People's Democratic Republic Of Algeria
Ministry Of Higher Education And Scientific Research
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Faculty Of Natural And Life Sciences
Department Of Biotechnology

TECHNOLOGY OF FOOD INDUSTRY II

Target: L3 Food Biotechnology " 2nd Semester

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Overview

This module is meticulously designed to equip students with a robust scientific and technological foundation essential for navigating the complexities of the modern food industry. It comprehensively explores the technological principles underpinning the transformation of diverse agricultural and animal raw materials into safe, nutritious, high-quality, and commercially viable food products. The curriculum is structured around three pivotal sectors: cereal technology, fruit and vegetable technology, and meat and fish technology.

The initial segment of the module delves into cereal technology, commencing with an introduction to the classification of cereal sectors and their global and regional significance, particularly within Algeria. Students will gain an in-depth understanding of the intricate structure and biochemical composition of cereal grains. A significant focus is placed on wheat, examining the unique properties of its proteins, the sequential steps of primary processing (including cleaning, conditioning, and milling), and the industrial transformations that yield staple products such as bread, pasta, and couscous. Furthermore, this section meticulously covers established methodologies for assessing wheat quality, differentiating between soft and durum varieties, and evaluating their suitability for various applications through baking, semolina, pasta, and couscous value assessments.

The second part is dedicated to fruit and vegetable technology, providing students with critical insights into the biochemical composition of these perishable commodities, their post-harvest physiology, and the multifactorial influences on their quality during storage and transportation. It elucidates key quality criteria, referencing international standards such as those from the EU and Codex Alimentarius. The module then transitions to advanced processing technologies, encompassing both thermal methods (e.g., pasteurization, sterilization, drying) and innovative non-thermal approaches (e.g., High-Pressure Processing (HPP), irradiation, UV treatment, biopreservation). Emphasis is also placed on the development of processed products, the sustainable valorization of by-products, contemporary packaging technologies (materials and innovative processes), rigorous quality control techniques, sensory analysis, and the imperative role of innovation and sustainability in shaping the future of this sector.

The concluding section of the module addresses meat and fish technology. It offers a comprehensive overview of the composition and structural characteristics of meat, detailing the

slaughter processes for various animal species and the subsequent processing and valorization of by-products, including the economically significant fifth quarter. The module also covers the distinct composition and nature of fish. Students will explore diverse cold preservation methods, such as refrigeration, freezing, and quick freezing, applicable to both meat and fish. Finally, this part examines third-stage meat products, with a particular focus on Algerian processing technologies (cooking, mincing, curing) and the intricate structuring of fine pastes (e.g., pâté, cachir), alongside the preservation techniques for fish products like sardines and tuna.

Upon successful completion of this module, students will be proficient in identifying the critical characteristics of raw materials, comprehending complex industrial transformation operations, and accurately evaluating product quality. They will recognize the paramount importance of hygiene, safety, appropriate packaging, and continuous innovation in food processing. Moreover, the module prepares students to critically analyze and address contemporary industrial challenges, including sustainability, efficient by-product recovery, strategic product diversification, and dynamic adaptation to evolving consumer expectations.

Prerequisites

Students enrolling in this course are expected to have a solid background in the basic sciences, particularly in chemistry, biochemistry, microbiology, physics, thermodynamics, and energy principles. These prerequisites are important for understanding the composition of raw materials, the mechanisms of food processing, heat and mass transfer, microbial control, and the technological transformations involved in cereal, fruit and vegetable, meat, and fish industries.

Information about this course

Target: Third year (food Biotechnology)

Coefficient: 3

Semester: 2nd (UE fundamentals)

Global Hourly volume: 67 h30

List of abbreviations

Abbreviation	Signification
1-MCP	1-Methylcyclopropene (1-Méthylcyclopropène)
a*	Red-green axis (Axe rouge-vert)
ABTS	2,2'-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)
ALC	Adherent Liquid Coating (Revêtement liquide adhérent)
AMP	Adenosine Monophosphate (Adénosine monophosphate)
ATP	Adenosine Triphosphate (Adénosine triphosphate)
Aw	Water Activity (Activité de l'eau)
b*	Yellow-blue axis (Axe jaune-bleu)
BPA	Bisphenol A (Bisphénol A)
CA	Controlled Atmosphere (Atmosphère contrôlée)
CIE	Commission Internationale de l'Éclairage
cm³	Cubic centimeter (Centimètre cube)
CO2	Carbon Dioxide (Dioxyde de carbone)
CO2TR	Carbon Dioxide Transmission Rate (Taux de transmission de CO2)
DCPIP	2,6-Dichlorophenolindophenol
DFD	Dark Firm Dry (Foncé, ferme, sec)
DHA	Docosahexaenoic Acid (Acide docosahexaénoïque)
DPPH	2,2-Diphenyl-1-picrylhydrazyl
EC	Electrochemical (Électrochimique)
ELISA	Enzyme-Linked Immunosorbent Assay
EMAP	Equilibrium Modified Atmosphere Packaging
EPA	Eicosapentaenoic Acid (Acide eicosapentaénoïque)
EU	European Union (Union européenne)
EVOH	Ethylene Vinyl Alcohol (Alcool vinylique d'éthylène)
F0	Lethality value (Valeur de létalité - stérilisation)
FAO	Food and Agriculture Organization
FRAP	Ferric Reducing Antioxidant Power
g	Gram (Gramme)
GAE	Gallic Acid Equivalents (Équivalents d'acide gallique)
GC-MS/MS	Gas Chromatography-Tandem Mass Spectrometry
GPC	Gel Permeation Chromatography
h	Hour (Heure)
HDPE	High-Density Polyethylene (Polyéthylène haute densité)
HHP	High Hydrostatic Pressure (Haute pression hydrostatique)
HMW-GS	High Molecular Weight Glutenin Subunits
HPLC	High-Performance Liquid Chromatography
HPP	High-Pressure Processing (Traitement sous haute pression)
HT	High Temperature (Haute température)
HTST	High-Temperature Short-Time (Haute température, courte durée)
HVK	Hard Vitreous Kernels (Grains vitreux durs)
Hz	Hertz
IQF	Individually Quick Frozen (Surgelé individuellement rapide)
ISO	International Organization for Standardization
kg	Kilogram (Kilogramme)
kGy	KiloGray (Kilogray - unité de dose d'irradiation)
kJ/m²	KiloJoule per square meter
L	Liter (Litre)
L*	Lightness (Clarté)
LAB	Lactic Acid Bacteria (Bactéries lactiques)
LC-MS/MS	Liquid Chromatography-Tandem Mass Spectrometry
LLE	Liquid-Liquid Extraction (Extraction liquide-liquide)
LMW-GS	Low Molecular Weight Glutenin Subunits
LOD	Limit of Detection (Limite de détection)
LOQ	Limit of Quantification (Limite de quantification)
LOX	Lipoxygenase (Lipoxygénase)

LTLT	Low-Temperature Long-Time (Basse température, longue durée)
m/s	meters per second (mètres par seconde)
mA	milliAmpere (milliampère)
MA	Modified Atmosphere (Atmosphère modifiée)
MAP	Modified Atmosphere Packaging (Emballage sous atmosphère modifiée)
mg/kg	milligrams per kilogram
min	Minute
mL	milliLiter (millilitre)
MPa	MegaPascal (Mégapascal)
MRLs	Maximum Residue Limits (Limites maximales de résidus)
MSPD	Matrix Solid-Phase Dispersion
Mt	Million tons (Millions de tonnes)
MTI	Mixing Tolerance Index (Indice de tolérance au pétrissage)
mTorr	milliTorr (millitorr)
NFC	Not-From-Concentrate (Non concentré)
ng/kg	nanograms per kilogram
NIR / NIRS	Near-Infrared / Near-Infrared Spectroscopy
NIRT	Near-Infrared Transmission
nm	Nanometer (Nanomètre)
OTR	Oxygen Transmission Rate (Taux de transmission d'oxygène)
P/L	Tenacity/Extensibility Ratio (Rapport ténacité/extensibilité)
PA	Polyamide (Polyamide)
PE	Polyethylene (Polyéthylène)
PEF	Pulsed Electric Field (Champ électrique pulsé)
PLA	Polylactic Acid (Acide polylactique)
PME	Pectinmethylesterase (Pectinestérase)
POD	Peroxidase (Peroxydase)
PP	Polypropylene (Polypropylène)
ppm	parts per million (parties par million)
PPO	Polyphenol Oxidase (Polyphenoloxydase)
ppt	parts per trillion (parties par billion)
PSD	Particle Size Distribution (Distribution granulométrique)
PSE	Pale Soft Exudative (Pâle, mou, exsudatif)
PVC	Polyvinyl Chloride (Chlorure de polyvinyle)
Q10	Temperature coefficient (Coefficient de température)
QR	Quick Response (Code QR)
R/E	Resistance/Extensibility (Résistance/Extensibilité)
RFID	Radio-Frequency Identification
RH	Relative Humidity (Humidité relative)
rpm	Revolutions Per Minute (Tours par minute)
RVA	Rapid Visco Analyser (Analyseur viscosimétrique rapide)
s	Second (Seconde)
SDS	Sodium Dodecyl Sulfate (Dodécylsulfate de sodium)
SFE	Supercritical Fluid Extraction
SPE	Solid-Phase Extraction (Extraction en phase solide)
SPME	Solid-Phase Micro-Extraction
SPS	Sanitary and Phytosanitary (Sanitaire et phytosanitaire)
SRC	Solvent Retention Capacity (Capacité de rétention de solvant)
SSC	Soluble Solids Content (Teneur en solides solubles)
STEC	Shiga Toxin-Producing Escherichia coli
t/ha	tons per hectare (tonnes par hectare)
TA	Titratable Acidity (Acidité titrable)
THT	Très Haute Température (Very High Temperature)
TKW	Thousand Kernel Weight (Poids de mille grains)
TPC	Total Plate Count (Dénombrement sur plaque)
TTIs	Time-Temperature Indicators (Indicateurs temps-température)

TVB-N	Total Volatile Basic Nitrogen (Azote basique volatile total)
TVC	Total Viable Count (Dénombrement total des germes viables)
UAE	Ultrasound-Assisted Extraction (Extraction assistée par ultrasons)
UHP	Ultra-High Pressure (Ultra-haute pression)
UHT	Ultra-High Temperature (Température ultra-élevée)
Vis/NIR	Visible/Near-Infrared
W	Watt
WAI	Water Absorption Index (Indice d'absorption d'eau)
WHO	World Health Organization
WSI	Water Solubility Index (Indice de solubilité dans l'eau)
WTO	World Trade Organization (OMC)
WVTR	Water Vapor Transmission Rate (Taux de transmission de vapeur d'eau)
°Brix	Degrees Brix (Degrés Brix - teneur en sucres)
°C	Degrees Celsius (Degrés Celsius)
µm	Micrometer (Micromètre)

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Part 1: Cereal Technology

Introduction

The term cereal is a derivative from Latin word 'cerealis' meaning ‘grain’ which is botanically, a type of fruit called a caryopsis, composed of the endosperm, germ, and bran. The cereals are annual common grass members of the grass family, which usually have long, thin stalks, such as wheat, rice, maize, sorghum, millet, barley and rye, whose starchy grains are used as food. The term cereal is not limited to these grains, but also refers to foodstuff prepared from the starchy grains of cereal like flours, breads and pasta.

Cereals have developed their importance as food plants because they are high yielding, with world average yields around three tons per hectare. The grains are very nutritious; generalized cereal grain contents (which will of course vary with species, growing conditions and variety) are: carbohydrates (70%), protein (10%), lipids (3%). Being desiccated at harvest with a water content of about 12%, cereal grains are easy and economical to transport and store. Different cereals have risen to eminence in different quarters of the globe because of geographical provenance and of differing climatic and environmental requirements for growth, but their shared favorable characteristics underline their importance as staple foodstuffs. Three cereals, wheat, maize and rice make up the bulk of world cereal production, but five other cereal crops also make important contributions to world nutrition, and to food and drink production.

1. Classification

Cereals are monocotyledonous plants that mostly belong to the Poaceae family (or Grasses). They are cultivated for their starch-rich grains. They are botanically classified into subfamilies, tribes, and genera, including wheat, barley, oats, rye, corn, rice, sorghum, and millet (Figure 1).

2. Use of cereals in the world

Global cereal production and consumption have experienced sustained growth in recent years, with recent records reached in 2025 thanks to favorable weather conditions and productivity gains.

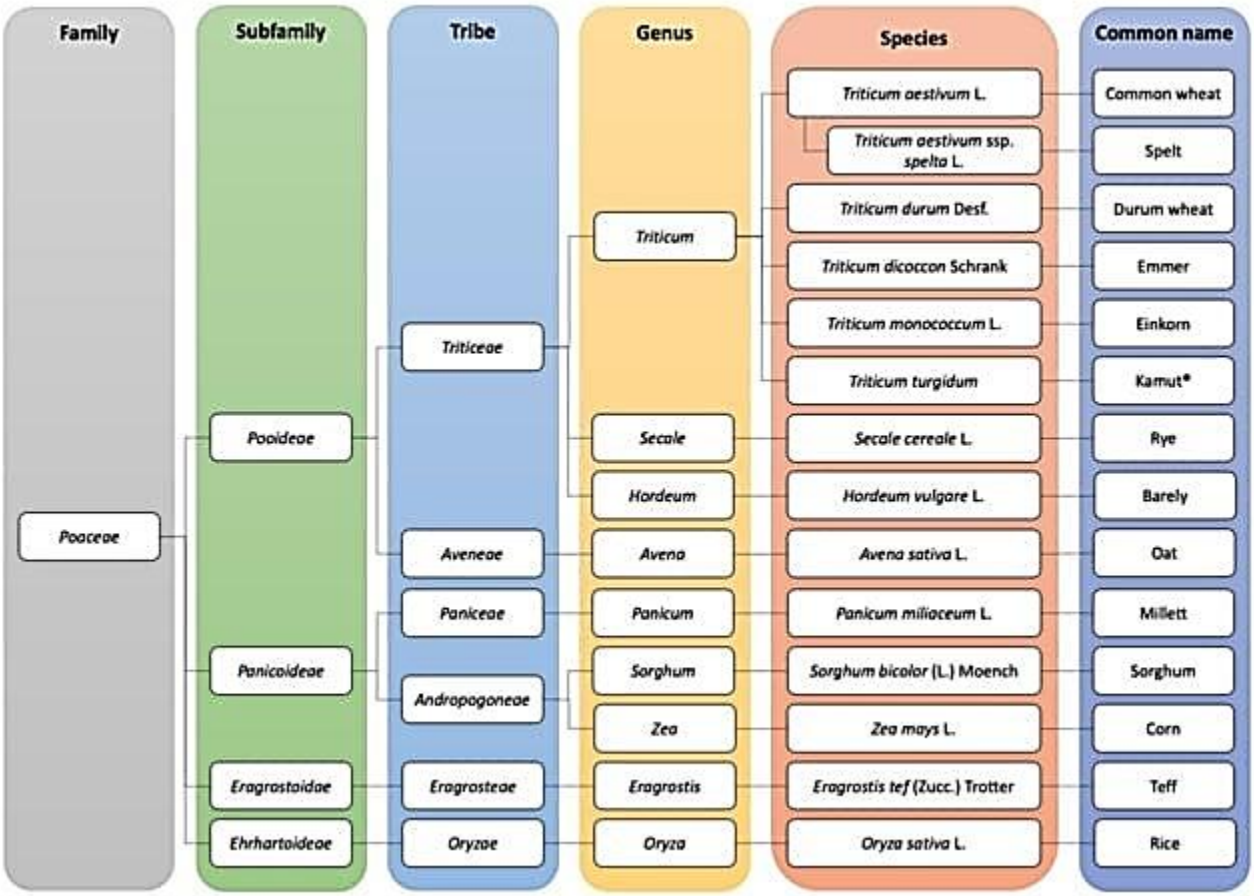

Figure 1: Classification of cereals

In 2025, global cereal production exceeded 3 billion tons for the first time, marking an increase of nearly 5% compared to 2024, driven by record corn (United States, China), wheat (up 5.2% to over 840 Mt), and rice (555.6 Mt) harvests. Global consumption reached a record level of 2,943 Mt in 2025-2026, up by 0.2%, mainly due to increased demand for animal feed (secondary cereals like corn) and human consumption.

