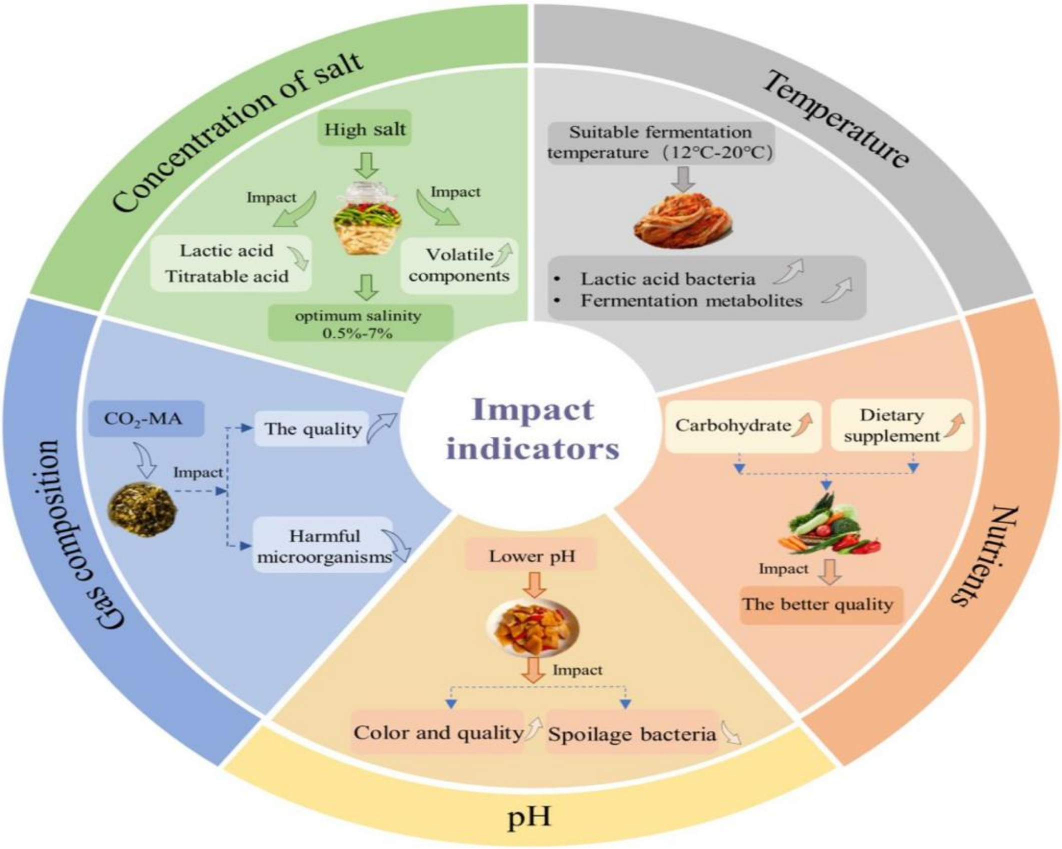


Figure 27. Influencing factors of fermented vegetables (Lu et al., 2024).

D. Role of lactic acid bacteria in the preservation and microbiological safety of fermented foods.

Lactic acid bacteria play an essential role in the preservation and microbiological safety of fermented foods due to their ability to produce various antimicrobial compounds, including organic acids, bacteriocins, and hydrogen peroxide (figure 28). These metabolites inhibit the growth of pathogenic and spoilage microorganisms by altering their environment and disrupting their cellular functions. Through their metabolic activity, lactic acid bacteria contribute to the microbiological stability of foods, extend their shelf life, and enhance their sanitary quality.

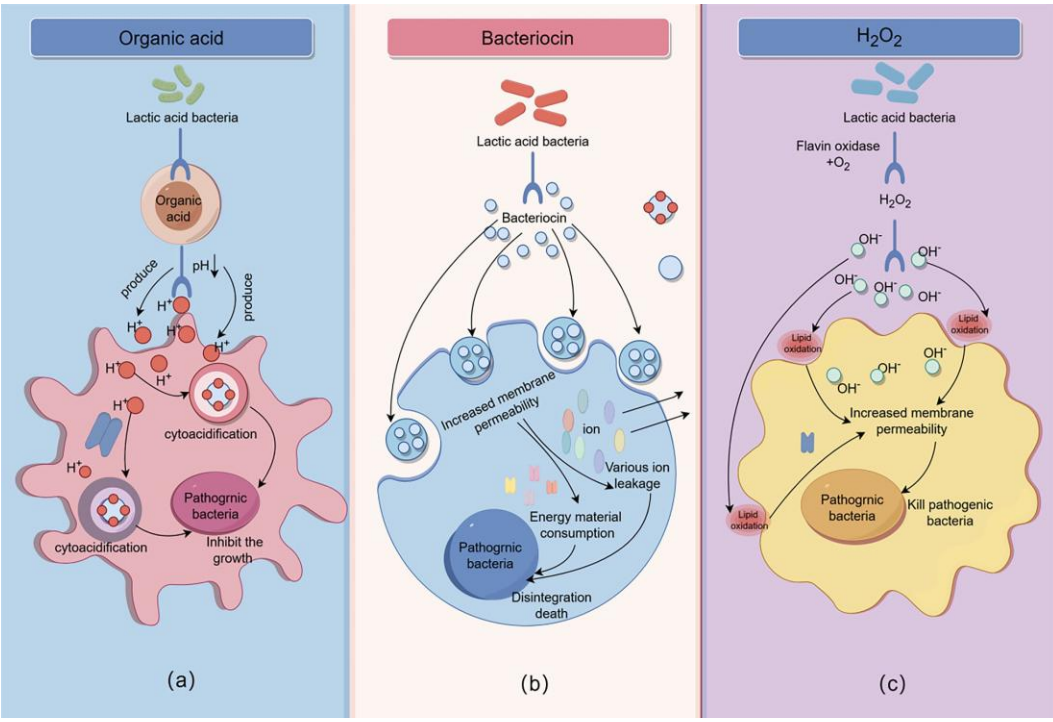


Figure 28. Antimicrobial mechanisms of lactic acid bacteria in fermented foods (Lu et al., 2024).

1.9. Food irradiation

Food irradiation is a non-thermal food preservation technique that involves the controlled exposure of food products to radiation, mainly ionizing radiation such as gamma rays, X-rays, or accelerated electron beams. This technology is used to reduce or eliminate pathogenic microorganisms (bacteria, viruses, and other microbial agents), insects, and parasites present in food or agricultural commodities. It also helps delay the ripening of fruits and vegetables, improve food hygiene and safety, and extend the shelf life, storage, and distribution period of food products. One of the major advantages of this method is that it largely preserves the organoleptic and nutritional qualities of foods, having minimal effects on their flavor, color, taste, nutritional value, and other essential characteristics.

1.9.1. Types of radiation

The radiations used in food irradiation can be classified into ionizing radiation and non-ionizing radiation according to their ability to ionize matter (figure 29).

Figure 29. Electromagnetic spectrum (Munir and Federighi, 2020).

1.9.1.1.Ionizing radiation

Ionizing radiation possesses sufficient energy to remove electrons from atoms and molecules, leading to the formation of ions and free radicals capable of damaging microbial cells and their genetic material.

A. Gamma rays (γ)

Gamma rays are emitted by radioisotopes such as Cobalt-60 and Cesium-137. They are characterized by a very high penetration capacity, allowing the treatment of packaged foods and products of considerable thickness. Their antimicrobial action is based on the destruction of microbial DNA, thereby preventing the multiplication of microorganisms.

B. X-rays

X-rays are artificially produced by electron accelerators. They have a penetration power comparable to that of gamma rays and are used for the disinfection and preservation of various food products. Their main advantage is that they can be generated on demand without the use of radioactive materials.

C. Accelerated electron beams (Electron Beam or E-beam)

This technology uses high-energy accelerated electrons. Electron beams provide rapid and effective food treatment; however, their penetration capacity is lower than that of gamma rays and X-rays. Therefore, they are particularly suitable for thin products or foods packaged in thin layers.

1.9.1.2.Non-ionizing radiation

Non-ionizing radiation does not possess sufficient energy to ionize molecules. Its antimicrobial activity relies on other physical or photochemical mechanisms.

A. Ultraviolet radiation (UV)

UV radiation, particularly UV-C (200–280 nm)**,** exerts a germicidal effect by inducing DNA damage in microorganisms. It is mainly used for the disinfection of food surfaces, water, and air in food-processing facilities.

B. Visible light

Certain wavelengths of visible light, especially blue light, can exhibit antimicrobial activity by generating reactive oxygen species that damage microbial cells.

C. Infrared radiation

Infrared radiation acts primarily through a thermal effect. It is used for drying, surface heating, and certain food decontamination processes.

D. Radio waves and microwaves

These radiations cause the agitation of water molecules present in foods, thereby generating heat. They are widely employed for heating, cooking, pasteurization, and reducing microbial loads.

In the food industry, only gamma rays, X-rays, and accelerated electron beams are officially approved for food irradiation aimed at preservation and microbial decontamination. Non-ionizing radiations, on the other hand, are mainly used for disinfection, heating, and surface-treatment applications.

1.9.2. Irradiation dose

The irradiation dose refers to the amount of energy absorbed by a food product when it is exposed to ionizing radiation. It is the main parameter determining the effectiveness of the treatment, as it directly influences the inactivation of microorganisms, parasites, and insects, as well as any potential changes in the characteristics of the product.

The absorbed dose is expressed in Gray (Gy), the International System unit corresponding to the absorption of one joule of energy per kilogram of matter:

$1\ \text{Gy} = 1\ \text{J kg}^{-1}$

In the food industry, doses are generally expressed in kilogray (kGy), where:

$1\ \text{kGy} = 1000\ \text{Gy}$

Depending on the intended purpose, different dose ranges may be applied (figure 30):

- **Low doses (< 1 kGy):** Used to inhibit the sprouting of tubers (potatoes, onions), delay the ripening of fruits, and control insects in cereals and dried fruits.
- **Medium doses (1–10 kGy):** Employed to reduce microbial load, eliminate certain pathogenic microorganisms, and extend the shelf life of fresh or processed foods.
- **High doses (> 10 kGy):** Used to achieve near-complete sterilization of certain foods Intended for specific applications, particularly hospital diets or foods for immunocompromised individuals.

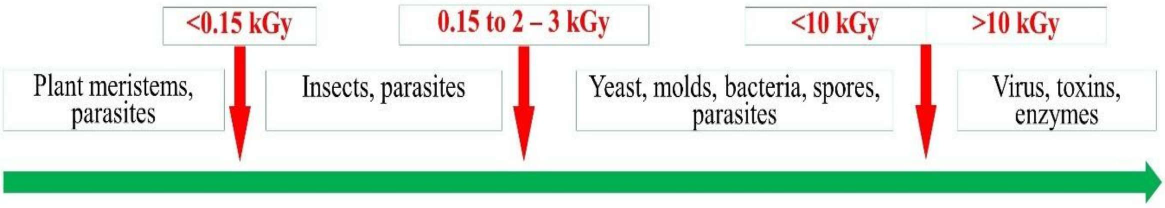


Figure 30. Range of lethal doses for different biological treatment targets (Munir and Federighi, 2020).