In Algeria, cereal cultivation relies on an area of approximately 4 million hectares in 2020, primarily dedicated to wheat, barley, and corn, with a total production reaching 4.5 million tons in 2019, marked by annual variations due to climatic conditions; durum wheat dominates with 3.2 million tons, followed by soft wheat (300,000 tons), barley for animal feed (500,000 tonnes), and corn (200,000 tons).

The main cultivation areas are concentrated in the High Plateaus (Sétif, M'sila, Biskra; 60% of production), the Tell (Tizi Ouzou, Algiers, Oran, Blida; 30%), and the irrigated South (10%) (Figure 2)., but the sector faces major challenges such as an arid climate covering 80% of the territory, low yields (1.5-2 t/ha for durum wheat and 1.2 t/ha for barley, compared to 3-4 t/ha in France or the United States), and post-harvest losses estimated at 20% due to inadequate storage infrastructure

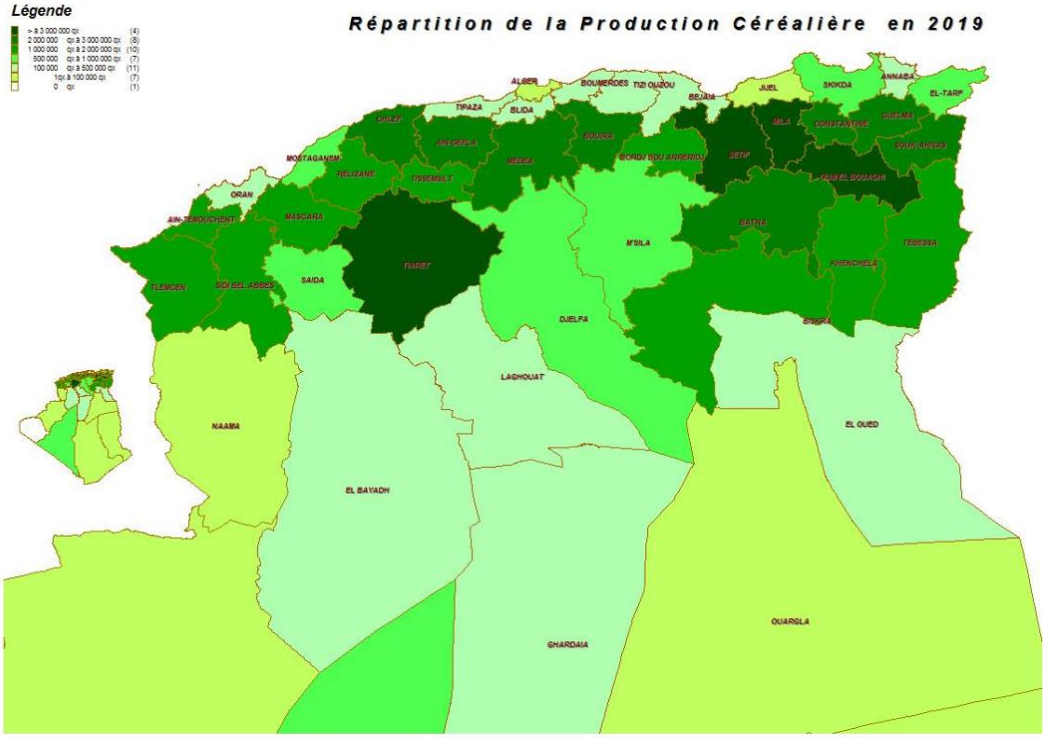

Figure 2: Cereals production in Algeria (2019)

Approximately 55% of the world's cereal production is intended for direct human food and beverages, 36% for animal feed, and 9% for industrial uses, primarily starch production and, increasingly, bioethanol as a vehicle fuel. Table 1 illustrates the wide variety of applications of the main cereals.

Table 1: The major uses of different cereals

Cereal type	Main food uses	Beverage uses	Animal feed	Industrial uses
Barley	Gruels, malt breads, malt extract	Malt for beers and whisky	Cattle, pigs	—
Maize	Breakfast cereals, snacks, gruels, porridges, tortillas, tacos	Brewing/distilling adjuncts	Cattle, companion animals, pigs, poultry	Starch, hydrolyzed starch syrups, bioethanol
Millets	Gruels, porridges, couscous, rice	Malt, non-alcoholic beverages	Poultry, companion birds	—
Oats	Breakfast porridges/cereals, flatbreads, multigrain bakery products, granola bars	—	Cattle, pigs	—
Rice	Rice, noodles, gruels, porridges, confectionery, breakfast cereals, gluten-free foods	Rice wines, distilled liquors, brewing adjunct	Cattle, buffalo	Starch
Rye	Breads, crispbreads	Malt (whisky)	Cattle, pigs, poultry	—
Sorghum	Gruels, porridges, flatbreads, rice, gluten-free bakery products	Malt beverages, malts, adjuncts, distilled liquor, gluten-free beer	Cattle, pigs, poultry, companion birds	—
Triticale	Multigrain bakery products	—	Cattle, pigs	—
Durum wheat	Pasta products, bread	—	—	—
Bread/common wheat	Leavened breads, cakes, muffins, cookies, flatbreads, tortillas, noodles, breakfast cereals, crackers, couscous, pasta products	Malt, brewing adjunct, distilled liquors	Cattle, pigs, poultry	Starch

I. Cereals Grain

I.1. Structure

The cereal grain, or caryopsis (e.g., wheat, corn, barley), has a macroscopic structure organized into three main parts (Figure 3):

- The outer envelopes (pericarp and testa, forming the bran, ~15% of the grain, rich in fibers and minerals),
- The endosperm or albumen (starchy ~80-85%, reserve of starch and proteins for germination),
- The basal germ (embryo + scutellum, ~2-3%, rich in lipids and enzymes), with an elongated oval shape, a ventral groove, and an apical brush.

This organization determines the milling operations and the technological value of the grain.

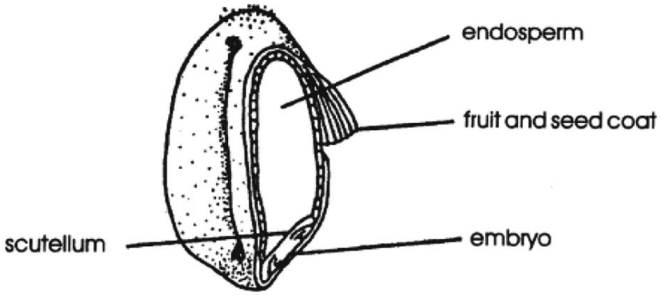

Figure 3: Cereal structure

I. 2. Composition

1.2. 1. Average Composition

Cereals are important staple foods and are also used for animal feed and some industrial applications. Their composition varies by species, but they mainly contain carbohydrates in the form of starch, as well as proteins, lipids, fiber, minerals, vitamins, and bioactive compounds. Starch is the main energy reserve, while cereal proteins are generally rich in glutamine and proline but relatively low in lysine. Lipids are mostly found in the germ and influence technological quality. Vitamins and minerals are concentrated mainly in the bran, germ, and aleurone layer. Cereals also contain bioactive compounds such as β-glucans, phytosterols, and phenolic compounds, which are nutritionally important (Table 2).

Table 2: Chemical composition of some cereals

Grain	Carbohydrate (%)	Protein (%)	Lipid (%)	Total dietary fiber (%)	Sugar (%)
Wheat, hard white	75.90	11.31	1.71	12.2	0.41
Wheat, soft white	75.36	10.69	1.99	12.7	0.41
Durum wheat	71.13	13.68	2.47	—	—
Maize, yellow	74.26	9.42	4.74	7.3	0.64
Rice, brown	76.17	7.50	2.68	3.4	—
Barley	77.72	9.91	1.16	15.6	0.80
Sorghum	72.09	10.62	3.46	6.7	2.53
Oats	66.27	16.89	6.90	10.6	—
Millet	72.85	11.02	4.22	8.5	—
Rye	75.86	10.34	1.63	15.1	0.98
Triticale	72.13	13.05	2.09	—	—

1.2.2. Distribution of Constituents in the Grain

The distribution of constituents in the cereal grain is non-uniform, with each component concentrated in specific parts of the grain. The grain consists of three main parts: the bran (outer

layer), the germ (embryo), and the endosperm (largest part). Starch, which accounts for 70-90% of carbohydrates, is primarily located in the endosperm, while fiber components such as cellulose, pentosans, and lignin are concentrated in the bran and hulls. Proteins are distributed throughout the grain, with albumins and globulins found mainly in the outer bran tissue, while glutelins are primarily in the endosperm. Lipids and oils are concentrated in the germ, which is the nutrient-dense part containing healthy fats and polyunsaturated oils. Minerals and ash are highest in the bran and hulls, with potassium being the most abundant mineral. B-complex vitamins are also concentrated in the bran and germ. This compartmentalization, where chemical constituents are separated by cell walls and barriers, is responsible for the grain's stability during storage, as degrading enzymes and their substrates are protected from contact until water activity increases (such as during germination). Consequently, whole grain cereals are more nutritious than refined cereals because refining removes the nutrient-rich bran and germ, leaving mostly starchy endosperm that lacks most other essential nutrients.

II. Wheat

Wheat is one of the predominant cereals consumed worldwide. The main parts of wheat include bran, germ, and endosperm. Wheat grain is composed of approximately 85% endosperm, 13% husk/bran, and 2% embryo. The outer portion of wheat is known as bran that constitutes 13% of the total portion. Bran further consists of several layers predominantly epidermis, hypodermis, tube cells, cross cells, testa (seed coat), and nuclear tissue. Testa (seed coat) protects the endosperm and is responsible for the color of wheat. Germ or embryo constitutes 2% of the wheat seed and is known as sprouting section of the seed. Germ holds maximum amount of protein, lipids, and sugar. The major portion (85%) of the seed is composed of endosperm (Figure 4), which is the storehouse of nutrients like riboflavin, thiamine, pantothenic acid, niacin, and proteins and is used to make white flour.

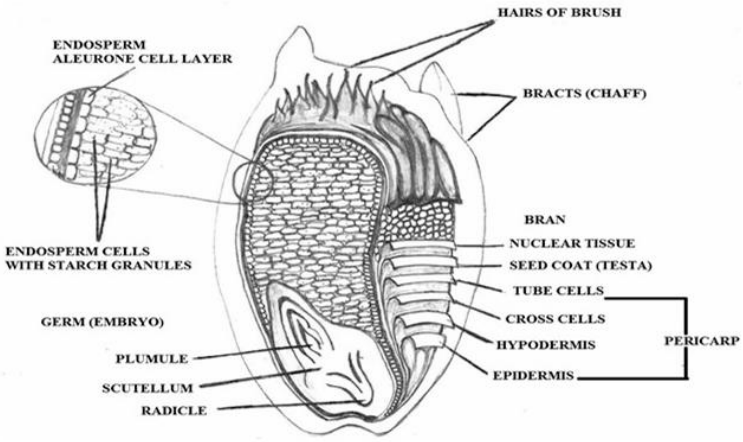

Figure 4: structure of wheat grain

Two species of wheat are involved in current productions (Table 3):

- **Soft wheat (Triticum aestivum)**

The grains are rounded, the husks are thick, without transparency. They are particularly well-suited for milling, releasing the kernel and yielding a very high proportion of bran. Soft wheats allow for the production of high-quality flour, containing about 8 to 10% gluten, with good baking properties.

- **Durum wheat (Triticum durum)**

This category of wheat is cultivated in countries with a hot and dry climate. The grains are elongated, often even pointed, the husks are quite thin and slightly translucent. They yield less bran than soft wheats, and the flour obtained, although containing more gluten (12 to 14%), is less suitable for bread-making.

II.1. Properties of Wheat Proteins

II.1.1. Classification of Wheat Proteins

Wheat proteins are classified according to the Thomas Burr Osborne system, which distinguishes four major fractions based on their solubility (Figure 5):

• **Albumins**: soluble in water; metabolically active proteins (enzymes, inhibitors), mainly present in the germ and bran layers

Table 3: main differences between Durum wheat and soft wheat

Criteria	Durum Wheat (Triticum durum)	Soft Wheat (Triticum aestivum)
Characteristics	Hard and vitreous grains	Soft and mealy grains
Protein content	High (10-15%)	Lower (8-12%)
Gluten	High quality, elastic gluten	Less elastic gluten, suited for breadmaking
Uses	Pasta, couscous, semolina	Bread, pastries, bread-making flour
Processing	Coarse milling (semolina)	Fine milling (flour)
Preferred climate	Hot and semi-arid regions	Temperate and humid climates
Resistance	Drought resistant	Less drought resistant
Economic value	Higher price (specific demand)	Lower price (mass production, versatile)
Nutritional properties	Rich in fiber, B vitamins, magnesium, iron	Good source of fiber, vitamins, and minerals

- **Globulins**: soluble in dilute saline solutions; also metabolically active
- **Prolamines (Gliadins)**: soluble in aqueous alcohol (70–90% ethanol); monomeric storage proteins of the endosperm
- **Glutenins**: soluble in diluted acids or bases after reduction; polymeric storage proteins of the endosperm

Gliadins and glutenins constitute approximately 30% and 50% of the total protein in the wheat grain, respectively. These two fractions together form gluten, a viscoelastic protein network essential for baking and the production of numerous cereal products.

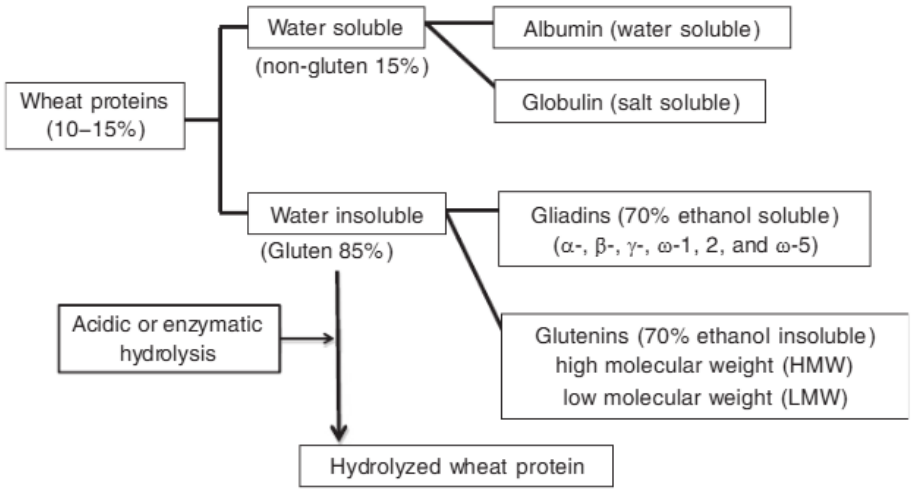

Figure 5: Components of wheat protein

II.1.2. Gliadins

Gliadins are monomeric storage proteins, typical of prolamins, insoluble in neutral water but soluble in 70% ethanol. They represent about 40–50% of the total storage proteins in wheat grain. From a rheological perspective, they impart to the dough its flow properties (viscosity), that is, its extensibility and deformability.

Gliadins are classified into four groups according to their electrophoretic mobility: α-, β-, γ-, and ω-gliadins. The α- and γ-gliadins possess a structure rich in α-helices in their C-terminal domain, stabilized by intramolecular disulphide bonds; their repetitive N-terminal domain adopts a poly-L-proline II and β-turns structure. The ω-gliadins, devoid of cysteine residues, do not have an α-helical structure and only exhibit poly-L-proline II structures and β-turns

II.1.3.Glutenins

Glutenins are polymeric proteins held together by intermolecular disulphide bonds. They are composed of high molecular weight subunits (HMW-GS) and low molecular weight subunits (LMW-GS). These macropolymers intertwine with gliadin particles through non-covalent interactions to form the gluten aggregate.

The HMW subunits are particularly important: they form the "elastic skeleton" of gluten and are primarily responsible for the elasticity and toughness of the dough. The suppression of HMW-GS significantly decreases the quality of the bread, while a high content of gliadins reduces the dough's resistance but increases its deformability. The variation in the composition and physical properties of glutenin polypeptides is largely responsible for the differences in gluten viscoelasticity among wheat cultivars.

II.1.4. The Gluten Network

When wheat flour is mixed with water, gliadins and glutenins hydrate and interact to form a continuous viscoelastic network called gluten. The formation of this network relies mainly on covalent bonds and non-covalent bonds (ionic bonds, hydrogen bonds, hydrophobic interactions). The glutenin/gliadin ratio is a critical parameter: an increase in this ratio leads to an increase in kneading time, extension resistance, and bread volume, while a decrease in this ratio increases dough extensibility (figure 6). This balance between viscosity (provided by gliadins) and elasticity (provided by glutenins) is crucial for the quality of bakery products, pasta making, and noodle

production. Gluten is also a very widely used binding and extensible agent in the processed food industry to improve the texture, moisture retention, and flavour of products. From a nutritional standpoint, gliadins contain peptide sequences that are highly resistant to gastric and intestinal proteolytic digestion, which implicates them in intolerance reactions such as coeliac disease.

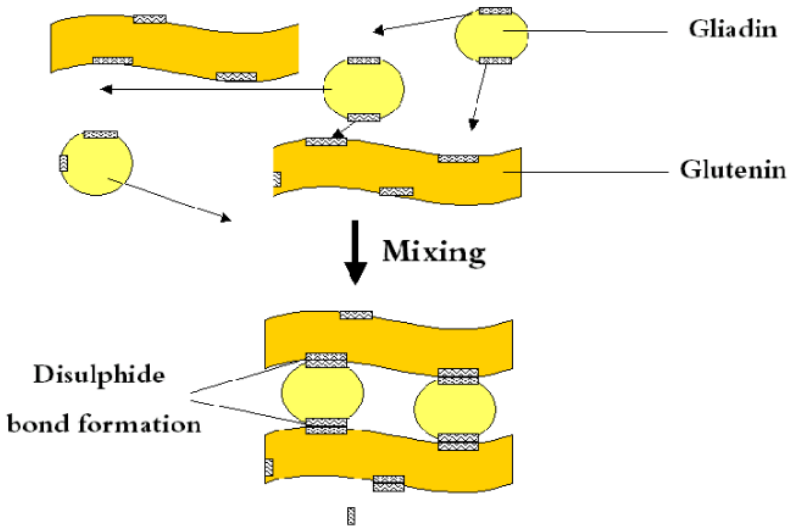

Figure 6: structure formation of gluten -gliadin and glutenin

II.2. Primary processing of wheat

The primary processing of wheat refers to all the operations that allow the transition from raw grain to flour or semolina. It includes three fundamental steps: cleaning, preparation (conditioning), and milling. The quality of the incoming wheat and the rigorous management of each of these steps determine the quality, yield, and functional properties of the final flour.

II.2.1.Cleaning

Cleaning is the first crucial step in the milling process. It involves removing all impurities accumulated during the cultivation, harvesting, and transportation of wheat. Its importance is twofold: to protect milling equipment (especially the rollers) from damage caused by hard foreign bodies, and to ensure the purity and safety of the finished product.

II.2.1.1. Dry cleaning

It constitutes the core of the process and combines several separation principles:

• **Screening (sieving)**: Coarse screens (scalping screens) retain large impurities (straw, large stones); grading screens separate materials smaller than the grains (fragments, small seeds, fine debris); fine mesh screens eliminate dust and very small particles.

• **Gravity separators**: Exploit the differences in density between wheat and contaminants; heavy materials (stones) fall to the bottom, light materials (chaff, stems) float, while the wheat concentrates in the intermediate layer.

• **Air classifiers (vacuum cleaners)**: Use a controlled airflow to separate light materials (dust, chaff, empty grains) from dense grains

• **Magnetic separators**: Capture dangerous metal fragments from harvesting or transport machines

• **Optical sorters**: Recent innovation using high-resolution digital cameras to detect and eliminate discolored grains, ergot, burnt grains, and fungal contaminants (Fusarium); this technology is increasingly being adopted in modern mills.

II.2.1.2. Wet cleaning (washing)

After dry cleaning, washing helps eliminate pesticide residues on the surface, microorganisms, and dust particles adhering to the grains by electrostatic attraction. It also allows for density separation in an aqueous medium: light materials (weed seeds, chaff) float and are removed, while dense mineral materials settle at the bottom.

II.2.1.3. Scouring / Debranning

The brushing of grains by mechanical friction (wheat scourer) removes residual contaminants lodged in the ventral groove of the grain (dirt, sand, microorganisms, insect eggs). Dehulling (debranning) is an important technological advancement that involves partially removing the outer layers of bran through friction and abrasion before milling; it improves flour yield, microbiological purity, and the quality of by-products (bran enriched with fibres, minerals, and polyphenols). The main targeted contaminants include ergot sclerotia (containing toxic alkaloids), seeds of poisonous plants (datura, castor), stones, metals, broken grains, and other cereals. The generally targeted quality criterion is a foreign matter rate of less than 1% after cleaning.

II.2.2. Preparation

Conditioning (or tempering) is the operation of preparing wheat prior to milling. It involves adding water to the cleaned wheat and letting the grain rest in soaking tanks until the moisture is evenly

distributed throughout the grain. This step is essential to:

• Strengthening of the bran: Moisture makes the grain husks more flexible, tenacious, and resistant to crushing, which promotes their removal in the form of large particles during milling and limits the contamination of flour with ash.

• Softening of the endosperm: Hydration of the endosperm makes it easier to grind and separate from the bran

• Optimization of extraction: The final moisture content of the conditioned grain directly influences the extraction rate and the ash content of the flour.

The amount of water to add depends on the initial moisture content of the grain and its hardness. The target moisture content varies depending on the type of wheat: 14.5–15% for soft wheat, 15.0–15.5% for semi-soft wheat, 15.5–16.0% for semi-hard wheat, and 16–17% for hard wheat. The soaking duration typically ranges between 12 and 48 hours; durum wheat, which is more resistant to water penetration, requires longer durations than soft wheat. Studies show that the best bread and semolina performance is achieved with a grain moisture content of 13 to 15%. To reduce soaking time and improve energy efficiency, several methods have been developed, including steam conditioning (which accelerates water penetration and reduces lipase activity), ultrasonic techniques, vacuum impregnation, enzymatic conditioning (using cellulase, xylanase, and pectinase), and intensive dampeners with high-frequency vibration. Without conditioning, the bran becomes brittle and breaks into small fragments during grinding, which increases the ash content of the flour and decreases its quality.

II.2.3 Milling

Milling is the central operation of primary processing. Its objective is to separate the endosperm from the bran and germ, and then to reduce the endosperm into fine flour. Due to the presence of a deep furrow in the wheat grain, this separation can only be achieved through a sequence of several grinding, sieving, and reduction passes, constituting the milling diagram.

II.2.3.1. Roller Milling (dominant industrial method)

Roller milling is the most widely used method in the modern industry for the production of refined flour. It includes three sequential systems:

• **Grinding System (Break System)**: Fluted rolls open the grain and release clean endosperm particles in the form of coarse semolinas (middlings), while keeping the bran in large particles. The objective is to achieve a high extraction rate with a low ash content.

• **Sizing System**: Classifies endosperm particles resulting from milling into different grades of particle size, thereby optimizing the performance of the reduction system.

• **Reduction System**: Smooth rolls gradually reduce the middlings into fine flour that meets the defined refining standards.

Between each grinding pass, a sieving (plansichter) separates the obtained flour from the coarser particles that will return to the milling circuit. This gradual process ensures an effective separation of the bran/germ/endosperm fractions. The cylinders can be smooth or fluted with different fluting profiles, significantly influencing the particle size distribution of the obtained flour. Modern mills incorporate automatic systems for adjusting the gap between the rollers, sensors for measuring grinding force, and programmable control systems to optimize yield, quality, and energy consumption.

II.2.3.2 Stone Milling

Stone milling is the oldest milling technique. The grain is crushed between two stone millstones, which directly produces whole flour incorporating all fractions of the grain (endosperm, bran, germ). If the goal is refined white flour, the obtained product is sifted. This method is still preferred by many artisanal bakers and organic producers due to a perceived superior nutritional profile and marketing advantages related to tradition. Research shows that flour obtained by stone milling has a different particle size distribution compared to that obtained by roller milling, with a higher proportion of particles between 315 and 710 µm.

II.2.3.3. Ultra-fine milling

Advanced grinding technologies make it possible to reduce flour particle size far below conventional levels:

- Jet milling uses compressed air jets to produce particles ranging from 1 to 10 µm. It increases solubility and specific surface area without altering the molecular structure of soluble arabinoxylans.
- Ball milling reduces particle size to about 30 µm, increases damaged starch, and changes the functional properties of gluten.
- Superfine grinding produces improved whole wheat flours with particles smaller than 40 µm, which increases water absorption and modifies dough rheology.

Overall, ultra-fine grinding enhances the surface characteristics and reactivity of flour components, improves the bioavailability of certain nutrients, and offers new opportunities for developing cereal products with high nutritional and functional value.

II.3. Linear processing of wheat

The linear (or secondary) processing of wheat refers to all the processes that transform the flour or semolina obtained by milling into finished or semi-finished food products. The main sectors are baking/breadmaking, pasta production (pasta), couscous, biscuit making, and noodle manufacturing.

II.3.1 Bread Manufacturing

Breadmaking is the most important value-added sector for soft wheat (Triticum aestivum). The wheat used for baking must have a high protein content (generally > 12%) with good gluten quality, meaning an optimal balance between extensibility and dough strength.

II.3.1.1 Raw materials in breadmaking

Bread making relies on four fundamental pillars: flour, leavening agents, salt, and water, each playing a critical role in the final quality of the product (Table 4). Flour is the essential base, and its quality directly dictates the bread's texture and integrity, with common varieties including wheat, rye, and spelt. To achieve the necessary fermentation, bakers choose between yeast and sourdough: while yeast offers a faster, easier process that yields a lighter, more consumer-friendly

crumb, sourdough requires a longer fermentation time but rewards the baker with deeper, more subtle flavors, improved nutritional value, and an extended shelf life. Salt serves as more than just a flavor enhancer; when added during kneading, it strengthens the dough's structure, promotes crust coloration, and regulates fermentation by retaining moisture and controlling gas production, which ultimately contributes to better preservation. Finally, water acts as the binding and hydration medium, essential for dissolving ingredients, enabling yeast activity, and forming a cohesive dough, while its use as steam during the baking process is vital for achieving an attractive, high-quality crust.

Table 4: Raw materials in breadmaking and their roles

Ingredient	Primary Role
Flour (Wheat)	Proteins (gliadin/glutenin) form gluten (structure, gas retention); starch forms a gel upon gelatinization.
Water	Hydrates proteins, gums, and starch; acts as a solvent/medium for chemical/biochemical reactions; provides dough mobility.
Baker's Yeast	Leavening agent: ferments sugars into CO_2 (aeration) and ethanol (flavor/aroma precursors).
Salt (NaCl)	Controls fermentation; toughens the gluten network; extends required dough development time.
Milk	Adds protein (lysine) and calcium; enhances flavor and browning; provides a buffering effect.
Sugar Sucrose)	Fermentable substrate; enhances sweetness and crust color (Maillard/caramelization); tenderizes crumb; improves shelf life.
Fats	Improves gas retention; tenderizes the crumb; extends shelf life; lubricates the dough matrix.

II.3.1.2 Process of breadmaking

The bread-making process includes the following steps:

1. The Kneading Process

Kneading is a mechanical operation designed to hydrate flour particles and organize proteins into a continuous 3D viscoelastic network. It is typically divided into two key phases:

- **Frasage (Blending Phase):** This initial low-speed mixing phase focuses on the uniform hydration of the flour. The objective is to incorporate water, salt, yeast, and flour into a homogeneous, cohesive mass. At this stage, the dough consistency is adjusted, and the gluten begins its initial formation without significant structural stress.
- **Second Speed (Intensive Phase):** Once the ingredients are unified, the mixer speed is

increased to apply shear and elongation forces. This mechanical energy is crucial for the development of the gluten network (polymerization of glutenins and gliadins). This phase facilitates the incorporation of atmospheric oxygen, which is essential for stimulating yeast activity and promoting the oxidation of disulfide bonds, which "locks" the gluten structure into a strong, elastic framework (Figure 7).