1.9.3. Food irradiation process

Food products are loaded onto a conveyor system that continuously transports them to an irradiation chamber. During their passage through this enclosure, they are exposed to a radiation source for a predetermined period in order to receive the required irradiation dose. This treatment helps reduce or eliminate pathogenic microorganisms, parasites, and insects while improving food preservation. Once the exposure is completed, the products continue along the conveyor to the unloading area, where they are removed for storage, distribution, or further processing. Thanks to this automated process, irradiation is carried out in a uniform, controlled, and safe manner, ensuring the effectiveness of the treatment while preserving food quality (figure 31).

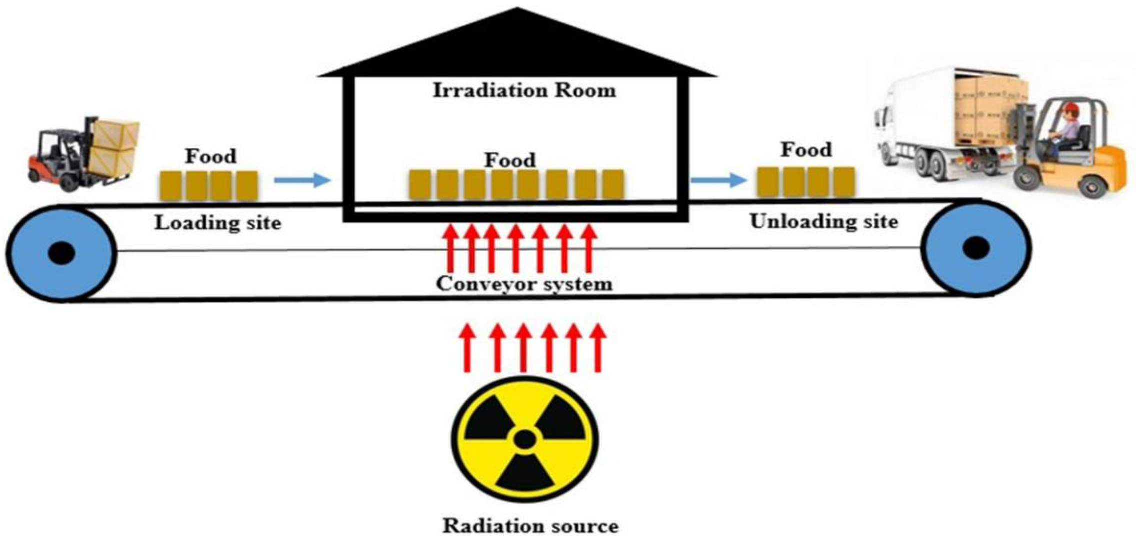


Figure 31. Food irradiation process (Mshelia et al., 2023).

1.9.4. Main applications of food irradiation

One of the main applications of food irradiation is the inhibition of sprouting in bulbs, tubers, and rhizomes such as potatoes, onions, and garlic. This treatment helps reduce post-harvest losses and extends storage life.

Irradiation is also used to delay the ripening of fresh fruits and vegetables, thereby helping to maintain their quality during transportation and marketing. In addition, it plays an important role in insect disinfestation, particularly in fruits, cereals, legumes, dried fruits, and spices, facilitating international trade and compliance with phytosanitary requirements.

Another major application involves the reduction of microbial load and the elimination of pathogenic microorganisms present in foods. This use is particularly important for meat, poultry, seafood, dehydrated foods, and ready-to-eat products. Irradiation thus helps reduce the risk of foodborne diseases while extending the shelf life of food products.

In certain products, especially fish, seafood, and meat, irradiation is employed to control parasites that may be transmitted to humans. It is also used to limit the growth of moulds in certain dried foods of animal or plant origin.

Higher irradiation doses can be applied to achieve food sterilization for specific purposes, such as military rations, space foods, and foods intended for hospitals or immunocompromised individuals. Through these diverse applications, irradiation represents a versatile technology that enhances food quality, safety, and shelf life while reducing post-harvest losses and health risks.

Table 12 provides examples of the main applications of food irradiation according to food categories, treatment objectives, and irradiation doses.

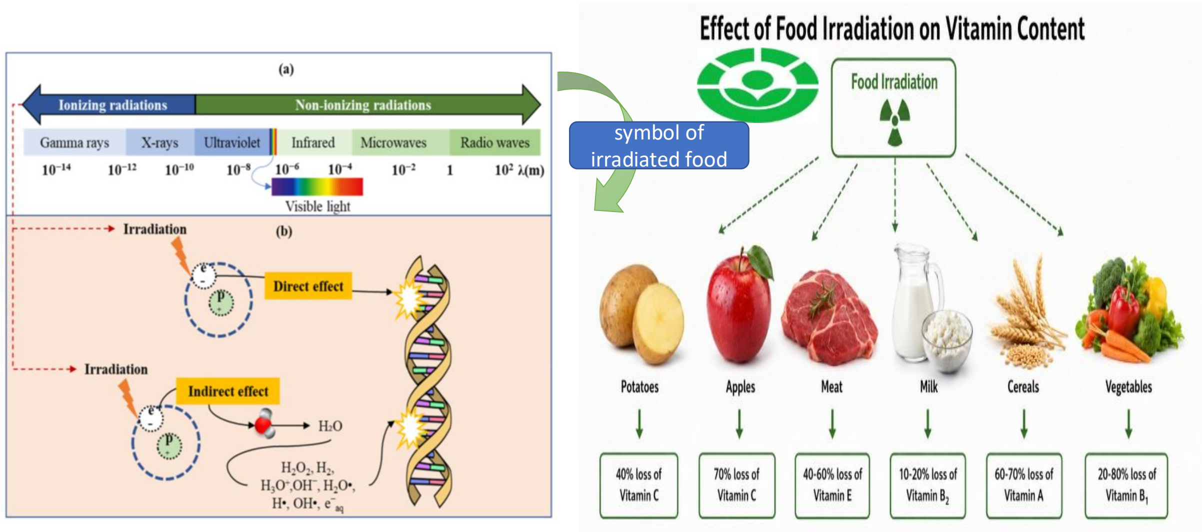
Table 12. Examples of the main applications of food irradiation (Singh and Singh, 2020).

Food	Purpose of Treatment	Absorbed dose range (kGy)
Bulbs, stem and root tubers, rhizomes	Inhibit sprouting	0.02 – 0.2
Fresh fruits and vegetables	Delay ripening	0.2 – 1.0
	Insect disinfestation	0.2 – 1.0
	Shelf life extension	1.0 – 2.5
	Quarantine application	0.1 – 1.0
Cereals and their milled products, pulses and their milled products, nuts, oil seeds, dried fruits and their products	Insect disinfection	0.25 – 1.0
	Reduction of microbial load	1.5 – 5.0
Fish, aquaculture, seafood and their products (fresh or frozen) and crustaceans	Elimination of pathogenic microorganisms	1.0 – 7.0
	Shelf life extension	1.0 – 3.0
	Control of human parasites	0.3 – 2.0
Meat and meat products including poultry (fresh and frozen) and eggs	Elimination of pathogenic microorganisms	1.0 – 7.0
	Shelf life extension	1.0 – 3.0
	Control of human parasites	0.3 – 2.0
Dry vegetables, seasonings, spices, condiments, dry herbs and their products, tea, coffee, cocoa and plant products	Microbial decontamination	6.0 – 14.0
	Insect disinfestation	0.3 – 1.0
Dried foods of animal origin and their products	Insect disinfestation	0.3 – 1.0
	Control of moulds	1.0 – 3.0
	Elimination of pathogenic microorganisms	2.0 – 7.0
Ethnic foods, military rations, space foods, ready to-eat, ready-to-cook, minimally processed foods	Quarantine application	0.25 – 1.0
	Reduction of microbial load	2.0 – 10.0
	Sterilisation	5.0 – 25.0

1.9.5. Impact of irradiation on food quality and contaminating microorganisms

Food irradiation significantly improves microbiological safety by reducing or eliminating pathogenic and spoilage microorganisms. As illustrated in the figure 32, ionizing radiation acts either directly on nucleic acids (DNA and RNA) or indirectly through the formation of free radicals generated by water radiolysis. These mechanisms cause irreversible damage to the genetic material of microorganisms, preventing their replication and thereby enhancing food preservation. This technology also extends shelf life while reducing post-harvest losses and the need for chemical preservatives.

Despite its advantages, irradiation may induce certain changes in the nutritional quality of foods. The figure 32 shows that several vitamins are sensitive to ionizing radiation, with losses varying according to the type of food and the irradiation dose applied. For example, reductions in vitamin C content have been reported in potatoes and apples, while vitamins A, B_1, B_2, and E may also be partially degraded in cereals, vegetables, milk, and meat products. At high doses, irradiation may additionally affect color, texture, odor, and flavor, mainly due to oxidative reactions involving food constituents.



Effect of irradiation on nucleic acids. effect of irradiation on nucleic acids.

Loss of certain vitamins

Figure 32. Impact of irradiation (Indiarto et al., 2023).

1.10. Membrane filtration technologies in food preservation

Filtration is a preservation technique that consists of passing a liquid or gas through a porous material or membrane in order to remove undesirable particles, microorganisms, or specific compounds. In the food industry, it is widely used to improve the microbiological quality of liquid foods such as milk, fruit juices, fermented beverages, and process water. Unlike thermal treatments, filtration is a non-thermal process that helps preserve the nutritional, sensory, and functional properties of foods while extending their shelf life.

The principle of membrane filtration is based on the selective separation of the components of a mixture using a semi-permeable membrane. As illustrated in the figure, the fluid to be treated (*feed*) comes into contact with the membrane. Some molecules or particles are retained and form the retentate, while others pass through the membrane after undergoing sorption, diffusion, and desorption processes, thereby constituting the permeate**.** Separation mainly depends on particle size, molecular weight, and the interactions between the compounds and the membrane. This principle forms the basis of microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, which are widely applied for the clarification, concentration, and microbiological stabilization of food products.