The intensity and duration of the kneading process directly dictate the crumb characteristics:

- **Intense Kneading:** Leads to a fine, tight crumb with small, regular alveoli (pores). This is ideal for sandwich breads or refined products.
- **Low-Speed/Short Kneading:** Results in a rustic, open crumb with large, irregular alveoli, common in artisanal or sourdough breads.
- **Excessive Kneading (Over-mixing):** Represents a structural failure. Excessive mechanical energy ruptures the gluten network, leading to depolymerization. The dough loses its elasticity, becomes sticky, and fails to retain gas, resulting in a collapsed loaf with poor volume.

Precision in control parameters is vital for industrial and artisanal consistency:

- **Temperature Management:** Controlling the "base temperature" is critical for the fermentation rate. A dough temperature of 20–25 °C is generally preferred for slower, more flavorful fermentation
- **Timing & Texture:** The process typically lasts 5 to 15 minutes depending on the mixer type (spiral, planetary, or manual). The end-point is determined by the "window-pane test": the dough should be smooth, dry to the touch, and sufficiently elastic to be stretched into a thin, translucent membrane without tearing.

2. Fermentation

Fermentation is a biochemical process in which yeast (*Saccharomyces cerevisiae*) acts as a biocatalyst to convert fermentable sugars into structural and aromatic compounds. During this process, yeast metabolizes glucose through anaerobic respiration, producing ethanol, carbon dioxide, and energy. The carbon dioxide generated is trapped within the viscoelastic gluten network, causing it to expand and creating the internal porosity of bread. This process is controlled by several parameters, including temperature, which is ideally maintained at 28–30 °C to ensure optimal enzymatic activity, humidity, which should be kept between 80 and 90% to prevent surface drying and allow gas expansion, and duration, which is usually about 90 minutes to promote proper

alveoli development.

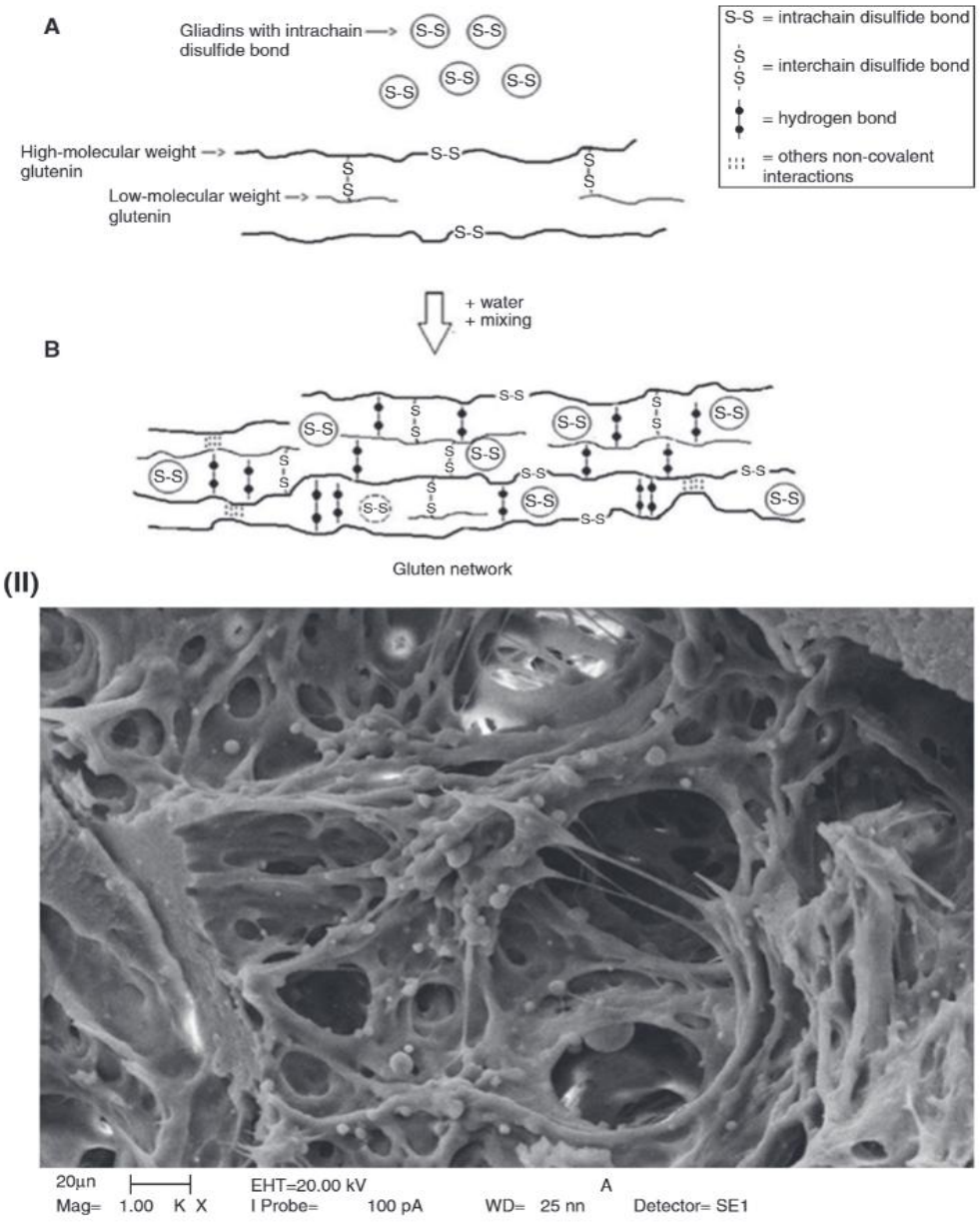

Figure 7: I. molecular interpretation of the gluten network and the effect of water addition and mixing. II. scanning electron micrograph of the gluten network, illustrating how gluten structure develops during hydration and mixing.

3. Dividing and Shaping

Once bulk fermentation is complete, the dough is segmented into dough pieces.

- **Scaling:** Each portion is weighed precisely (e.g., 250g for a standard baguette) to ensure uniformity in baking time and consumer expectations.
- **Shaping:** The dough is molded into its final form, which helps organize the gluten network to manage gas retention during the final stages.

4. Final Proofing (Apprêt)

The *apprêt* is the final maturation phase before baking, where the dough rests at approximately 27 °C for 60–90 minutes. The dough should approximately double in volume. During this time, yeast enzymes (like maltase) hydrolyze maltose into glucose, sustaining the fermentation process.

Keeping the dough covered is mandatory to prevent the surface from drying out (skinning), which would restrict further expansion.

5. Scoring and Finishing

The final aesthetic and functional touches are performed just before baking.

- **Flouring:** Applying a light coating of flour protects the dough surface from drying, improves handleability, and adds a rustic, artisanal finish.
- **Scoring (Incisions):** Far from being purely decorative, scoring serves critical technical functions:
- **Structural Integrity:** It creates a "controlled weak point," preventing the bread from bursting in unintended places due to the rapid pressure increase from the oven spring.
- **Alveoli & Gas Management:** By facilitating the controlled release of steam and CO2, incisions prevent the rupture of the gluten network (glutenin/gliadin), ensuring a consistent crumb structure.
- **Thermal Control:** Scoring allows heat to penetrate the loaf more uniformly, ensuring even baking and preventing the crust from setting before the internal structure has finished expanding.

6. Baking

During baking, the gelatinization of starch and the coagulation of gluten proteins are the two major thermal reactions that definitively set the structure of the bread. Irreversible modifications of starch

and proteins at high temperatures (> 200 °C) and surface dehydration are responsible for the formation of the crust. The quality of bread (volume, crumb texture, crust) directly depends on the composition and properties of gluten proteins, particularly the content and composition of the HMW and LMW subunits of glutenin.

II.3.2 Pasta manufacturing

The production of pasta primarily uses durum wheat (*Triticum durum*) in the form of semolina, characterized by its amber-yellow color (high carotenoid content), its high protein content, and its specific rheological properties. Durum wheat semolina is distinguished by its coarser granulation and sharp edges, unlike soft wheat flour.

II.3.2.1. Composition of pasta

1. Semolina (*Durum Wheat*)

Semolina is the gold standard for pasta production due to its unique physicochemical properties (Figure8). It contains strong, high-quality gluten that forms a firm, cohesive matrix, which is essential for maintaining pasta structure during cooking. Its high vitreousness and hardness allow for clean, coarse milling, producing the characteristic granular texture that is critical for proper extrusion and shaping of pasta. Additionally, semolina provides a superior sensory profile, delivering the signature golden-yellow color, enhanced flavor, and the highly desirable "al dente" texture that consumers expect from high-quality pasta after cooking.

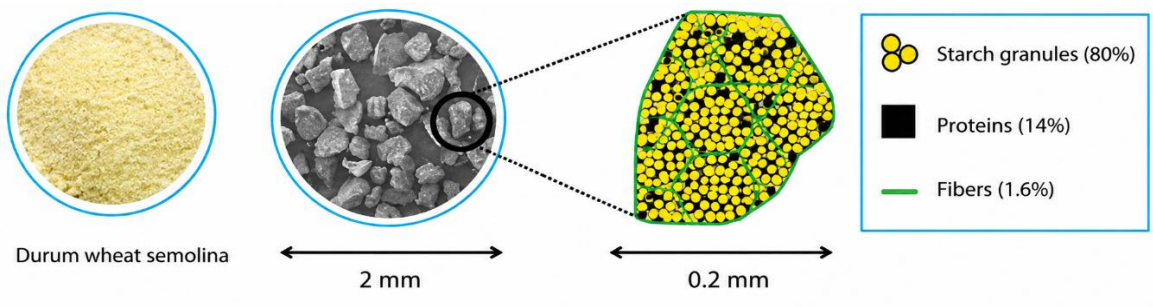

Figure 8: Characteristics of semolina used for pasta production

2. Water

Water is not merely a solvent; its mineral composition significantly influences the pasta's rheology

and final appearance.

The hardness of water used in pasta production significantly affects the final product quality. Calcium strengthens the gluten network, leading to increased firmness and better structure retention during boiling, which helps maintain pasta integrity. Magnesium influences the elasticity and handling of the dough, affecting how easily it can be worked during extrusion and shaping. Iron content must be carefully controlled, as excessive iron can cause oxidation that negatively alters the pasta's appearance by dulling its natural yellow brightness. Additionally, pH balance plays an important role, as slightly alkaline water with a pH between 7 and 8 is generally preferred to stabilize the texture and prevent the dough from becoming too sticky during processing.

3. Eggs

The inclusion of eggs in pasta production is strictly regulated by law to ensure quality standards, typically requiring 140 to 350 g of fresh eggs per kilogram of semolina. Eggs transform the pasta by providing a distinct, richer taste and a vibrant, attractive color that enhances its culinary appeal. From a nutritional perspective, eggs significantly increase the protein and lipid profile of the product, making it more valuable for consumers. Additionally, eggs improve the pasta's structural integrity by enhancing its "hold" or cooking stability, ensuring that the product does not soften or disintegrate easily in boiling water, which maintains its texture and form throughout the cooking process.

4. Vegetables and Spices

These ingredients are used primarily for differentiation, allowing manufacturers to create a diverse range of gourmet products.

II.3.2.2. Classification of Pasta

Pasta can be categorized based on several industrial and sensory criteria, reflecting the diversity of production methods, composition, and shelf stability.

1) By Shelf Life and Storage

- **Fresh Pasta:** Typically characterized by a higher moisture content; it requires refrigerated storage and is intended for immediate or short-term consumption.
- **Dry Pasta:** Processed through controlled dehydration to achieve a low moisture content

(usually <12.5%), allowing for long-term storage at ambient temperatures.

2) By Preparation Method

- **Cold Kneading**

Dough at 12-18 °C limits starch gelatinization, enables controlled gluten development, and improves structure and gas retention for better texture, volume, and freshness.

- **Hot Kneading**

Dough at >25-28 °C accelerates starch gelatinization and protein hydration, leading to faster gluten development but with lower stability and reduced gas retention.

3) By Manufacturing Technology

- **Extruded (Pressed) Pasta:** The dough is forced through a die under high pressure. This category includes:
- **Long Pasta:** (e.g., spaghetti, linguine).
- **Cut Pasta:** (e.g., penne, fusilli, macaroni).
- **Laminated (Sheeted) Pasta:** The dough passes through counter-rotating rollers to form a wide, uniform sheet. This sheet is subsequently cut or stamped into specific shapes (e.g., lasagna, tagliatelle, ravioli).

4) By Composition

These varieties are formulated with functional or sensory additives to enhance specific nutritional or organoleptic profiles:

- **Egg Pasta:** Enriched with egg for superior texture, color, and nutritional value.
- **Vegetable-Enriched Pasta:** Incorporating ingredients such as tomato or spinach for unique flavoring and coloration.
- **Dairy-Enriched Pasta:** Containing milk or milk solids for a softer texture.
- **Gluten-Free/Specialty Grain Pasta:** Formulated with alternative flours or specialized protein bases to meet dietary requirements.

II.3.2.3. Pasta manufacturing process: pasta making

The preliminary steps to pasta manufacturing include receiving the semolina at the factory, storing it in silos where the outside temperature and the product temperature are rigorously monitored to prevent condensation of water inside the silo, dosing the semolina according to volume or mass, mixing (in the case of semolina and flour) and transporting it to the manufacturing location (Figure 9).

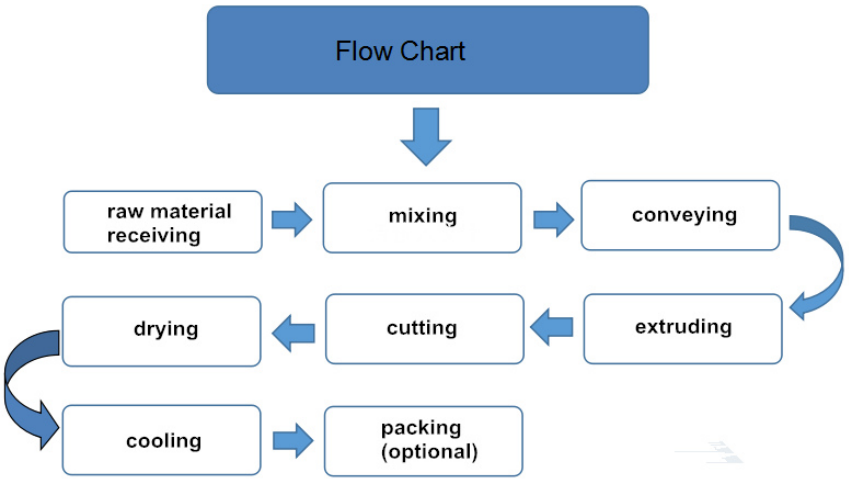

Figure 9: industrial pasta manufacturing

1) The purge

Before processing, the semolina undergoes a final cleaning to remove any remaining flour dust and impurities (small wood splinters, label fragments, small lumps of semolina granules, insect larvae, etc.). Removing these foreign bodies is crucial, as their presence can lead to manufacturing defects. This is typically done by sieving.

2) Hydration and kneading

The first step involves spraying approximately 25 to 34 kg of water onto 100 kg of semolina, so that the final moisture content is around 44 to 49% of the dry matter. This amount of water takes into account the initial moisture content of the semolina, which is generally around 14%. The semolina is mixed with a minimal amount of water, and the lack of water is compensated for by energy work that allows the semolina particles to bind together. The water temperature is around

35°C, and this operation lasts approximately 7 minutes.

The semolina granules clump together into crumbly balls, the mixing being carried out by blades on a horizontal axis rotating at a speed of 120 rpm. Unlike kneading, mixing does not develop the dough.

Lasting 15 minutes, this step allows for the gradual and constant hydration of the semolina in order to obtain balls or agglomerates of varying sizes, up to 1 to 1.5 cm in diameter; this is referred to as a sandy granular dough or agglomerates.

In the most recent presses, water and semolina are mixed using a high-speed mixer (in just a few minutes). From the mixer, the mix is sent to the screw press to be extruded through a die.

3) Kneading

This step, which will form a homogeneous paste, only exists in rolling (not in the extrusion process).

4) The shaping

The shaping of the dough is achieved either by rolling or by extrusion, which is the most commonly used process.

a) The extrusion or wire drawing process

After kneading, the dough is forced through a vacuum chamber to prevent air from being extruded and to avoid the oxidation of the carotenoid and phenolic pigments in the fatty acids. The dough is then forced through an Archimedes screw to the die, also called an extrusion die. The dies determine only the shape and appearance, not the length.

The dies are made of bronze or Teflon; the latter material promotes a smooth pasta surface, unlike bronze, which creates a textured surface dotted with small bumps that can be beneficial for retaining sauce after cooking.

The pasta is extruded at a pressure of 80 to 140 bars, which also causes it to heat up. The extrusion temperature must not exceed 40° C, as at this temperature the protein structure becomes too compact, and above 40°C there is a risk of starch gelatinization. This is why the system is cooled by a circulation of cold water.

b) The rolling process

In the rolling process, the dough is kneaded and rolled into a sheet between two rotating cylinders until the sheet reaches the desired thickness. The sheet is then cut into strips of the desired width and length.

The two techniques differ in the mechanical energy used for forming. The energy transferred to the dough is higher with the extrusion process than with rolling, and some of this energy is dissipated as heat. Furthermore, during extrusion, the dough is subjected to shear stress, whereas during rolling, tensile stress is applied. These differences in parameters (stress, heat, and pressure) can lead to the formation of doughs with different structures.

5) Drying

Pasta produced by extrusion has a moisture content of 29 to 31%. It must be dried to a maximum moisture content of 12.5%, as this is the level at which pasta is perfectly preserved.

Pasta drying takes place immediately after the mixing and extrusion processes. This is the most important and certainly the most delicate step in the manufacturing process, and it comprises two phases: pre-drying and final drying. Drying stabilizes the qualities of the raw material and the previous mechanical treatment. It must not alter the shape or appearance of the pasta.

a) Pre-drying

This operation must be carried out by circulating hot air (55°C to 75°C) for a duration that varies depending on the pasta shape, but is generally within one hour for cut and stamped pasta and two and a half hours for long pasta.

b)Final drying

Manufacturers use two types of dryers:

i. **Traditional dryers**

The final drying phase must gradually bring long pasta (17% moisture) and cut and stamped pasta (21% moisture) to a standard moisture content of 12.5%. This delicate operation is performed in such a way as to maintain a uniform moisture gradient between the outer and inner parts of the pasta during drying.

Typical temperatures range from 35°C to 55°C; the temperature must be low enough to prevent protein denaturation and starch gelatinization. Drying times for long pasta vary from 12 to 15

hours, and for cut and stamped pasta, from 5 to 10 hours.

ii. **Modern dryers**

To reduce drying time and energy costs, large pasta manufacturers prefer high-temperature, short-duration drying schedules; "high temperature" (HT), between 70°C and 90°C, and "very high temperature" (THT), between 95°C and 105°C.

These new dryers offer the advantages of improved pasta color and cooking performance, reduced factory space requirements, increased production capacity, and lower energy costs, but the drawback in terms of nutrition is that they decrease lysine bioavailability more significantly than traditional dryers.

6) Packaging

Once cooled to a temperature of 25°C and after a quality control check, the dried pasta is carefully packaged in polypropylene sheets or in folding boxes or under cellophane.

II.3.3. Couscous manufacturing

Couscous is a product made from durum wheat steamed semolina (*Triticum durum*) that has been compacted into granules 1 to 2mm in diameter. It is made from semolina, either industrially or by hand.

Generally speaking, the quality of semolina for couscous is characterized by a high protein content (13.5% on a wet basis) and good shelf life, indicated by an acidity level that meets international standards. The types of semolina used to make couscous have a larger grain size than pasta.

II.3.3.1. Industrial production of couscous

Industrial couscous production incorporates continuous mixing and kneading to optimize the agglomeration of the durum wheat semolina grains (Figure 10).

a) Agglomeration

Native semolina particles agglomerate via water addition (up to 45% water content) and mixing at 20-25°C, passing glass transition of starch/protein amorphous zone (Figure 11). This enables enzymatic reactions (peroxidases/polyphenol oxidases reducing carotenoids), glutenin dissociation (↓ insoluble, ↑ soluble/SDS-soluble), and adhesion without full gluten network due to limited shear/water. Generates heterogeneous structures: fines (<0.5 mm, native residuals/erosion,

recycled), wet nuclei (0.5-0.8 mm), target wet agglomerates (0.8-2 mm for couscous grains), large dough pieces (>2 mm, recycled). Key controls: semolina PSD (↓ median diameter ↑ agglomerates), water amount/temp (↑ water ↑ agglomerates/dough, ↓ fines; cooler water better), mixing time (longer ↑ fines via breakage). Yield correlates with soluble glutenins.

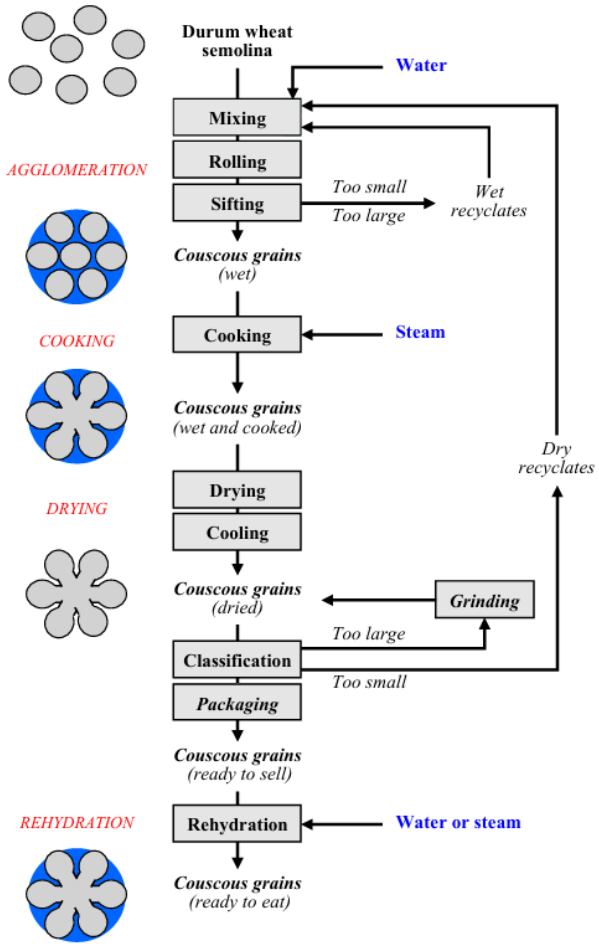

Figure 10: Production diagram and structural model for the processing of couscous grains from durum wheat semolina

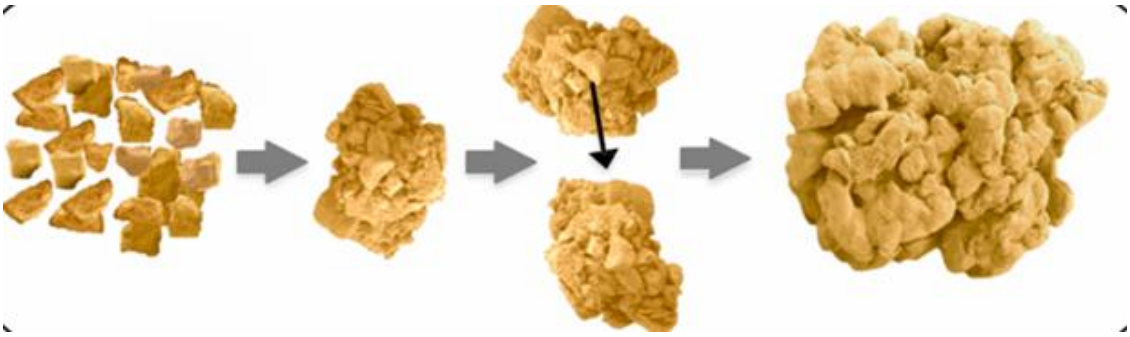

Figure 11: Schematic representation of wet agglomeration mechanisms of durum wheat

b) Consolidation

Wet grains consolidate via steam cooking (saturated vapor, 100°C, 20-30 min), inducing starch gelatinization (full in 3-5 min), protein crosslinking, adherent liquid coating formation acting as inter-particle glue. Transitions soft agglomerates to rigid-gelatinized state; plastic densification (8-10% volume reduction), reduced fragility; water-independent post-agglomeration.

c) Drying

Cooked grains dry in sequential drums (60-80°C pre-dry, 80-120°C final, helical motion for thin layers) to 10-12% moisture (Aw ~0.5) for physicochemical/microbiological stability. Isotropic shrinkage via capillary water transfer; initial saturation maintenance, then rapid compaction; cooling to <40°C.

d) Rehydration

Dried grains rehydrate pre-consumption via cold water addition, steaming, or hot immersion, ensuring homogeneous swelling, particle contacts, and growth for firm yet melt-in-mouth texture.

e) Rolling & Sifting

Post-mixing, room-temperature rolling on successive sieves (no water change): granular movement densifies/eroses for sphericity, slight compaction. Size classification (Codex: 0.63-2 mm, <6% outliers) recovers target wet agglomerates (0.8-2 mm), recycles fines (<0.8 mm) and dough (>2 mm).

f) Steam Cooking

Detailed consolidation: steam raises temp/water (0.48→0.53 g/g), quick heat transfer (1 min). Starch gelatinization forms sticky cement; ALC with monoglycerides strengthens, reduces post-

rehydration stickiness; protein insolubilization (glutenins via disulfides). Extent controls absorption/texture; precooking for direct rehydration.

g) Drying and Cooling

Couscous is dried by stirring it in a thin layer in dry air. Water moves out at a steady rate, with drying happening faster at 60-80°C. As the couscous loses water, it shrinks slightly, which helps balance the water loss. When temperatures are higher (90-120°C), this boosts the development of alcohol compounds, Maillard reactions, and volatile flavors, giving couscous its characteristic taste and aroma.

h) Calibration by Size

Post-drying, dried couscous grains undergo size classification via a vibrating sieve column (plansifter) at room temperature, maintaining constant low water content (~10-12%). This step ensures low granulometric dispersion per Codex standards (0.63-2 mm diameter, <6% outliers).

i) Storage

Dried, calibrated grains are packed in moisture-proof packaging (e.g., multilayer paper/polyethylene bags, 500g-5kg) to preserve quality during shelf life (12-24 months).

III. Methods for assessing wheat quality

III.1. Evaluation of Soft Wheat

Soft wheat (*Triticum aestivum*) is primarily intended for the production of bakery, pastry, and biscuit products. Its evaluation is based on two complementary axes: the assessment of the intrinsic baking quality of the flour and the conduct of baking tests to confirm the actual technological aptitudes.

III.1.1. Bakery value

The bakery value of soft wheat refers to all the physicochemical and rheological properties that determine the flour's ability to produce quality bread. It depends on both the protein content, gluten strength, starch content, and enzymatic activity.

III.1.1.1. Protein content.

Protein content is a key parameter in evaluating baking quality, as it determines the water absorption capacity of the flour and the properties of gluten. A high protein content is generally

sought for products requiring an elastic and soft texture like bread, while a low protein content is preferred for crumbly products like cakes and biscuits. The reference method for measuring protein is nitrogen combustion analysis (Dumas method), which involves burning a sample at 952°C and measuring the volume of nitrogen released. Near-infrared spectroscopy (NIR/NIRT) is also widely used routinely in mills and control laboratories for its speed and reliability.

III.1.1.2. Ash content.

The ash content is determined by high-temperature incineration (585°C) of a flour sample in a muffle furnace. It measures the inorganic mineral residue after complete combustion of organic matter. As minerals are primarily concentrated in the bran layers, the ash content of the flour serves as an indirect indicator of the level of refinement and bran contamination during the milling process.

III.1.1.3. Falling Number (Hagberg Falling Number)

This test measures the alpha-amylase activity of the flour, particularly associated with germination damage on the ear. A falling number greater than 300 seconds indicates low amylase activity and good grain quality. An index lower than 250 seconds reveals excessive enzymatic activity, resulting in a sticky dough during baking and a poor texture of the finished product.

III.1.1.4. Sedimentation (Zeleny test)

The sedimentation test simultaneously evaluates the quantity and quality of the flour's gluten. A high sedimentation volume indicates strong gluten and good baking quality. Values below 20 ml characterize weak gluten flours, while values above 70 ml correspond to very strong gluten flours.

III.1.1.5. Wet gluten and gluten index (Glutomatic)

The glutomatic allows for the measurement of wet gluten by washing the flour with a 2% saline solution to remove starch and soluble components. The residue obtained constitutes the wet gluten, whose content is expressed as a percentage based on 14% moisture. The gluten index, determined by centrifugation, is an estimate of gluten strength: a high index indicates strong gluten.

III.1.1.6.Rheological properties of the dough.

Several instruments are used to characterize the rheological behavior of doughs made from soft

wheat flours:

❖ **The Farinograph (Brabender**): This instrument records the resistance of a dough to kneading. It measures water absorption, dough development time (Peak Time), stability (the duration during which the dough maintains maximum consistency), arrival time, and mixing tolerance index (MTI). A low-gluten flour has reduced water absorption and lower stability compared to a high-gluten flour.

❖ **The Extensograph (Brabender**): It measures the resistance to extension and the extensibility of the dough by stretching a cylinder of dough until it breaks. The R/E ratio (Resistance/Extensibility) provides an indication of the balance between the toughness and extensibility of gluten, an essential parameter for bread-making.

❖ **The Alveograph (Chopin)**: This device evaluates the strength of gluten by inflating a dough pellet until it bursts. The key results are: the P value (tenacity), the L value (extensibility), the P/L ratio, and the W value (deformation energy), which represents the overall baking strength of the flour. A high-gluten flour has high P values, while a low-gluten flour is suitable for confectionery products.