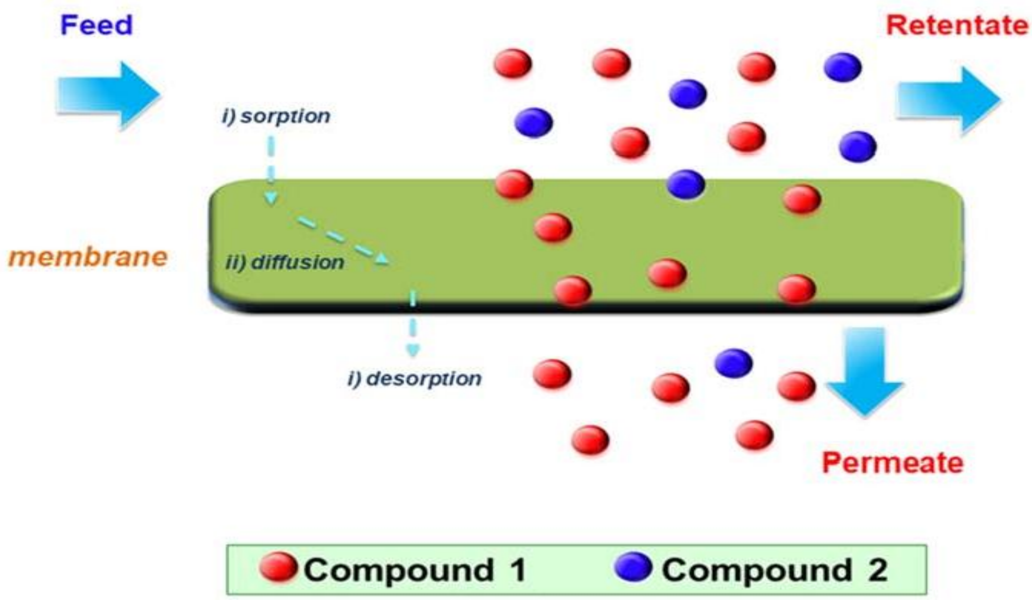


Figure 33. Schematic representation of membrane filtration process (Conidi et al., 2020).

1.10.1. Different membrane filtration processes

Membrane processes are mainly distinguished by the pore size of the membrane and, consequently, by the nature of the particles retained. The smaller the pore size, the smaller the molecules that can be retained. The main membrane filtration techniques include microfiltration, ultrafiltration, nanofiltration, and reverse osmosis (figure 34).

1.10.1.1. Microfiltration

Microfiltration is the membrane filtration process with the largest pore size (10–0.1 µm). It primarily retains suspended particles, emulsions, microbial cells, and most bacteria, while allowing water and small dissolved molecules to pass through the membrane. This process operates under relatively low transmembrane pressures, typically ranging from 0.2 to 5 bar. In the food industry, microfiltration is widely used for fruit juice clarification, microbiological stabilization of beverages, milk processing, and the clarification of wine and beer.

1.10.1.2. Ultrafiltration

Ultrafiltration employs membranes with smaller pore sizes than microfiltration (0.1–0.01 µm), enabling the retention of macromolecules such as proteins, polysaccharides, certain viruses, and colloidal particles, while low-molecular-weight compounds can still pass through the membrane. The process generally operates at transmembrane pressures ranging from 1 to 10 bar. In the food industry, ultrafiltration is widely applied for the concentration of milk proteins, the production of protein concentrates, the fractionation of biomolecules, and the clarification of various food liquids.

1.10.1.3. Nanofiltration

Nanofiltration (0.01–0.001 µm) is an intermediate membrane separation process between ultrafiltration and reverse osmosis. It is capable of retaining small organic molecules as well as a significant proportion of multivalent ions, while allowing water and some monovalent ions to pass through the membrane. The process typically operates at transmembrane pressures ranging from 5 to 10 bar. In the food industry, nanofiltration is commonly used for the partial demineralization of whey, sugar concentration, purification of plant extracts, and reduction of salt content in various food products.

1.10.1.4. Reverse osmosis

Reverse osmosis (0.001–0.0001 µm) is the most selective membrane filtration process, employing extremely dense membranes that allow almost exclusively water molecules to pass while retaining dissolved salts, ions, and nearly all other solutes. Due to this high degree of selectivity, the process requires relatively high operating pressures, typically ranging from 10 to 150 bar. In the food industry, reverse osmosis is widely used for the concentration of fruit juices and beverages, the pre-concentration of milk prior to drying, and the reduction of water activity to enhance product preservation and shelf life.

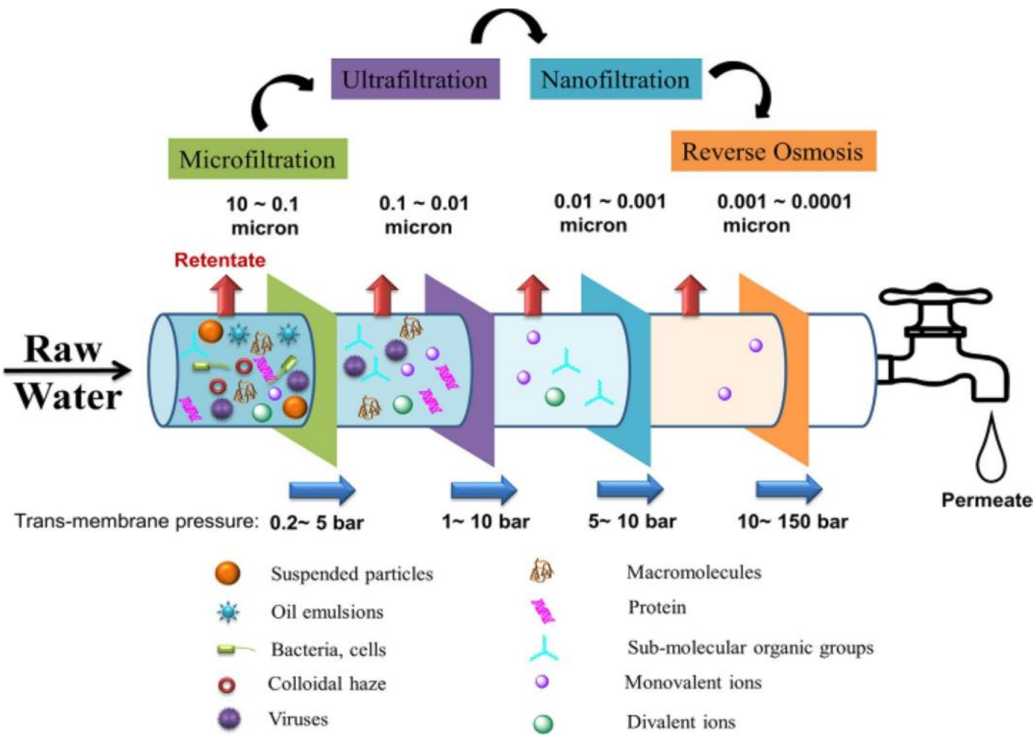


Figure 34. Schematic representation of different membrane filtration techniques (Aziz et al., 2024).

1.11. Food preservation by high pressure processing

Food preservation by High Pressure Processing (HPP), also known as pascalization, is a non-thermal technology that involves subjecting packaged foods to very high pressures (figure 35), typically ranging from 100 to 600 MPa, for periods varying from a few seconds to several minutes. This pressure is transmitted uniformly through a liquid medium, usually water, according to Pascal's principle, allowing the food to be treated homogeneously regardless of its shape or size.

High-pressure processing is widely used in the food industry for the preservation of fruit juices, beverages, dairy products, seafood, processed meats, sauces, and ready-to-eat meals. However, certain highly resistant microbial forms, such as bacterial spores, may require the combination of high-pressure treatment with other preservation methods, such as moderate heat or antimicrobial agents, to ensure optimal microbiological safety.

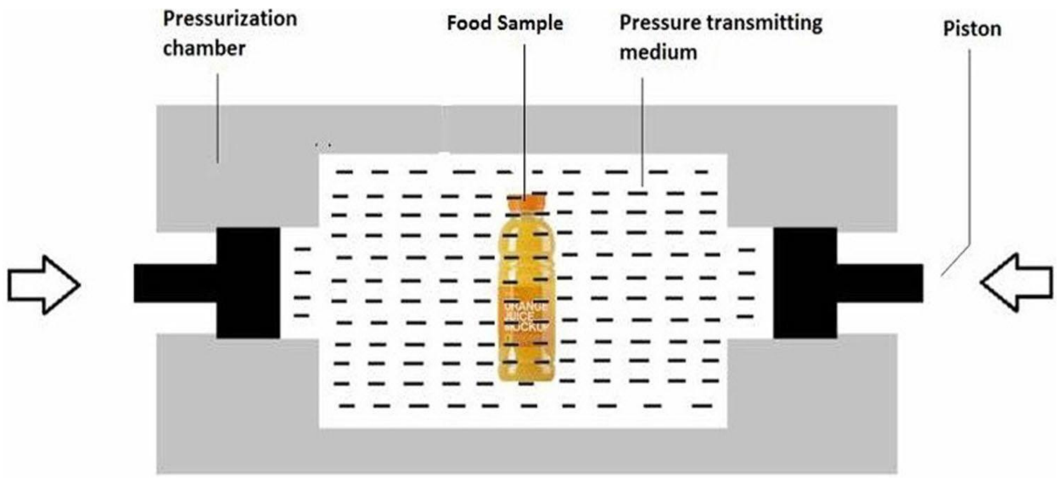


Figure 35. Isostatic pressurization of food (Sehrawat et al., 2020).

1.11.1. Microbial inactivation by high pressure processing

High Pressure Processing (HPP) inactivates microorganisms primarily by disrupting the structural and functional integrity of microbial cells. Under the effect of very high pressures, the cell membrane becomes more permeable, leading to the leakage of intracellular components such as metal ions and other solutes into the surrounding medium (figure 36). At the same time, pressure induces structural and conformational changes in essential cellular constituents, including cytoplasmic proteins, ribosomes, and nucleic acids, thereby impairing metabolic functions and the ability of microorganisms to reproduce. These damages result in a loss of cellular viability and microbial inactivation. However, as illustrated in the figure 36, the effectiveness of microbial inactivation depends on the intensity and duration of the pressure treatment applied. In some cases, cells that have undergone sublethal injury may recover and regain viability when the pressure conditions are insufficient to cause irreversible damage.

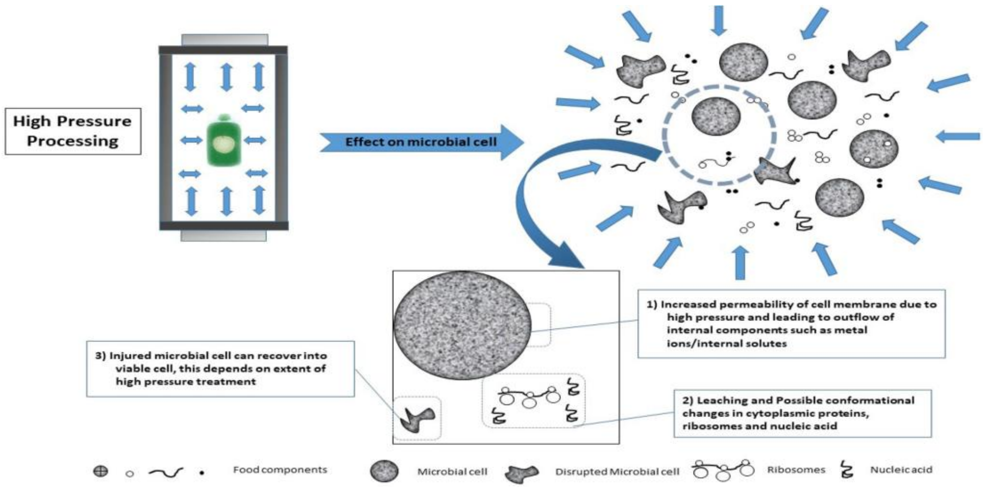


Figure 36. Schematic diagram representing cell membrane modification on high pressure processing (Sehrawat et al., 2020).

1.11.2. Effects of high-pressure processing on food components

High Pressure Processing (HPP) is a non-thermal preservation technology widely used in the food industry to enhance microbiological safety and extend the shelf life of food products. Owing to its ability to inactivate pathogenic and spoilage microorganisms without the use of high temperatures, this technology helps preserve the nutritional and sensory qualities of foods to a greater extent. Unlike conventional thermal treatments, HPP better retains vitamins, aroma compounds, natural color, and food texture. It is particularly suitable for heat-sensitive products such as fruit juices, dairy products, seafood, processed meats, and ready-to-eat foods. Furthermore, this technology reduces the need for chemical preservatives, thereby meeting the growing consumer demand for more natural and minimally processed foods.

Despite its numerous advantages, High Pressure Processing (HPP) may also induce certain modifications in food components. Proteins are particularly pressure-sensitive (figure 37) and may undergo denaturation, aggregation, or changes in their functional properties, which can affect the texture, viscosity, and water-holding capacity of foods. Polysaccharides and plant cellular structures may also be altered, resulting in changes in firmness and consistency (figure 38). Although vitamins are generally better preserved than during thermal treatments, some pressure-sensitive vitamins may be partially degraded under severe processing conditions.

High pressure also influences enzymatic activity: some enzymes are inactivated, whereas others may remain active and contribute to quality deterioration during storage. Furthermore, in certain lipid-rich foods, pressure can promote oxidative reactions that may adversely affect flavor and product stability. Therefore, although High Pressure Processing is an effective preservation method that retains many of the original characteristics of foods, processing parameters must be carefully optimized to maximize microbiological safety while minimizing undesirable effects on product quality.

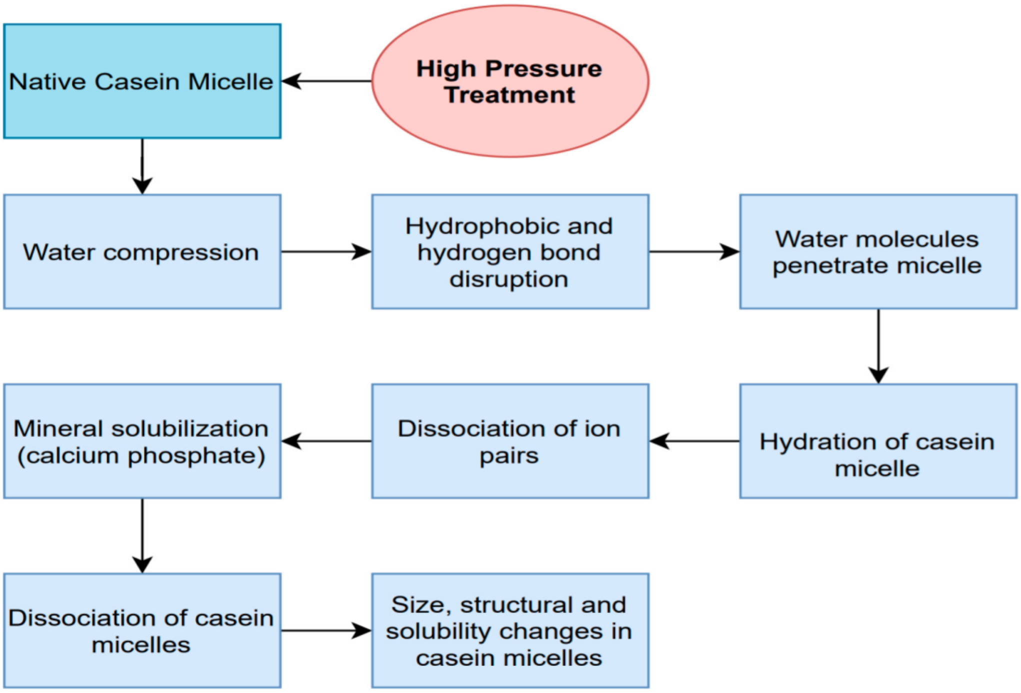


Figure 37. Sequence of effects regarding the denaturation of casein micelles (Serna-Hernandez et al., 2021).

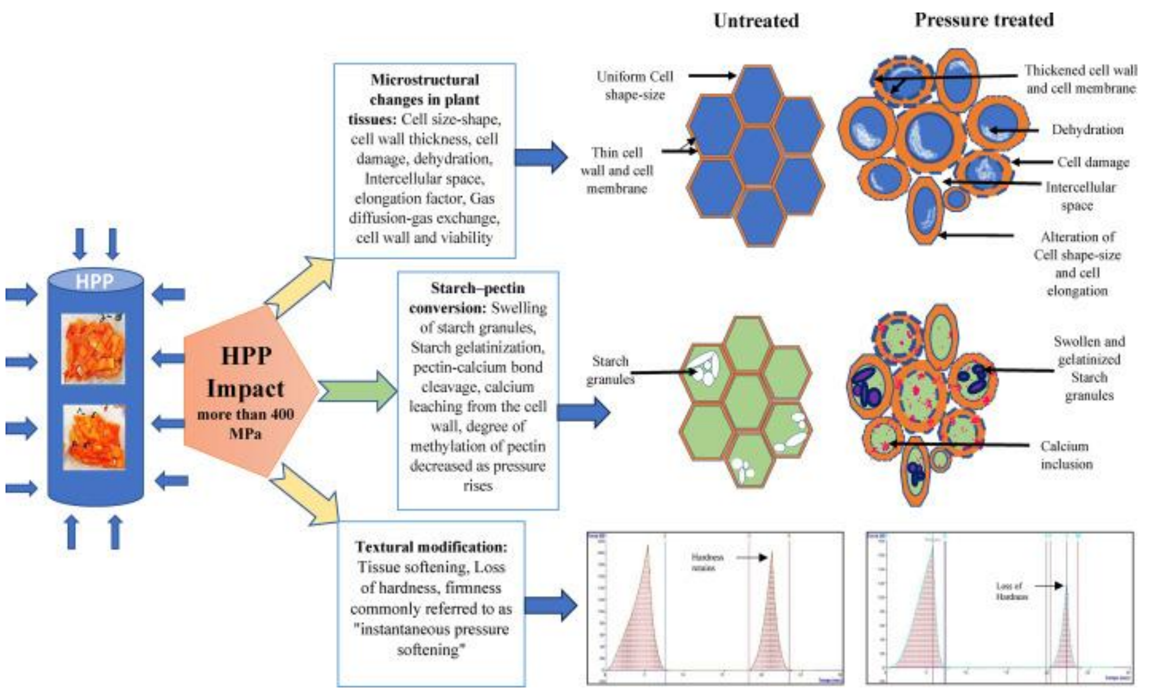


Figure 38. The effect of high-pressure processing on structural quality changes in Vegetables (Dhenge et al., 2023).

1.12. Food preservation under modified atmospheres

Food preservation under modified atmospheres refers to a group of preservation techniques that involve modifying or controlling the gaseous composition surrounding a food product in order to slow down microbiological, enzymatic, and oxidative spoilage processes, thereby extending shelf life while maintaining product quality.

These techniques mainly include:

- **Vacuum packaging**, which involves removing air from the package to reduce the< oxygen concentration.
- **Modified atmosphere packaging**, in which the air is replaced by a specific gas mixture, generally composed of carbon dioxide (CO_2), nitrogen (N_2), and sometimes oxygen (O_2).
- **Controlled atmosphere storage**, which consists of continuously maintaining and adjusting the gaseous composition around the product during storage.

The main objective of these methods is to limit microbial growth, reduce oxidative reactions, and preserve the nutritional, sensory, and technological characteristics of foods.

1.12.1. Application of modified atmospheres for food preservation

Modified atmospheres have numerous applications in food preservation.

- **In fresh meat and meat products**, the use of oxygen-rich atmospheres helps maintain the characteristic red color of the meat, while carbon dioxide inhibits the growth of spoilage microorganisms, thereby extending shelf life.
- **For fish and seafood products**, gas mixtures containing high concentrations of CO_2 are generally used to slow the growth of psychrotrophic bacteria and preserve both freshness and sensory quality.
- **In fresh fruits and vegetables**, reducing oxygen levels and controlling carbon dioxide concentrations decrease respiration rates, delay ripening and senescence, limit water loss, and help maintain texture.
- **Bakery products** also benefit from this technology through the inhibition of mold growth, which increases shelf life without the need for chemical preservatives.
- **In dairy products and cheeses**, modified atmospheres help limit the development of molds and spoilage bacteria while preserving organoleptic properties, particularly flavor, texture, and appearance.

Table 13 presents some examples of modified atmosphere applications in different food groups, specifying the gas mixtures commonly used for each type of product

Table 13. Gas combinations and concentrations of modified atmospheric packaging (Rasheed et al., 2025).

Food Items	Percentage of different gases			Remarks
	Oxygen	Carbon di Oxide	Nitrogen	
Fruits	3-5%	5-20%	75-85%	Oxygen should be in low concentration to reduce the post-harvest respiration and transpiration
Vegetables	3-5%	5-20%	75-85%	Oxygen should be in low concentration to reduce the post-harvest respiration and transpiration
Red Meat	60-65%	15-40%	---------	Oxygen gives red colour.
Processed meat	-------	20-35%	65-80%	
Fish	30%	40%	30%	For fatty fish, nitrogen concentration can be increased.
Poultry	-------	25%	75%	Oxygen may lead to greyish tinges on meat.
Ready Meals	10%	40%	50%	Minimum level of oxygen needed to prevent anerobic bacteria.
Dairy products	-------	30%	70%	Oxygen causes oxidative rancidity.

1.12.2. Effects of modified gas atmospheres on microorganisms and foods

The main effect of modified atmospheres is based on reducing the oxygen (O_2) concentration and/or increasing the carbon dioxide (CO_2) concentration surrounding the food. CO_2 has a well-established antimicrobial activity: it dissolves in the water present in foods and forms carbonic acid, which slightly lowers the pH and disrupts the metabolism of microorganisms (figure 39). This action slows the growth of many spoilage bacteria, yeasts, and molds, thereby extending the shelf life of food products.

The reduction in oxygen concentration also limits the growth of aerobic microorganisms and decreases oxidative reactions responsible for lipid rancidity, enzymatic browning in fruits and vegetables, and the degradation of certain food pigments.