❖ **The Mixograph:** It quickly evaluates the gluten strength of a flour by measuring the resistance of a dough to mixing with pins. The results include water absorption, optimal development time (Peak Time), and kneading tolerance. It is particularly useful for screening lines in varietal selection.

❖ **Solvent Retention Capacity (SRC)**: This four-solvent method (water, sucrose, sodium carbonate, lactic acid) allows for the establishment of a flour functionality profile. The SRC with lactic acid is associated with gluten strength, the SRC with sodium carbonate is associated with damaged starch, and the SRC with sucrose is associated with pentosan content. This profile is particularly suitable for evaluating soft wheats intended for biscuits and cakes.

❖ **The Amylograph and the RVA (Rapid Visco Analyser)**: These instruments measure the viscosity of the flour during progressive heating, allowing for the evaluation of starch gelatinization properties and alpha-amylase activity. A high peak viscosity indicates high-quality starch, while flour from sprouted wheat exhibits low peak viscosity and produces sticky doughs.

III.1.2. Baking Test

The baking test is the final reference test for evaluating the technological suitability of flour. It reproduces, on a laboratory scale, the conditions for bread making and allows for the evaluation of flour performance under conditions similar to those of industrial production.

III.1.2.1. Protocol for the bread-making test (sandwich bread)

The standard test consists of mixing the flour with dry yeast (1 g), shortening (3 g), water (variable 58–70 g), malted barley (0.2 g), and possibly oxidizing agents or dough improvers. The dough is kneaded until it reaches optimal development, then fermented at 30°C and 85% relative humidity for 105 minutes, with two intermediate degassing steps. After shaping, the dough is proofed for 62 minutes, then baked at 215°C for 24 minutes.

III.1.2.2. Criteria for evaluating bread

Bread is evaluated on several dimensions:

• Specific volume: ratio of volume (cm^3) to weight (g), a key indicator of the gas retention capacity of gluten.

•External characteristics: shape, crust color, symmetry.

• Internal characteristics: uniformity of the crumb, size and regularity of the holes, color.
• Texture: evaluated by sensory analysis or by texturometer for objective measurements of firmness, elasticity, and cohesiveness.

III.1.2.3. Test biscuit (sugar-snap cookie)

For soft wheats intended for the biscuit industry, the sugar-snap cookie test (AACC Method 10-52) is the reference test. It evaluates the diameter and surface appearance (top grain) of the biscuits. A low-protein and low-gluten flour produces biscuits with a large diameter and numerous surface cracks, indicators of good biscuit quality.

III.2. Evaluation of Durum Wheat

Durum wheat (*Triticum durum*) is distinguished from other wheats by its vitreous endosperm, high protein content, strong gluten, and yellow color due to carotenoid pigments. It is mainly processed into semolina for the production of pasta, couscous, and certain Mediterranean breads.

III.2.1. Semolina value

The quality of semolina is the first link in the value chain of durum wheat. It is determined both by the intrinsic characteristics of the grain and by the milling conditions.

III.2.1.1. Physical characteristics of the grain

The milling quality of durum wheat is evaluated thru several parameters:

a) Specific weight (weight per hectoliter

an indicator of the density and maturity of the grain. A high specific weight is associated with a better semolina yield.

b) Percentage of vitreous grains

The percentage of grains with a vitreous appearance (Hard Vitreous Kernels, HVK) is an essential grading criterion. Vitreous grains are correlated with higher protein content and gluten quality, and with better semolina yield.

c) Thousand kernel weight (TKW)

Reflects the average size and weight of the grains; a high TKW is associated with better milling yield.

d) Physical defects (black spots, ergot, smudge)

Surface color defects of the grains have a direct impact on the number of black spots in the semolina and thus on its commercial acceptability.

III.2.1.2. Protein and gluten quality

The protein content determines the semolina's ability to hydrate, form, and maintain the gluten network during pasta production. A minimum protein content of 13% is generally required for the production of quality pasta. The strength of the gluten is evaluated thru rheological tests (alveograph, mixograph, gluten index) to ensure that the semolina exhibits both tenacity and extensibility suitable for different pasta shapes and extrusion processes.

III.2.1. 3. Color and carotenoid pigment content

The bright yellow color of the semolina is an essential criterion for commercial quality. It is due to the carotenoids (mainly lutein) present in the endosperm. The pigment content is measured by

spectrophotometric extraction. The degradation of pigments can be caused by lipoxygenase (LOX) activity during kneading; therefore, varieties with low LOX activity are sought to maintain an intense color.

III.2.1 4. Ash content and semolina granulation

The ash content of semolina is an indicator of the level of refinement and the residual presence of bran. It is legally regulated in some countries (≤ 0.9% for durum wheat semolina in Italy). The granulation of the semolina (coarse: 500–630 µm or fine: <355 µm) determines the hydration quality during the production of pasta and couscous.

III.2.1. 5.Content of damaged starch

Mechanically damaged starch during milling influences the rheological properties of the dough and the cooking quality of the finished products. A high level of damaged starch causes an increase in water absorption and a sticky surface during cooking.

III.2.1. 6. Counting of black and brown specks (speck count)

The number of black and brown specks in the semolina is a determining visual quality parameter for the commercial acceptability of pasta and couscous. These points are counted in a given area and compared to standards; their presence is linked to grain impurities, grains of abnormal color, and milling conditions.

III.2.2. Pasta Value

The quality of pasta is evaluated at three levels: during manufacturing, in its dry state, and after cooking. It is a direct reflection of the quality of the semolina used and the parameters of the extrusion and drying process.

a. Laboratory pasta manufacturing protocol

The standard test for extruded pasta production (AACC Method 66-41) involves mixing 100 g of semolina with 31.5 g of water at a slow then fast speed for 4 minutes, extruding the dough thru an appropriate die, cutting the pasta to the desired length, and then drying it according to a controlled thermal profile.

b. Evaluation of raw pasta

On raw or fresh pasta, the parameters evaluated include:

• The mechanical breaking strength: important for the integrity of long pasta during cutting, packaging, and transport.

• The surface appearance: smooth, even, without cracks or visible stains.

• The color: measured by colorimetry (L*, a*, b*) in the CIE system. The b* parameter (yellowness) is particularly important for durum wheat, with high-quality pasta needing to exhibit a bright yellow color.

c. Cooking quality of pasta

The cooking parameters are the most important criteria for the consumer:

• Optimal cooking time: duration needed to reach the "al dente" state (core still slightly firm).

• Cooking losses: amount of dry matter released into the cooking water, expressed as a percentage. A residue of starch or proteins in the cooking water indicates poor consistency of the protein network.

• Cooked weight: a reflection of water absorption capacity.

• Firmness (texture): objectively measured by a texture analyzer (TA.XT2) or evaluated by a sensory panel, expressing the resistance to biting of cooked pasta.

• Sticky: assessment of the absence of adhesion between the pasta after cooking and draining.

d. Sensory evaluation of the pasta

A trained panel evaluates attributes such as appearance, firmness (bite), elasticity, cohesiveness, stickiness, and flavor. These criteria are rated on a hedonic scale or by reference to a control sample.

III.2.3. Couscous value

The quality of couscous is assessed based on several characteristics:

a) Color: measured by Hunter Lab colorimetry (L value for brightness, b+ value for yellowness). A bright and shiny yellow color is synonymous with good quality. It is directly linked to the carotenoid content of the semolina.

b) Uniformity of shape and size: couscous granules must exhibit a regular spherical shape and a

homogeneous size, parameters evaluated by granulometric analysis (sieving on standardized sieves).

c) Rehydration and cooking time: the time required for the couscous to absorb water or sauce and be ready for consumption. A short time is generally sought.

d) Water absorption index (WAI): the ability of couscous to absorb water or sauce, a parameter related to the degree of starch gelatinization.

e) Water Solubility Index (WSI): amount of dry matter solubilized during absorption. A high WSI can be associated with increased stickiness of the cooked couscous.

f) Starch gelatinization rate: measured by enzymatic method (glucoamylase) or calorimetric method, it reflects the degree of precooking of the couscous.

g) Stickiness during cooking: sensory evaluation or objective measurement of the adhesion of granules to each other after cooking or rehydration. A quality couscous must remain non-sticky and "granular" after cooking.

h) Sensory evaluation: a tasting panel assesses the appearance, mouthfeel (firmness and creaminess), flavor, and overall acceptability of the cooked couscous, usually on a 9-point hedonic scale.

Part 2. Fruit and vegetable technology

I. Characteristics of Fruits and Vegetables

I.1 – Biochemical Composition

I.1.1. Macronutrients and Micronutrients

Fruits and vegetables are fundamental components of a healthy human diet, providing a broad spectrum of essential nutrients with low caloric density. Their biochemical composition encompasses both macronutrients and micronutrients, which together define their nutritional and technological value.

I.1.1.1. Macronutrients

Fruits and vegetables are primarily composed of carbohydrates, which are the dominant macronutrient and exist as sugars (glucose, fructose, sucrose), starch (found in potatoes and unripe bananas), and dietary fibers (cellulose, hemicellulose, pectin). Proteins are generally present in low content (0.5–3%) but are critical for enzymatic activities that govern ripening and quality changes, such as polyphenol oxidases, peroxidases, and pectinmethylesterases. Lipids are typically very low except in avocado and olives, and they constitute membrane phospholipids and surface waxes that play important roles in barrier function and postharvest quality. Water accounts for 80–95% of fresh weight and strongly influences texture, weight loss, and microbial stability during storage.

I.1.1.2. Micronutrients

Fruits and vegetables contain important vitamins, minerals, and dietary fiber. Vitamin C (ascorbic acid) is the most abundant and heat-labile vitamin in fruits and vegetables, vitamin K is predominant in leafy greens, and provitamin A (β-carotene) is found in orange and dark-green produce. Minerals such as potassium, calcium, magnesium, iron, and zinc are present, with their bioavailability depending on the food matrix, processing methods, and interactions with other compounds. Dietary fiber includes both soluble forms (pectin, β-glucans) and insoluble forms (cellulose, lignin), and is associated with reduced risk of cardiovascular disease, type 2 diabetes, and colorectal cancer.

I.1.2. Phytochemical Compounds and Their Nutritional Impacts

Beyond classical nutrients, fruits and vegetables contain thousands of bioactive phytochemicals with significant health-promoting properties (Figure 12). These compounds are secondary plant metabolites with ecological roles (pigmentation, defense against pathogens, UV protection) that also confer nutritional benefits to consumers. Regular consumption of phytochemical-rich fruits and vegetables is epidemiologically linked to reduced incidence of chronic diseases including certain cancers, cardiovascular diseases, obesity, and type 2 diabetes. The bioavailability of these compounds depends on chemical form, food matrix structure, and processing conditions; the latter can both enhance (cell wall disruption improves carotenoid release) and reduce (heat degrades anthocyanins) phytochemical content.

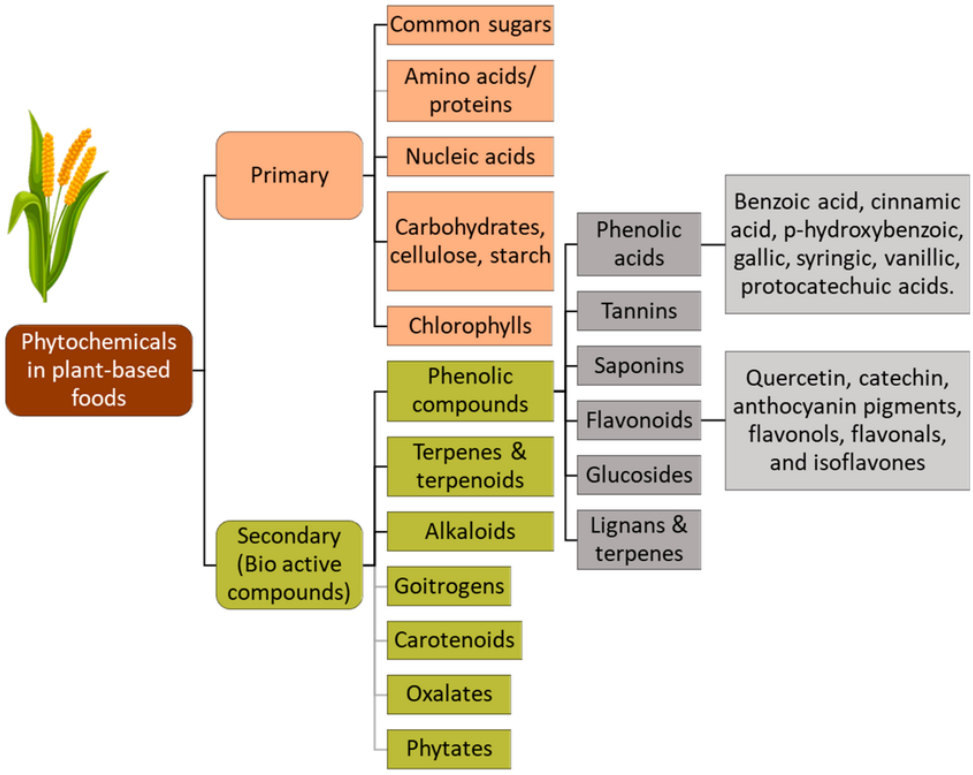

Figure 12: Major plant-based phytochemicals and antinutrients

I.1.2.1. Major classes of phytochemicals

- **Polyphenols and flavonoids:** The largest and most diverse group; includes anthocyanins (red/blue pigments), flavonols (quercetin), flavanones (hesperidin in citrus), catechins, and phenolic acids. They act as antioxidants, reducing oxidative stress associated with cardiovascular

disease, cancer, and neurodegeneration.

- **Carotenoids:** Lipid-soluble pigments (β-carotene, lycopene, lutein, zeaxanthin); involved in provitamin A activity, protection against macular degeneration, and reduction of cancer risk. Lycopene in tomatoes and lutein in leafy greens are key examples.

- **Glucosinolates:** Sulfur-containing compounds found in Brassica vegetables (broccoli, cabbage, Brussels sprouts); hydrolyzed to isothiocyanates (e.g., sulforaphane) with proven anti-carcinogenic activity.

- **Terpenes:** Monoterpenes and sesquiterpenes present in citrus peel and aromatic herbs; contribute to aroma and possess antimicrobial properties.

- **Phytosterols:** Structural analogs of cholesterol found in plant cell membranes; shown to reduce LDL cholesterol absorption.

I.2. Post-harvest Physiology

Post-harvest physiology is essential to ensure the efficiency of the entire food chain, reduce losses, maintain nutritional quality and maximize the economic value of agricultural products.

I.2.1. Respiration, Maturation, and Senescence

After harvest, fruits and vegetables are living organisms that continue active metabolic processes. Understanding postharvest physiology is essential for designing appropriate storage and preservation strategies.