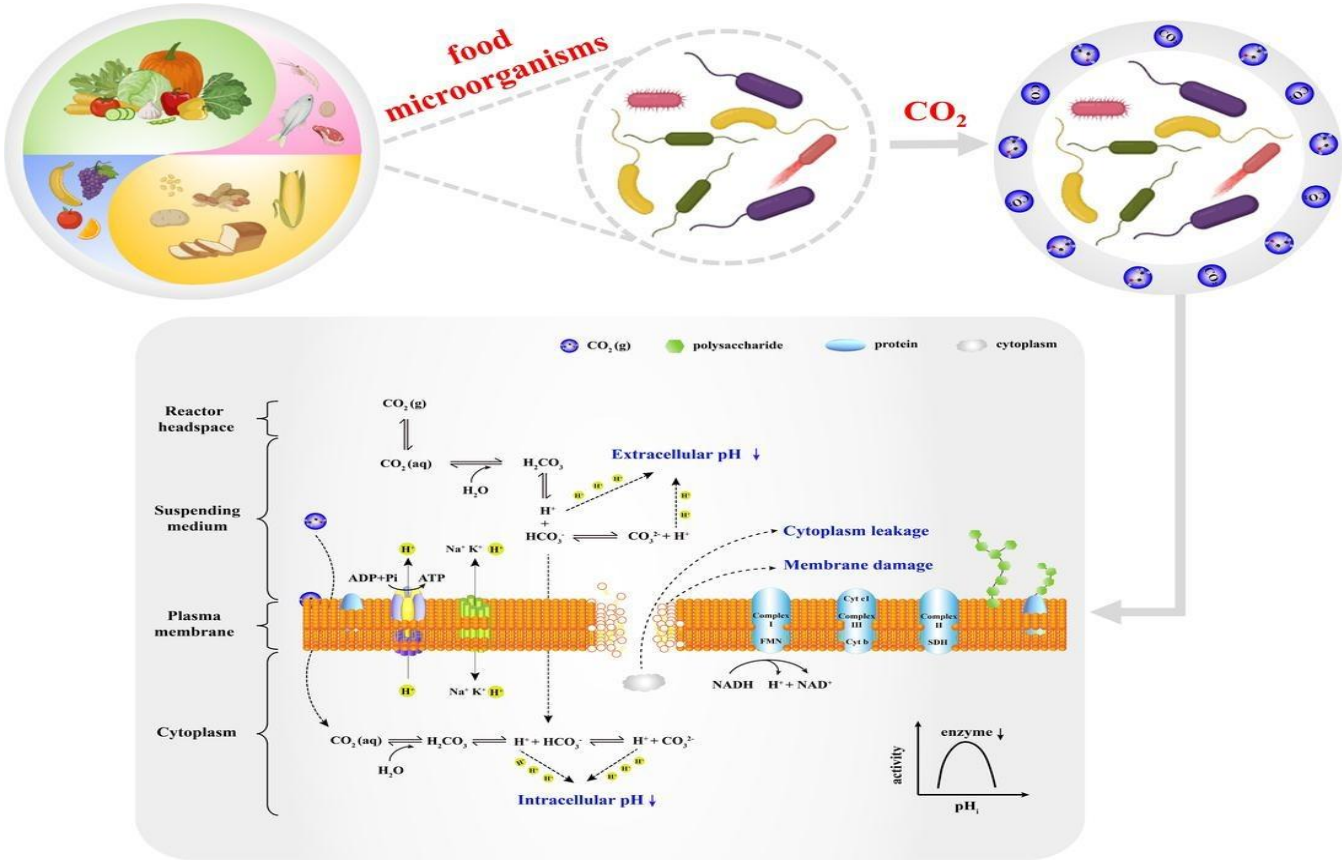


Figure 39. Mechanisms of carbon dioxide action on food microorganisms in modified atmosphere packaging and high-pressure carbon dioxide processing (Li et al., 2023).

In foods, modified atmospheres help maintain color, texture, flavor, and nutritional value more effectively than conventional preservation methods. In fresh fruits and vegetables, they reduce the respiration rate and delay ripening and senescence processes. In fresh meat products, they help preserve appearance and sensory quality during storage.

However, undesirable effects may occur when gas concentrations are not properly adjusted. Excessive CO_2 levels can cause texture changes, flavor losses, or physiological disorders in certain fruits and vegetables. Likewise, very low oxygen concentrations may promote anaerobic respiration in plant tissues, leading to the production of ethanol and other compounds responsible for off-flavors.

From a microbiological perspective, although modified atmospheres inhibit many spoilage microorganisms, they do not completely eliminate pathogenic microorganisms. Some anaerobic or facultative anaerobic bacteria may survive and, in certain cases, grow if storage temperatures are not adequately controlled. Therefore, the use of modified atmospheres should always be combined with refrigeration and good hygiene practices to ensure food safety.

1.13.Examples of application

Question 1:

A food processing company intends to develop several new food products. You are required to recommend the most appropriate physical preservation method for each product, considering the following factors:

- Microbiological stability;
- Water activity (aw);
- pH value;
- Sensitivity to heat treatment;
- Required shelf life;
- Preservation of nutritional and sensory attributes.

Product	Characteristics
A. Fresh strawberry juice	pH = 3.5; rich in vitamin C; desired shelf life: 30 days
B. Fish fillet	aw = 0.99; rich in unsaturated lipids; intended for long-distance export
C. Milk for rural areas without a cold chain	pH = 6.7; desired shelf life: 6 months
D. Premium instant coffee	Product sensitive to moisture and aroma losses
E. Spices for export	Low moisture content but high initial microbial contamination

For each product:

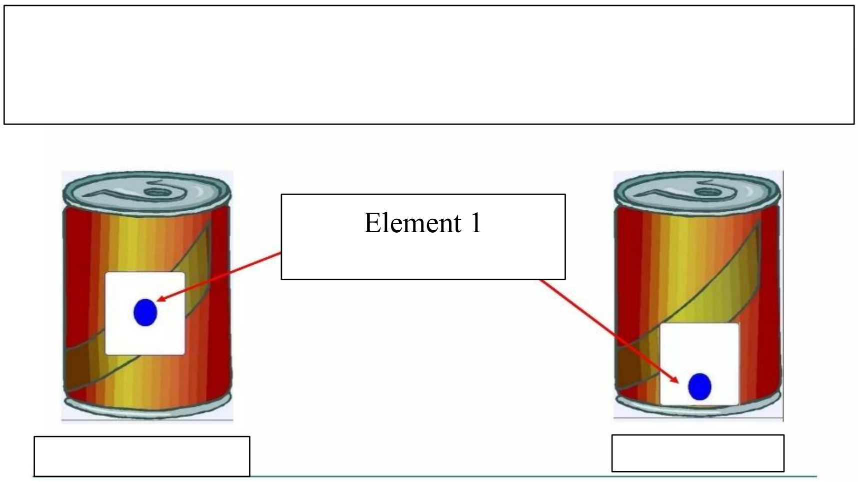
1. Propose the most appropriate physical preservation method.
2. Scientifically justify your choice.

Question 2:

The freezing kinetics of a food product are characterized by three phases. Explain these phases and support your explanation with a diagram (schematic representation).

Question 3:

Observe the figure below:



3.1. What does element 1 represent for both canned food containers?
………………………………………………………………
3.2. Explain the mechanisms of heat transfer occurring in the two canned food containers?

2. Food packaging

This chapter is devoted to food packaging and its importance in the food supply chain. It first presents the main functions of packaging, including the protection, preservation, transportation, and promotion of food products. It then describes the different packaging materials used in the food industry, such as glass, metal, paperboard, and plastics, highlighting their properties, advantages, and limitations. Finally, it addresses food labeling requirements by detailing the mandatory information displayed on packaging, including the product name, ingredient list and quantities, allergens, net quantity, expiration date, batch number, specific storage and usage conditions, nutritional information, and barcode.

2.1. History and evolution of food packaging.

The use of packaging dates back to the earliest human civilizations, when natural materials such as animal skins, plant leaves, wooden baskets, and pottery were used to contain, protect, and transport food. Over time, technological progress led to the development of new packaging materials (figure 40). The first glass bottles appeared approximately 2,000 years ago, while paper packaging emerged nearly two centuries ago. Tinplate cans were introduced about 150 years ago, whereas plastics, which are now widely used in the food industry, appeared around 70 years ago.

With scientific and technological advances, the food packaging industry has undergone remarkable development to meet the growing needs for food preservation, distribution, and marketing. Today, packaging performs many functions that go far beyond the simple protection of food. It also contributes to consumer information, product attractiveness, regulatory compliance, and the extension of shelf life.

Furthermore, the materials used in packaging manufacture are highly diverse. They include single materials such as wood, glass, metals, and paperboard, as well as multilayer and composite materials that combine several materials to optimize the mechanical, barrier, and functional properties of the packaging.

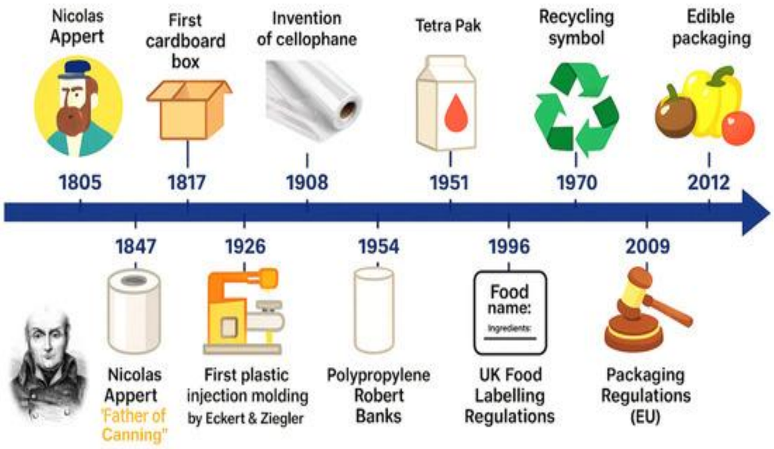


Figure 40. Historical evolution of food packaging (Davidescu et al., 2025).

2.2. Definition

Packaging is a material or a set of materials intended to contain, protect, preserve, transport, and present a product throughout the distribution chain, from its production to its consumption. In the food industry, it also plays an essential role in preserving food quality and safety, as well as in providing information to consumers.

Food packaging can be classified into different levels according to its role in the packaging and distribution chain, namely primary, secondary, and tertiary packaging, each performing specific functions of protection, grouping, and transportation of products.

2.3. Levels of packaging

Food packaging can be classified into different levels (figure 41) according to its role in the packaging and distribution chain, namely primary, secondary, and tertiary packaging, each performing specific functions of protection, grouping, and transportation of products.

Figure 41. Levels of packaging (Marsh et al., 2007).

2.3.1. Primary packaging

Primary packaging is the packaging that is in direct contact with the food product. It represents the first barrier between the product and the external environment. Its main role is to provide immediate protection of the food against microbiological, chemical, and physical contamination, while preserving its sensory and nutritional properties. It also helps extend shelf life by limiting exchanges with the external environment (oxygen, moisture, light). In addition, it carries essential information for the consumer, such as ingredients, expiration date, and storage conditions. Common examples include milk bottles, canned foods, biscuit packages, and meat trays.

2.3.2. Secondary packaging

Secondary packaging groups several units of primary packaging together in order to facilitate handling, storage, and distribution. It does not come into direct contact with the food product, but it plays an important role in logistics and in the commercial presentation of products. This packaging helps protect individual units from mechanical shocks and damage during transport or shelf display. It also facilitates inventory management and improves product organization at points of sale. Examples include cartons containing multiple yogurt pots, packs of bottled water, or boxes containing several canned products.

2.3.3. Tertiary packaging

Tertiary packaging is used to group large quantities of packaged products in order to facilitate their transport and large-scale storage. It is mainly intended for logistics operations and does not directly concern the end consumer. This type of packaging ensures product protection over long distances and allows for optimized handling, particularly in warehouses and during distribution. It also helps reduce the risk of damage and improves transport efficiency. Common examples include palletized and stretch-wrapped loads, transport crates, and containers used in supply chains.