I.2.1.1. Respiration: Respiration is the primary metabolic process consuming oxygen and releasing CO_2 and heat. It drives the catabolism of stored carbohydrates, organic acids, and lipids, leading to progressive weight loss, softening, and flavor changes. Two respiratory patterns are distinguished:

- **Climacteric fruits**: exhibit a characteristic respiratory burst (climacteric rise) associated with ethylene production and rapid ripening; particularly sensitive to exogenous ethylene exposure.

- **Non-climacteric fruits**: respiration rate declines progressively after harvest; ripening is not triggered by ethylene; must be harvested at commercial maturity.

Table 5: Climacteric and non-climacteric fruits

Climacteric	Non-Climacteric
Apple, Mango, Papaya, Kiwifruit, Tomato, Cherimoya, Banana, Pear, Apricot, Peach, Plum, Avocado, Plantain, Fig, Guava, Jackfruit, Muskmelon, Nectarine, Passion fruit, Persimmon, Quince, Blueberry, Cantaloupe, Feijoa, Sapodilla, Breadfruit, Broccoli, Durian, Mangosteen, Sapote, Soursop, Sweetsop	Citrus (orange, grapefruit, lemon, lime), Berries (cranberry, raspberry, strawberry, cherry, blackberry), Grape, Pineapple, Lychee, Melon, Loquat, Pomegranate, Cucumber, Tamarillo, Carambola, Cashew-apple, Eggplant, Jujube, Longan, Loquat, Okra, Peas, Pepper, Summer squash, Watermelon, Tangerine, Prickly pear, Rambutan, Snap bean, Cacao, Date, Olive, Pumpkin

- **Role of ethylene**

Ethylene (C_2H_4) is a gaseous plant hormone that plays a central role in fruit ripening, particularly in climacteric species. Two distinct ethylene production systems operate during fruit development (Figure 13):

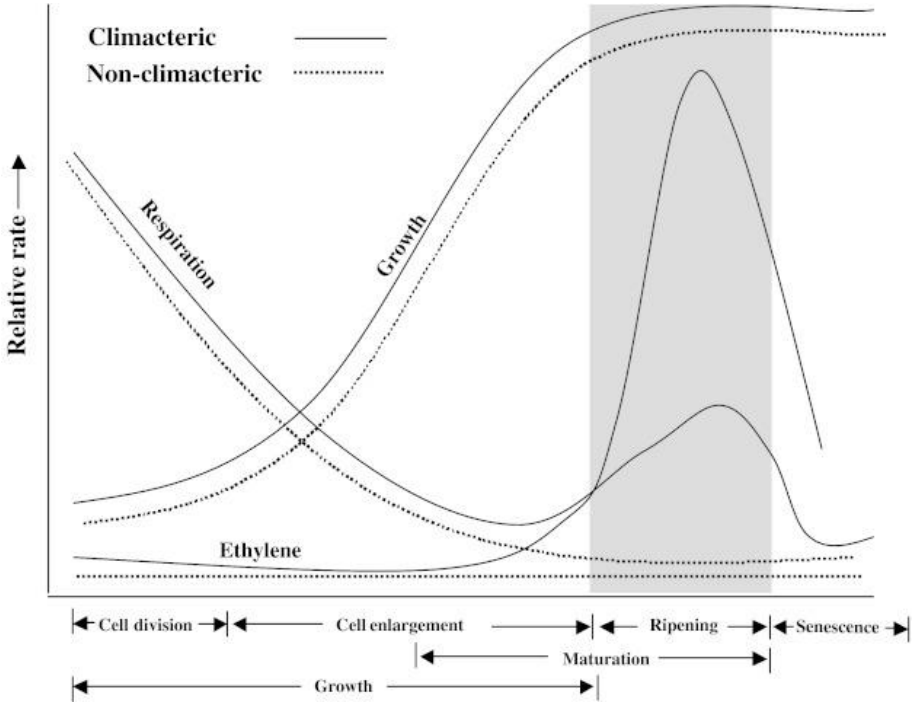

Figure 13: Generalized patterns of growth, respiration and ethylene during development, maturation and senescence of climacteric and non-climacteric fruits

System 1: operates during the immature and pre-climacteric stages. It produces low, basal levels of ethylene and is self-inhibiting – meaning the presence of ethylene actually suppresses further ethylene production. This system is present in both climacteric and non-climacteric fruits.

System 2: kicks in at the onset of ripening in climacteric fruits only. It is autocatalytic – ethylene stimulates the production of even more ethylene, creating the characteristic burst. This positive feedback mechanism maintains the ethylene peak until the fruit reaches an overripe state.

Ethylene's effects on ripening are wide-ranging; it triggers chlorophyll degradation (color change), activates enzymes that soften cell walls, promotes the conversion of starches to sugars, and stimulates the synthesis of flavor and aroma volatiles. In commercial settings, these properties are exploited through artificial ripening rooms where fruits like bananas and mangoes are exposed to controlled ethylene concentrations to ensure uniform ripening.

I.2.1.2. Ripening

Ripening is the next critical phase, during which the fruit or vegetable undergoes biochemical and physiological changes that lead to the development of the characteristics that are typically associated with edible and consumable produce. This process is triggered by the production of ethylene. During ripening, starch is converted into sugars, acids are broken down and volatile compounds responsible for aroma are produced. The fruit's texture softens due to the breakdown of cell walls and the skin color changes dramatically as pigments like carotenoids and anthocyanins are synthesized. In some fruits, like bananas and avocados, ripening continues even after they are harvested, making it possible to control the process for commercial purposes. Vegetables, unlike fruits, do not undergo such a dramatic ripening process. However, they may still experience changes in texture, color, and flavor as they mature.

I.2.1.3. Senescence

Senescence is the final stage in the life cycle of fruits and vegetables, marking the onset of ageing and deterioration. This stage is characterized by a decline in metabolic activity, cell breakdown, and increased susceptibility to spoilage, decay and disease. Fruits become overripe, soft and lose their flavor and nutritional value. Vegetables may become wilted, discolored, and develop off-flavors. Senescence is a natural process that eventually leads to the death of the fruit or vegetable.

1.2.2. Factors Influencing Quality

1.2.2.1. Temperature

Temperature is the single most important postharvest factor controlling the rate of physiological and biochemical deterioration. A reduction of 10°C approximately halves the rate of biological

reactions (Q_{10} principle). Each commodity has an optimal storage temperature; rapid cooling to this temperature immediately after harvest is critical for quality retention.

➢ **Temperature management strategies**

- **Cold chain:** Continuous refrigerated storage (0–15°C depending on commodity); prevents chilling injury in tropical and subtropical fruits (bananas, mangoes, avocados) which suffer membrane damage below 10–12°C.
- **Pre-cooling:** Forced-air, hydro-cooling, or vacuum cooling to rapidly remove field heat before storage and transport.
- **Heat treatments:** Hot water dips or vapor heat at 45–55°C can reduce surface pathogens and delay ripening without significant nutritional damage.

1.2.2.2. Relative Humidity (RH)

High RH (90–98%) is necessary to minimize transpiration and water loss. Weight losses of 3–5% cause visible wilting and turgidity loss. Conversely, excess condensation promotes fungal growth. Humidity control is achieved through refrigeration system design, packaging, and vapor barriers.

1.2.2.3. Controlled Atmosphere (CA) and Modified Atmosphere (MA)

Manipulation of O_2 and CO_2 concentrations around the product inhibits respiration, ethylene synthesis, and microbial growth.

- **CA storage:** Sealed rooms with precise control of O_2 (1–5%) and CO_2 (1–10%); extremely effective for apples and pears, extending storage by months.
- **Modified Atmosphere Packaging (MAP):** Films with selective gas permeability create a beneficial atmosphere within the package through commodity respiration; widely used for fresh-cut produce.
- **Ethylene management:** Ethylene scrubbers (permanganate-based), 1-MCP applications, and low-O_2 atmospheres delay climacteric ripening in storage.
- **Smart/Active Packaging:** Incorporates antimicrobial coatings, ethylene scavengers, and real-time freshness indicators to enhance traditional MAP systems.

I.3. Quality Criteria

Fruit and vegetable quality encompasses all organoleptic, compositional, safety, and commercial attributes that determine consumer acceptability and market value. Quality standards and testing methods have been established at national and international levels to ensure that produce reaching consumers meets defined requirements.

I.3.1. Intrinsic quality attributes

Fruit and vegetable quality is evaluated based on several key attributes:

✓ Appearance includes color (pigmentation stage, uniformity, defects), shape, size, gloss, and absence of mechanical damage, serving as the primary driver of purchase decision at the point of sale.

✓ Texture encompasses firmness (measured by penetrometry), crispness, and juiciness, which are directly related to cell turgor, cell wall composition, and degree of ripening.

✓ Flavor is a combination of taste (sweetness, acidity, bitterness) and aroma (volatile organic compounds), assessed by chemical analysis (SSC/TA ratio, gas chromatography) and sensory panels.

✓ Nutritional value covers vitamins, minerals, dietary fiber, and phytochemical content, and is increasingly measured for functional food claims and health labeling.

✓ Safety ensures the absence of pesticide residues above maximum residue limits (MRLs), mycotoxins, heavy metals, and microbial pathogens, guaranteeing consumer protection.

I.3.2. Calibration standards

Size and weight classifications allowing commercial sorting; defined by categories (Extra, Class I, Class II) that determine commercial value. EU regulations under Commission Implementing Regulation (EU) 543/2011 establish specific marketing standards for over 10 priority fresh commodities (tomatoes, apples, citrus, lettuce, etc.).

I.3.3. Codex Alimentarius standards

Developed by the Codex Alimentarius Commission (FAO/WHO), these international standards define minimum quality requirements, tolerances, sizing, marking, and labeling for fresh and processed fruits and vegetables. They serve as the reference for the World Trade Organization's

(WTO) Agreement on Sanitary and Phytosanitary (SPS) Measures and facilitate international trade.

II. Processing Technologies

II.1. Preservation Processes

II.1.1. Thermal Methods

Thermal treatment has been the cornerstone of fruit and vegetable preservation for over two centuries, relying on the application of heat to inactivate enzymes, destroy pathogenic and spoilage microorganisms, and extend product shelf life. However, heat treatments can induce quality degradation, including loss of thermolabile nutrients, color alterations, flavor modifications, and texture softening.

II.1.1.1. Pasteurization

Pasteurization is a mild heat treatment process used to destroy pathogenic microorganisms and extend the shelf life of food products without significantly altering their nutritional and sensory qualities. The process typically involves heating foods to a temperature below 100°C for a specific duration, depending on the type of food and the microorganisms targeted.

Pasteurization is widely applied in liquid foods such as milk, fruit juices, and certain alcoholic beverages. There are two primary methods of pasteurization (Table 6):

- Low-Temperature Long-Time (LTLT) pasteurization, which involves heating the product to around 63°C for 30 minutes
- High-Temperature Short-Time (HTST) pasteurization, where the temperature is raised to approximately 72°C for 15 seconds.
- Ultra-high temperature (UHT) pasteurization, a more intense form, heats food to about 135°C for a few seconds, making it shelf-stable for extended periods

Table 6: pasteurization types and conditions

Type of Pasteurization	Temperature (°C)	Time Duration	Common Applications
LTLT (Low Temp, Long Time)	63 °C	30 minutes	Milk, dairy products
HTST (High Temp, Short Time)	72 °C	15 seconds	Juices, liquid eggs
UHT (Ultra-High Temperature)	135 °C	2–5 seconds	Shelf-stable milk, cream

II.1.1.2. Sterilization

Sterilization is a more intense heat treatment process that eliminates all microorganisms, including bacterial spores, by heating food to temperatures above 100°C (table 7). Unlike pasteurization, which targets only pathogenic and spoilage organisms, sterilization ensures complete microbial inactivation, making foods shelf-stable for long periods without refrigeration.

Sterilization is commonly used for canned foods, retort pouch products, and other ready-to-eat meals that require long-term storage. The process involves exposing foods to temperatures typically ranging from 110°C to 130°C for varying durations, depending on the food's composition and packaging. Retort sterilization, a widely used method, involves placing packaged foods in pressurized steam chambers to achieve complete microbial destruction.

Table 7: sterilization types and conditions

Type of Sterilization	Temperature (°C)	Time Duration	Common Applications
Conventional Sterilization	110–130°C	10–60 minutes	Canned vegetables, meats
Retort Sterilization	115–121°C	15–40 minutes	Retort pouch meals
Aseptic Processing	135–150°C	2–6 seconds	Shelf-stable beverages

II.1.1.2.1. Appertization

Appertization is a preservation process that involves placing food in a hermetically sealed container and then subjecting it to heat treatment to destroy microorganisms and enzymes responsible for spoilage. Appertization could be defined as sterilization in an airtight container, protected from air.

- **Steps in Appertization** (figure 14)

1) Preparation: cleaning, sorting, peeling, cutting, or grading depending on the product.

2) Blanching/Pre-cooking: Blanching is a short heat treatment used before sterilization or

other processing steps. It consists of briefly heating foods, usually in hot water or steam, then cooling them quickly to stop cooking. This step helps inactivate enzymes that can cause color, flavor, and texture changes. It also softens the tissues, removes trapped air, reduces surface microbes, and makes the food easier to pack and process.

3) Packing/Filling: placing the product in a can, jar, or other container.

4) Sealing/Closing: airtight sealing of the container to prevent contamination.

5) Autoclaving/Heat Treatment: sterilizing the product in an autoclave at a precise temperature and time. This step involves heating the packaged food in an autoclave at a specific temperature and for a specific time in order to destroy microorganisms and spores, and to ensure commercial sterility.

6) Cooling: rapid cessation of heating to stabilize the product.

7) Labeling and Storage: product identification followed by preservation before distribution.