2.4. Role of food packaging

Packaging serves two main roles: a technical role related to food preservation, and a marketing role aimed at enhancing product attractiveness and increasing sales.

2.4.1. Technical functions of packaging

2.4.1.1. Food protection

Packaging primarily ensures a function of protecting food against external influences. It helps preserve hygienic quality by limiting microbiological, chemical, and physical contamination. It also contributes to maintaining the nutritional quality and organoleptic characteristics of the product, such as taste, odor, texture, and appearance, by preventing environmental-related deterioration.

2.4.1.2. Mechanical protection and distribution

Packaging plays an important role in the mechanical protection of food throughout the different stages of the supply chain. It protects products from shocks, vibrations, and stresses related to transportation, storage, and handling. It therefore facilitates distribution and allows products to withstand the numerous manipulations they undergo before consumption.

2.4.1.3. Safety and inertness of packaging

Packaging must be inert, meaning it should not interact with the food. It must not release substances that could migrate into the product, such as certain heavy metals (lead, tin) or compounds derived from plastics (vinyl chlorides). Although the risk is limited, such migration may alter the taste or odor of foods and pose health risks. For this reason, strict regulations govern the materials allowed for food contact in order to ensure their safety.

2.4.2. Marketing functions of packaging

The marketing functions of packaging play an essential role in enhancing product value and influencing consumer behavior. They help make the product visible, attractive, and easily identifiable at the point of sale, while also facilitating its use and strengthening its market positioning.

2.4.2.1. Alert and attractiveness function

The alert function aims to make the product quickly noticeable and to attract the consumer's attention. This is achieved through the use of colors, shapes, graphics, innovative materials, and original designs. These visual elements play a key role in differentiating the product from competitors and strongly influence the consumer's choice at the point of sale.

2.4.2.2. Information function

Packaging also performs an information function by providing the consumer with a set of essential data about the product. This includes, in particular, the composition, nutritional values, expiration date, storage conditions, and usage instructions. This function contributes to product transparency and helps the consumer make an informed choice.

2.4.2.3. Service function

The service function concerns the entire supply chain, from distribution to the consumer's use of the product. Packaging should therefore facilitate handling, manipulation, and use of the product. It may also include practical features such as easy-open systems, resealability, or portioning devices, thereby improving user convenience.

2..4.2.4. Positioning function

The positioning function makes it possible to situate the product in relation to its competitors in terms of quality, price, and image. Packaging plays an important role in shaping the perceived product level. For example, elegant, well-designed, and refined packaging is often associated with luxury products, thereby reinforcing their high-end positioning.

2.4.2.5. Attribution function

Packaging also makes it possible to associate the product with a specific universe through visual codes such as colors, shapes, and symbols. These elements facilitate the quick identification of the product by the consumer. For example, oil bottles are often yellow in color, which allows them to be easily recognized on the shelf even before reading the information.

2.5. Different packaging materials

In the food industry, different packaging materials are used to ensure the protection, preservation, and quality of food throughout the supply chain.

2.5.1. Glass packaging

Glass packaging includes a wide range of containers such as bottles, vials, jars, pots, glasses, and cups, allowing it to cover many types of food and beverage products (figure 42).

Figure 42. Types of glass packaging used in the food industry (Source: author).

In the food industry, it is widely used due to its numerous advantages. Indeed, glass is a material that is impermeable to gases, vapors, and liquids, ensuring excellent product protection. It is also chemically inert toward food products, preventing any compatibility issues or substance migration. Moreover, it is a hygienic and bacteriologically inert material that does not promote the growth of microorganisms and is easy to wash and sterilize. Glass has neither odor nor taste and does not alter the sensory properties of food. Being transparent, it allows visual inspection of the product, and it can also be colored to provide protection against ultraviolet rays that may degrade food quality. Furthermore, it is fully recyclable and can be used for reheating food due to its compatibility with microwaves. However, glass packaging also has some disadvantages, particularly its fragility and breakability, its relatively high weight, and its limited protection against light when it is transparent.

2.5.2. Metal packaging

Metal packaging is widely used in the food industry in various forms, including canned food containers, beverage cans, aluminum trays, as well as caps and sealing lids. It is mainly made from steel or aluminum, two materials that provide an excellent barrier against external agents (figure 43).

Figure 43. Types of metal packaging used in the food industry (Source: author).

This type of packaging plays a key role in food preservation, as it is completely impermeable to gases, light, moisture, and microorganisms, which helps maintain product quality and safety over long storage periods. In addition, it provides good mechanical strength, protecting food from shocks during transport and storage.

Metal packaging is also compatible with thermal sterilization processes, making it particularly suitable for canned products.

However, it also has some disadvantages, such as its relatively high weight (in the case of steel), production cost, and the risk of corrosion if it is not properly treated or coated. Despite this, it remains widely used due to its reliability and excellent protective properties.

2.5.3. Plastic packaging

Plastic packaging represents a major share of the materials used in the food industry due to its advantageous properties. Indeed, plastics are characterized by their light weight, with a density generally ranging from 0.9 to 1.8, which makes it possible to obtain much lighter packaging than metal while performing similar functions. They also offer good mechanical strength, ensuring product protection during transport and handling. Some plastics provide excellent transparency, with a light transmission coefficient close to that of glass, allowing good product visibility. From an aesthetic point of view, they are distinguished by a wide variety of colors and shaping possibilities, thus meeting marketing and presentation requirements. Finally, plastic materials have good thermal, electrical, and acoustic insulation properties, as well as effective impermeability to gases and water, which contributes to food preservation and protection.

2.5.4. Cellulosic packaging

Cellulosic packaging is a type of packaging made from cellulose, the main component of plant fibers, particularly those derived from wood or plants. It includes various materials such as paper, cardboard, and cellulosic films, which are widely used in the food industry (figure 44).

This type of packaging is valued for being natural, renewable, and biodegradable, making it an attractive alternative to conventional plastics. It is mainly used for packaging dry products, fruits and vegetables, as well as for transport cartons and secondary packaging.

Cellulosic packaging offers several advantages. It is lightweight, easily recyclable, and provides good rigidity and printability properties, allowing effective visual communication of the product. It can also be treated or combined with other materials to improve its resistance to moisture and grease.

However, it also has limitations, particularly its poor barrier properties against water and gases, which can reduce its preservation capacity without specific treatments. It is also mechanically less resistant than some plastic or metal materials when exposed to moisture.

Thus, cellulosic packaging plays an important role in sustainable packaging strategies due to its natural origin and low environmental impact, although it still requires improvements for certain food applications.

Figure 44. Types of cellulosic packaging used in the food industry (Source: author).

2.6. Food labeling

Food labeling refers to all the information and indications displayed on a food product or provided on any accompanying medium. It is an essential communication tool that enables consumers to understand the product’s characteristics, composition, nutritional qualities, storage conditions, instructions for use, and origin. According to Algerian Law No. 09-03 of February 25, 2009, relating to consumer protection and fraud prevention, labeling includes all mentions, writings, marks, labels, images, illustrations, or other signs relating to a product, regardless of the medium used (JORADP, 2009). Executive Decree No. 05-484 further specifies that

- A label refers to any tag, mark, image, or descriptive material affixed to or accompanying

the packaging, while

- A claim is defined as any statement suggesting that a food product possesses particular

properties or qualities related to its origin, composition, nutritional value, or processing method (JORADP, 2005).

Therefore, food labeling plays a fundamental role in consumer protection by ensuring that clear, reliable, and transparent information is provided about products placed on the market.

2.6.1. Role of food labeling

Food labeling plays a key role in communication between producers and consumers. It is the main source of information that enables consumers to make informed choices when purchasing food products (figure 45).

- First, it serves an informational function by providing details about the nature of the product, its composition, ingredients, nutritional value, net weight, date of minimum durability or expiration date, as well as storage and usage conditions. This information helps consumers use the product properly and safely.
- Food labeling also fulfills a public health protection function. The indication of allergens, food additives, storage conditions, and usage precautions helps prevent health risks and protects individuals who are sensitive or have food allergies.
- In addition, it plays an important role in food traceability by indicating the product's origin, the name and address of the manufacturer or distributor, and information that identifies production batches. This traceability facilitates product monitoring and recalls in case of health issues.
- Labeling also has a commercial and marketing function. Through brands, logos, quality labels, nutritional or health claims, and packaging design, it enhances product value and influences consumers' purchasing decisions.
- Finally, food labeling is a regulatory compliance tool, allowing manufacturers to meet legal requirements related to consumer information, food safety, and the prevention of fraudulent practices

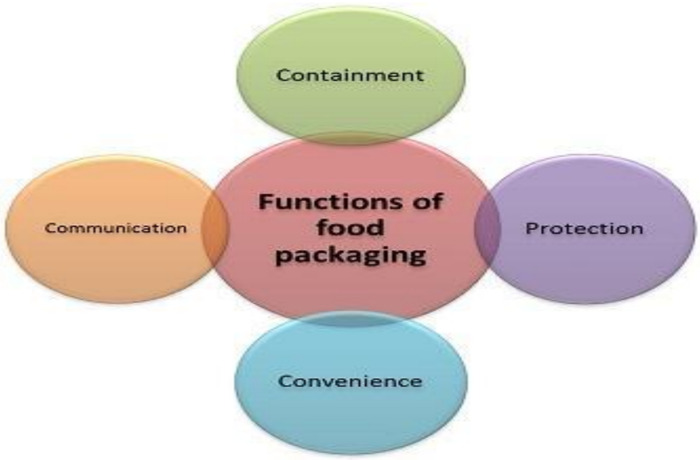


Figure 45. Role of food labeling (Source: author).

2.6.2. Food labeling information

Food labeling information" refers to all written or printed information (figure 46) on a food product's packaging. This information allows consumers to better understand the product before purchasing and consuming it. It includes both mandatory and optional labeling statements.

2.6.2.1. Mandatory food labeling

Mandatory food labeling information includes all essential information appearing on food product packaging in order to ensure transparency and consumer safety.

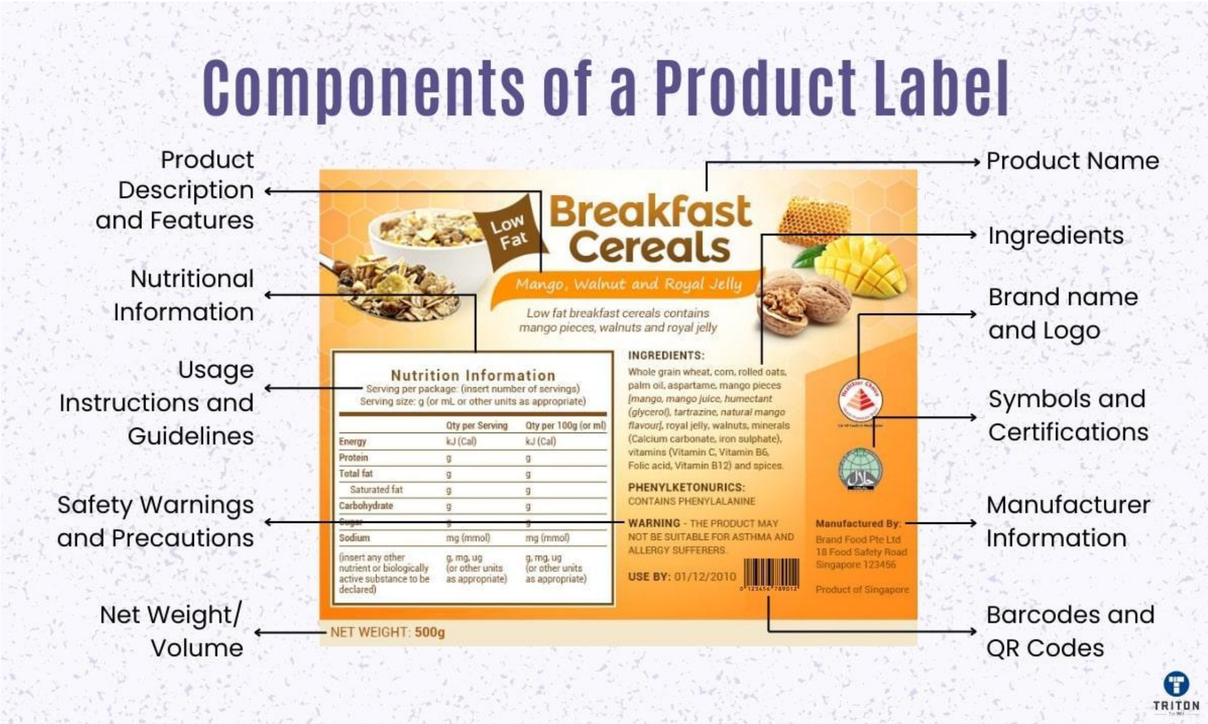


Figure 46. Food labeling information

A. Sales denomination

The sales denomination refers to the official name that describes a food product, specifying its nature as well as the treatments it has undergone during its preparation. It must be stated clearly, precisely, and unambiguously in order to properly inform the consumer about the true identity of the product. For example, it may take the form of "dehydrated tomato soup," "frozen peeled chestnuts," or "pasteurized semi-skimmed milk," thus making it possible to easily distinguish the product's essential characteristics.

B. List of ingredients

The list of ingredients includes all the substances used in the manufacture of a food product. These ingredients are usually listed on the packaging in descending order of their quantity. In addition, allergens are highlighted, often in bold, so that they can be easily identified by at-risk individuals and to help prevent any health risks.

C. Net quantity

The net quantity of a product must be clearly indicated on its packaging, either in volume or in mass. For foods preserved in liquid, such as canned green beans, it is necessary to indicate both the total weight of the product and the drained net weight, in order to reflect the actual amount of edible food.

D. Consumption date

The consumption date indicates the period during which the product retains its specific properties. It must also specify the storage conditions of the food product.

E. Batch number

The batch number is a code that ensures the traceability of each product. It thus facilitates the identification of products in the event of a defect, recall, investigation, or complaint. This number must be provided to the manufacturer in case of any request for information or complaint.

F. Identification of the manufacturer

The identification of the manufacturer, packer, or seller allows the consumer to know the operator responsible for placing the product on the market. The information provided must include the company's name and address in order to ensure clear traceability and transparency.

G. Instructions for use

The instructions for use, conditions of use, or usage guidelines specify how food products should be used and stored. This information must be clearly, visibly, and legibly indicated on the packaging. It is particularly important for products such as pizzas, frozen foods, or ready-made meals, in order to ensure proper use and adequate preservation.

H. Place of origin

The place of origin or provenance indicates the country or geographical area from which a food product comes. This information is not mandatory for all consumable products. However, it becomes compulsory in certain cases, particularly for prepacked food products such as pork, sheep, goat, or poultry meat, for which the places of rearing and slaughter must be specified. For beef, the indication of the place of birth is also required.

Additional mandatory food labeling

There are also additional mandatory labelling statements, which complement the labelling information. These are summarized in figure 47.

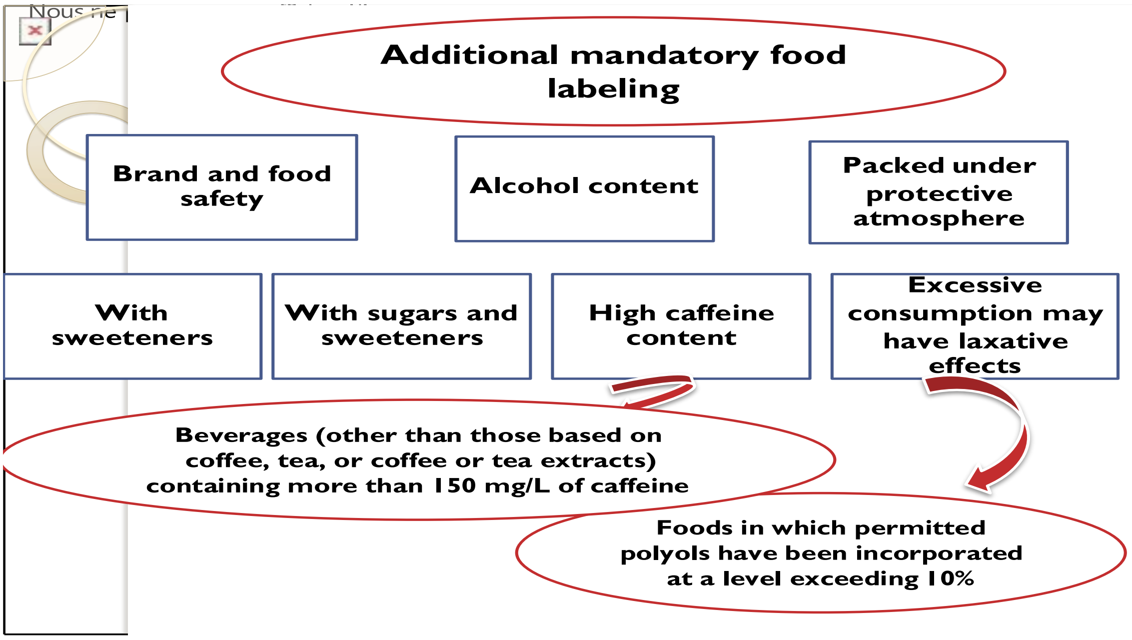


Figure 47. Additional mandatory food labeling (Source: author).

2.6.2.2. Optional food labeling

Optional information is information that may appear on the labeling of a food product, but which is not required by regulations. It is voluntarily added by the manufacturer to provide additional information to the consumer.

They may include:

A. The barcode corresponds to labels made up of numbers and successive black bars that allow the product to be scanned when shopping. This code also provides information about the product's origin.

The first digit corresponds to the country of origin, the next five digits to the product code, the following five digits to the manufacturer code, and the last digit is the check digit (figure 48).

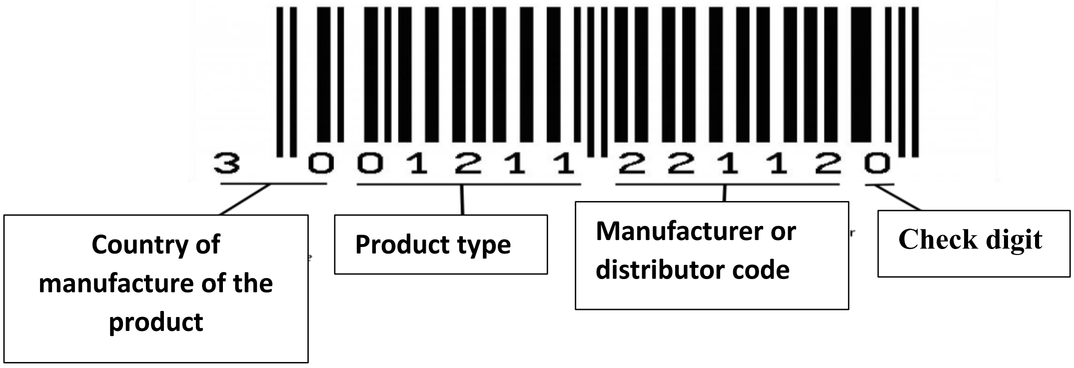


Figure 47. The barcode (Source: author).

B. Brand

Producers are not required to display their brand on packaging. However, doing so allows them to personalize their product and stand out from the competition.

C. Quality labels

Quality labels are official or private signs displayed on food products to guarantee specific characteristics related to their quality, origin, production method, or compliance with particular standards. They serve as a means of enhancing the value of products and informing consumers about their distinctive features. Quality labels certify that a product complies with a specific set of requirements and has been subjected to inspections by competent authorities or certification bodies. They therefore help strengthen consumer confidence and facilitate purchasing decisions. Table 13 presents some official quality labels.

Table 13. Official quality labels (Scarset, 2008).

Names	Meaning	Official signs
Red Label	It certifies that a product has specific predefined characteristics that give it superior quality	Label Rouge
Protected Designation of Origin	It guarantees the consumer that all stages of production take place within the designated geographical area of the appellation.	Appellation d'Origine Protégée
Protected Geographical Indication	It guarantees a link with the geographical origin at least at one stage of production, processing, or preparation.	Indication Géographique Protégée
Traditional Specialities Guaranteed	It certifies that a product is made according to a traditional recipe.	Spécialité Traditionnelle Garantie
Organic farming	It applies to products in which at least 95% by weight of the agricultural ingredients are organic.	AB
Halal Certificate of Conformity	It is a distinctive national collective mark owned by IANOR (Algerian Institute of Standardization), certifying compliance with Algerian standards specifying the requirements for Halal products.	Halal Certification Services حلال HALAL CERTIFIED

D. Nutrition labeling

Nutrition labeling refers to all the information displayed on a food product's packaging that indicates its nutritional composition. It allows consumers to know the energy value and nutrients contained in the food in order to make more informed choices.

E. Nutri-Score

The Nutri-Score is a rating system that ranges from A to E and provides an indication of the nutritional quality of a product.

F. Claims

Claims are statements displayed on food labels that are intended to inform consumers or highlight certain characteristics of a product. They can be classified into three main categories (figure 49):

- **general claims**, which emphasize an overall quality of the product without specific reference to its composition or health effects;
- **nutrition claims**, which describe the nutritional properties of a food, such as its energy, protein, fiber, or fat content;
- **health claims**, which indicate a relationship between the consumption of a food or nutrient and a health benefit. These different types of claims are important sources of information for consumers and help guide their food choices.

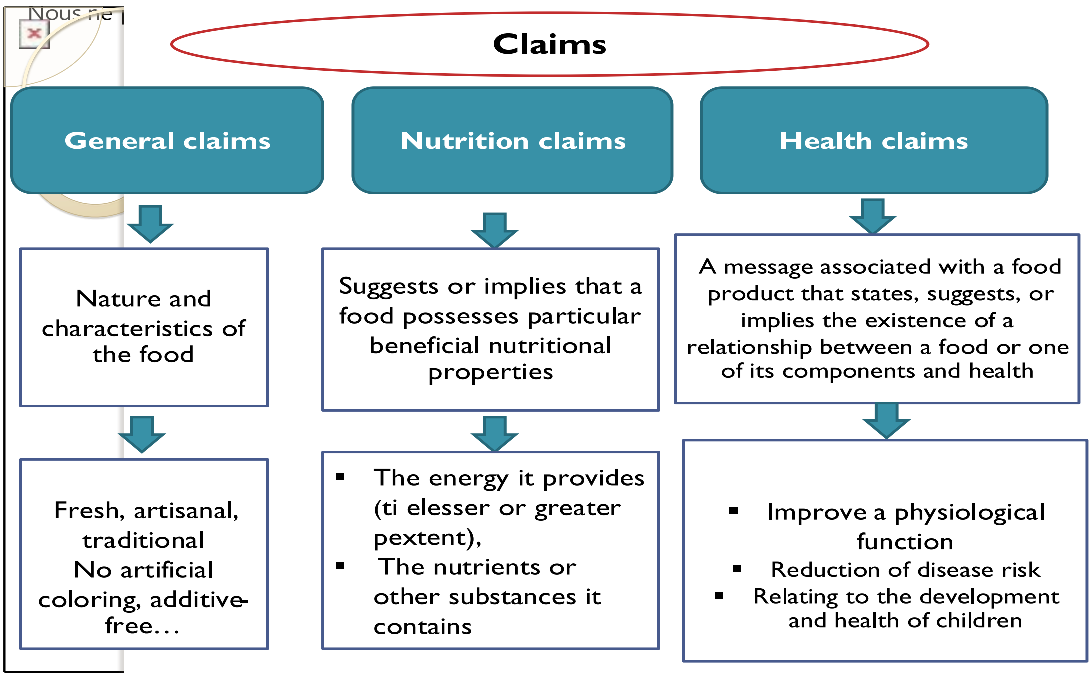


Figure 49. Types of food claims (Source: author).

2.7. Active and intelligent packaging

Intelligent and active packaging are two types of innovative packaging designed to improve food quality, safety, and shelf life (figure 50).

- **Active packaging** acts directly on the product or its internal environment in order to slow down degradation processes. For example, it can absorb oxygen, regulate humidity, or release antimicrobial substances, thereby helping to preserve freshness and limit the growth of microorganisms.
- **Intelligent packaging** does not directly interact with the product itself, but provides a monitoring function. It incorporates devices capable of indicating temperature changes, detecting spoilage, or signaling freshness status through visual indicators or sensors. Thus, these two technologies are complementary: one works to maintain product quality, while the other provides information about its condition, contributing to improved food safety and reduced losses.

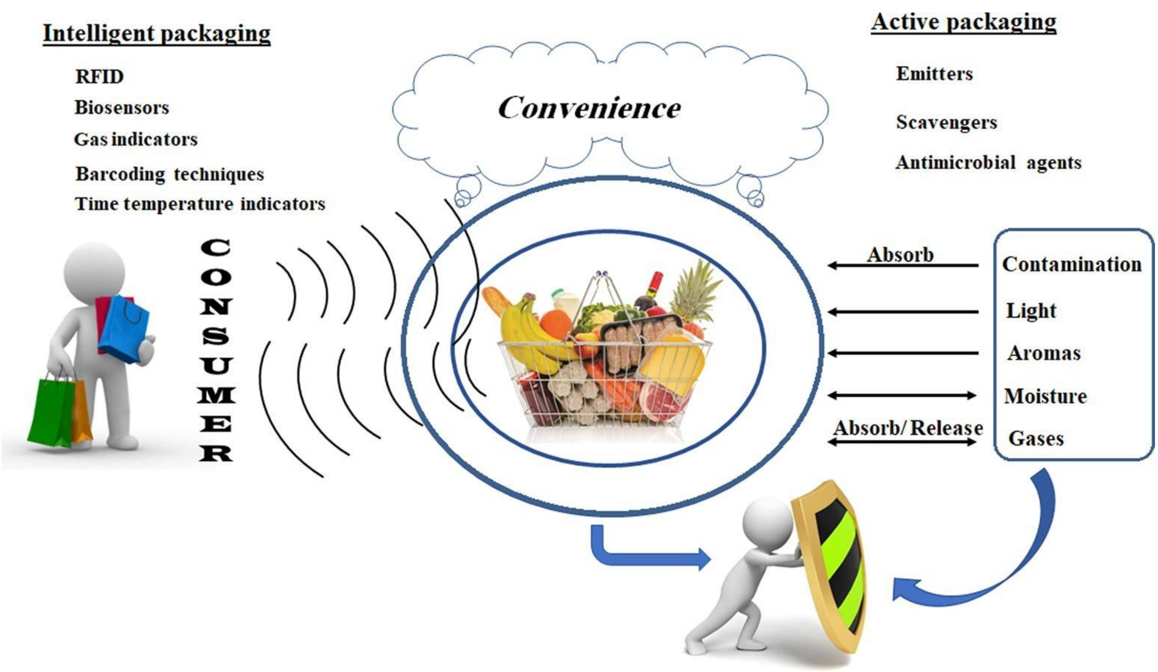
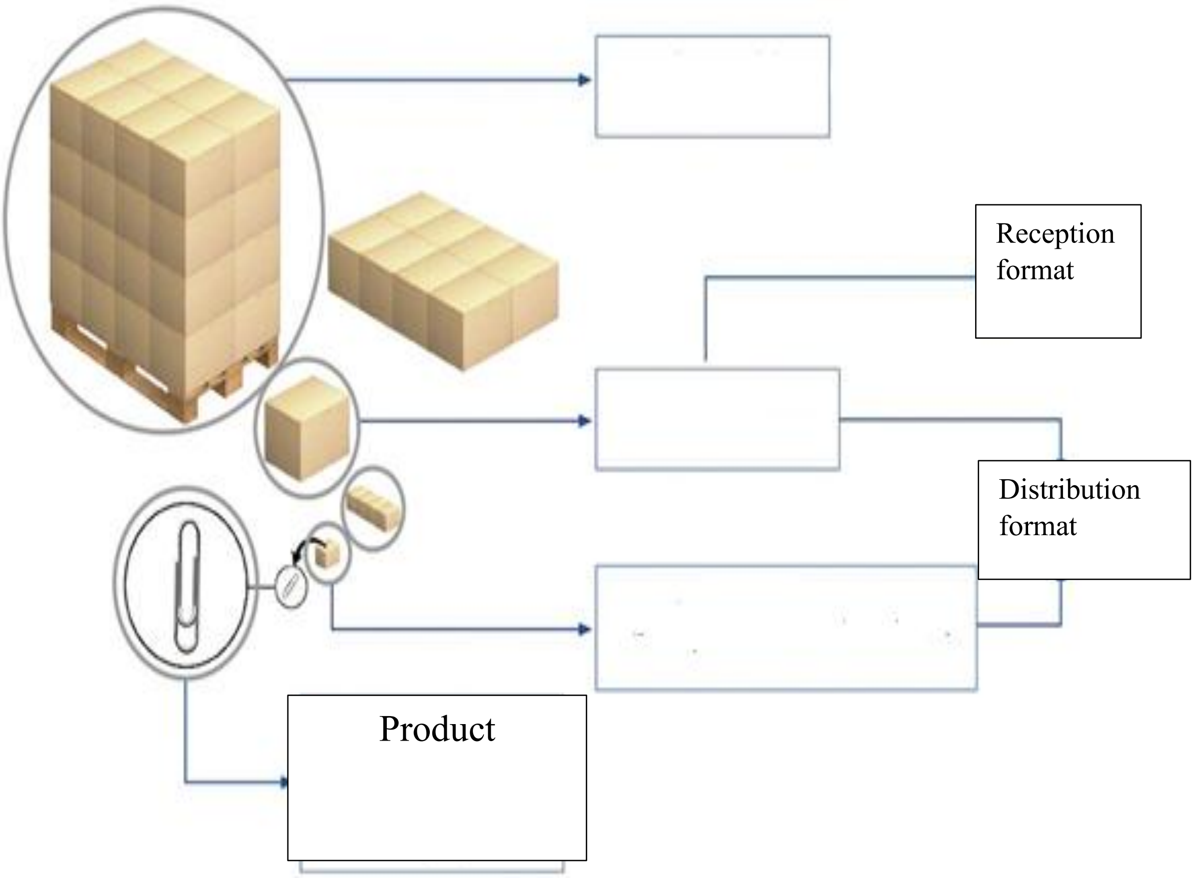


Figure 50. Representation of the functions of intelligent and active packaging (Firouz et al., 2021).

2.7.Examples of application

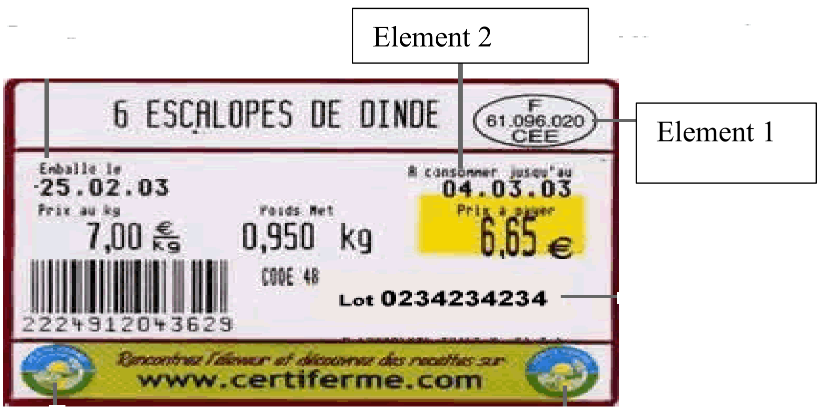
Question 1:

Indicate the levels of food packaging shown in the following figure.



Question 2:

1. Based on your knowledge, what is the element that ensures the traceability of a food product?
2. What does element 1 in Figure 1 represent and what is its role?
3. What does element 2 in Figure 1 represent?



Food preservation and packaging technologies are essential components of modern food systems, contributing significantly to food safety, quality maintenance, shelf-life extension, and the reduction of post-harvest and processing losses. The continuous development of preservation methods, ranging from conventional techniques to emerging technologies, reflects the growing need to meet consumer expectations while ensuring compliance with regulatory and quality requirements.

The choice of an appropriate preservation method depends on several factors, including the nature of the food product, its physicochemical and microbiological characteristics, economic considerations, and the desired shelf life. Likewise, the selection of packaging material and system must ensure adequate protection of the product while facilitating its distribution, marketing, and consumer information.

Through the study of preservation processes, packaging materials, food labeling, and recent innovations such as active and intelligent packaging, students acquire the scientific and technological foundations necessary to understand, control, and optimize food preservation systems. These competencies are fundamental for future professionals involved in food production, quality assurance, food safety management, and research and development in the agri-food sector.

Ultimately, mastering food preservation and packaging technologies not only contributes to improving food quality and safety but also supports sustainable food systems and strengthens food security in a constantly evolving global context.

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