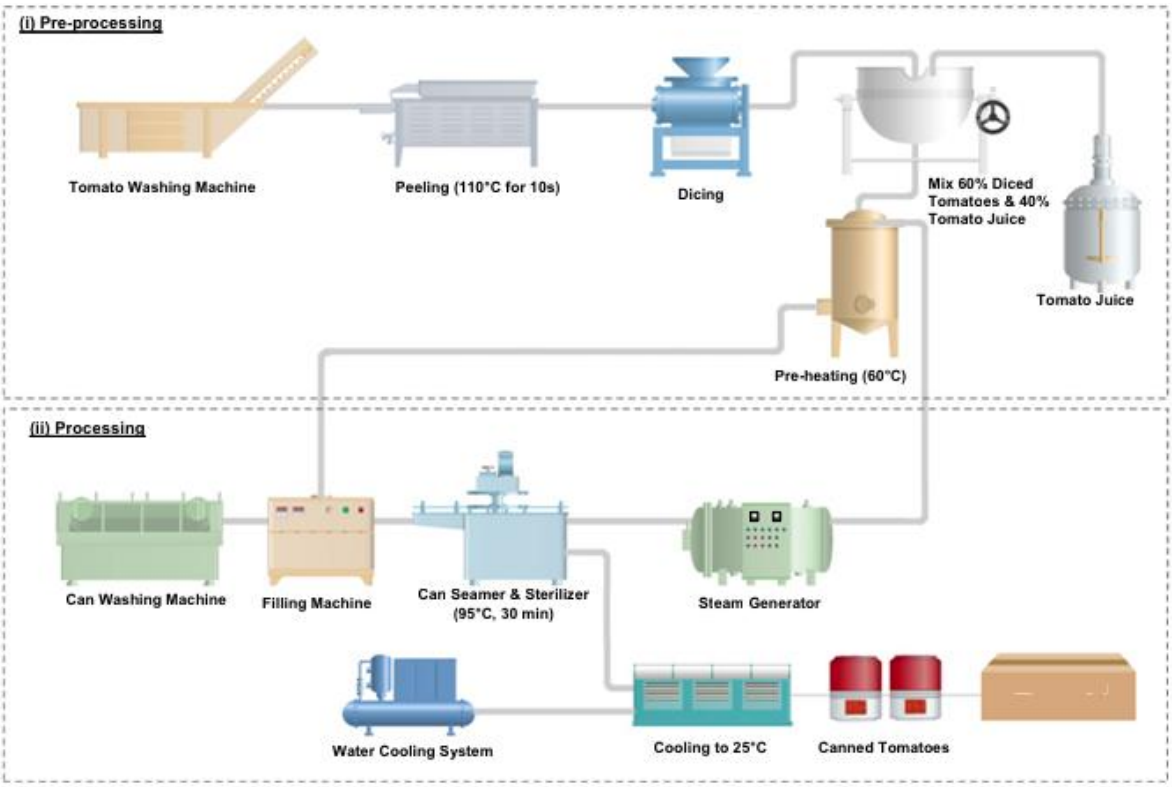

Figure 14 : Apperitization steps for tomato canning

II.1.1.3. Drying

Drying is a dehydration process that is widely used, and has been one of the most popular methods of food preservation in the food processing and preservation industry for many years, where the volume of water is reduced and the main aim is to achieve long-term preservation of food by reducing the water activity in the cells. The drying process of food prevents microbial contamination and chemical changes such as enzymatic and non-enzymatic browning, prolongs the storage life, and reduces packaging, handling and transport costs. The drying process has been used in a wide range of food products such as meat, rice, pasta, dairy, fruit and vegetable products.

II.1.1.3.1. Freeze-drying (Lyophilization)

Freeze-drying is a process in which water is sublimated by the direct transition of water from solid (ice) to vapor, thus omitting the liquid state, and then desorbing water from the "dry" layer (Figure 15). Therefore, the taste, smell, and content of various nutrients do not change. Raw food materials contain a lot of water, ranging from 80% to 95%. The removal of water by sublimation results in the creation of highly porous structure of the freeze-dried products, and the rehydration of lyophilizates occurs immediately.

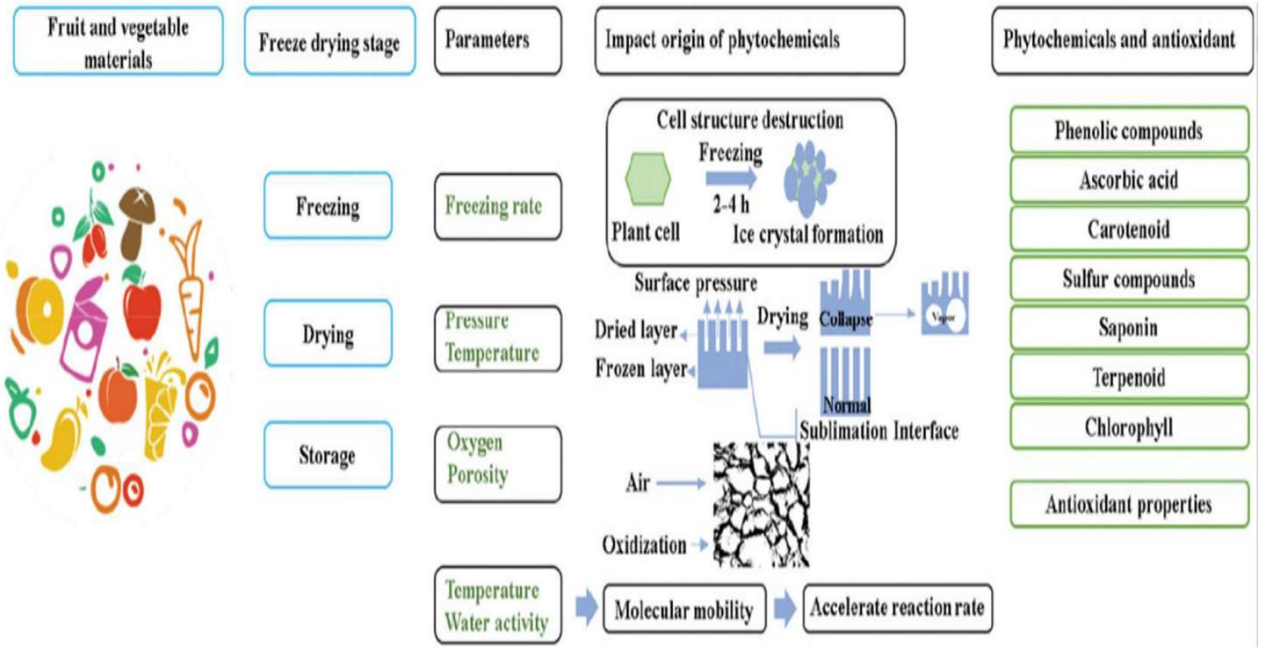

Figure 15: A typical freeze-drying process, including freezing, primary drying and secondary drying (the data were adopted from production type vacuum freeze dryer)

The water in the products can be free water or water bound to the matrix by various forces. Free water freezes, but bound water does not freeze. In the freeze-drying process, all ice water and some bound water must be removed. Therefore, lyophilization is a highly complex and multi-step process that consists of (Figure 16):

- The freezing of the product, most often under atmospheric pressure.
- Primary drying—proper freeze-drying—ice sublimation, most often at reduced pressure.
- Secondary drying—desorption drying—drying the product to the required final humidity.

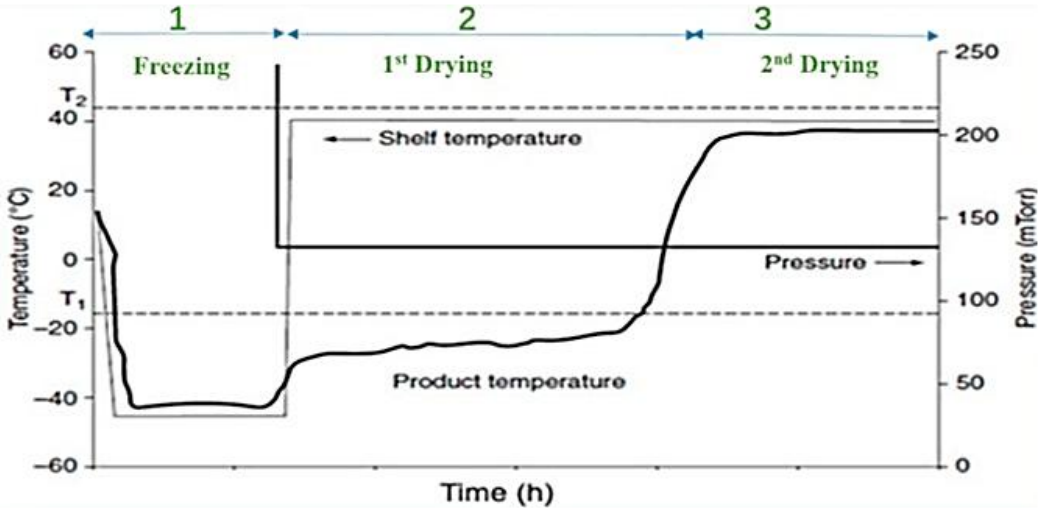

Figure 16: Temperature profile of product during freeze-drying process, where T1 (dotted line) is the collapse temperature and T2 (dotted line) is the glass transition temperature of dry solids

➢ Parameters of Freeze Drying

The main parameters of freeze drying are temperature, drying time, sample species, pretreatment, size, and pressure. These factors strongly influence the final quality of the product, especially its bioactive compounds, flavor, color, texture, and preservation level.

a) Pretreatments

Pretreatments are used to improve product quality, reduce drying time, and protect physical and bioactive properties. Common pretreatments include blanching, ultrasound, pulsed electric field (PEF), CO2 laser perforation, high hydrostatic pressure (HHP), freeze–thaw treatment, and

osmotic dehydration. In general, the right pretreatment can improve drying efficiency and preserve color, taste, and antioxidant compounds.

b) Size

Sample size affects drying time and product quality. Smaller samples usually dry faster and may retain more bioactive compounds, while larger samples need more time. However, in some cases, size or cutting style does not significantly change the final quality.

c) Temperature

Temperature is a critical factor because it must support sublimation without damaging the product. Low temperatures generally preserve bioactive compounds better, while high temperatures can cause color change and degradation. Temperature is closely linked with pressure during the process.

d) Samples

The effect of freeze drying depends on the type of sample. Different plants, fruits, and vegetables respond differently, so the preservation of phenolics, antioxidants, and texture varies by species. In other words, sample composition strongly influences the final result.

e) Time and Pressure

Drying time and pressure work together to control the process. Lower pressure can reduce drying time and help preserve quality, but the conditions must be optimized for each product. Proper control of time and pressure reduces collapse, improves structure, and protects sensitive compounds.

II.1.1.3.2. Solar and Conventional Hot-Air Drying

Sun drying is the oldest and lowest-cost preservation method; widely practiced in developing countries for raisins, figs, apricots, and tomatoes, but subject to contamination, uncontrolled conditions, and quality variability.

A. Open Sun Drying

Also known as natural or open sun drying (OSD), this method spreads crops in thin layers directly on the ground or trays, exposed to sunlight and wind. Short-wavelength solar radiation is absorbed, converting to thermal energy that raises crop temperature (enhanced by dark colors) to drive evaporation, with natural wind providing air circulation to remove moisture though reflective, evaporative, and convective losses reduce efficiency (figure 17A).

B. Direct Drying

Direct solar drying (DSD) protects products inside a chamber with a transparent cover (glass/plastic); solar radiation passes through, partially reflects or absorbs to heat the chamber via greenhouse effect. Ambient air enters via bottom holes, picks up evaporated moisture from the warmed crop, and exits from the top, minimizing external convection but risking UV discoloration and internal condensation on the cover (figure 17B).

C. Indirect Drying

In indirect solar drying (ISD), an opaque drying cabinet with trays is separate from the solar collector; ambient air is heated in the collector (passively or with fans) and flows to the crop, evaporating moisture due to concentration differences between hot dry air and wet product surface. This avoids direct sun exposure for better quality preservation, though it requires higher temperatures and precise flow control (figure 17C).

D. Hybrid Solar-Thermal Drying

Hybrid solar dryers (HSD) integrate direct solar radiation (via collectors) with backup energy (electric, biomass, thermal storage, or PV-powered fans); heated air circulates forcibly into the chamber, enabling continuous operation day/night regardless of weather. Key components include drying chamber, solar collector, energy accumulator, and fans, offering optimized control at higher costs and environmental footprint (figure 17D).

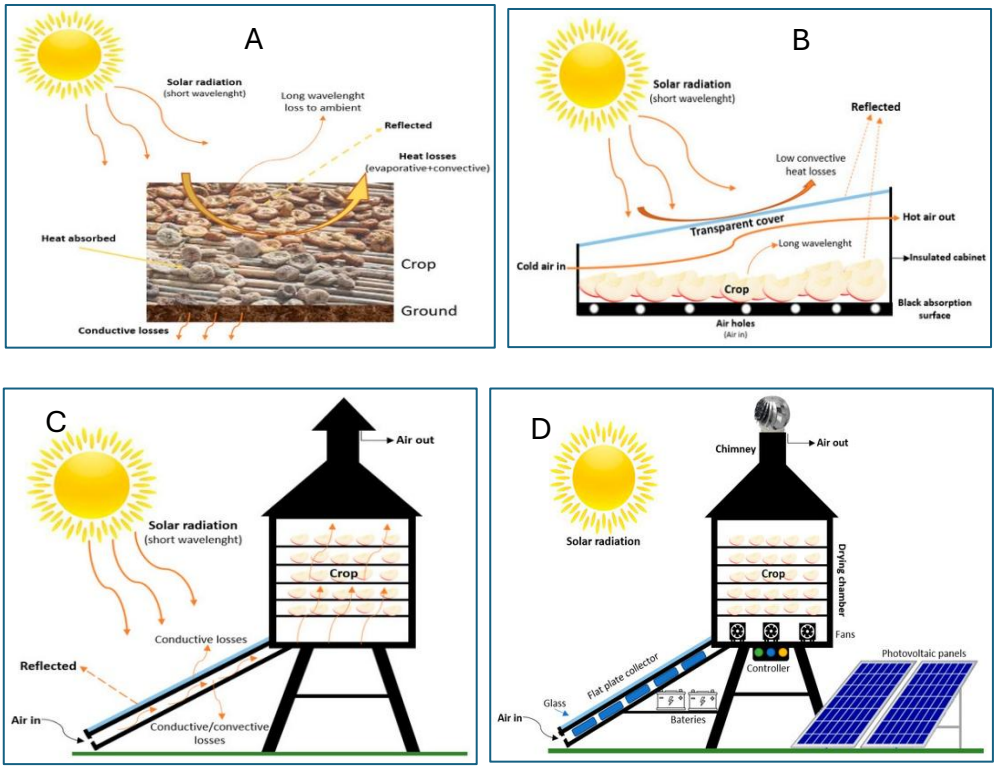

Figure 17: Drying methods. A: Schematic of working principle of open sun drying method. B: Schematic of working principle of direct drying method. C: Schematic of working principle of indirect drying method. D: Schematic of working principle of hybrid (solar–thermal) drying method.

II.1.2. Non-Thermal Methods

Non-thermal processing technologies have emerged as alternatives to heat treatment, offering the ability to inactivate microorganisms and enzymes while preserving heat-sensitive nutrients, flavor, and organoleptic properties.

II.1.2.1. High Pressure Processing (HPP)

High-Pressure Processing (HPP), also called ultra-high pressure (UHP) or high hydrostatic pressure (HHP), is a novel food preservation technology used to inactivate microorganisms while preserving the sensory and nutritional quality of foods. HPP normally operates in the range of 100 to 800 MPa. It is used for both solid and liquid foods to achieve pasteurization, and in some advanced systems, higher pressure combined with heat can also lead to sterilization.

HPP is based on three main principles (figure 18):

- Le Chatelier's principle: pressure favors changes that reduce volume, which helps disrupt microbial structures.
- Isostatic principle: pressure is applied equally in all directions, so the food is treated uniformly.
- Principle of microscopic ordering: pressure affects membranes, proteins, and cellular structures at the microscopic level.

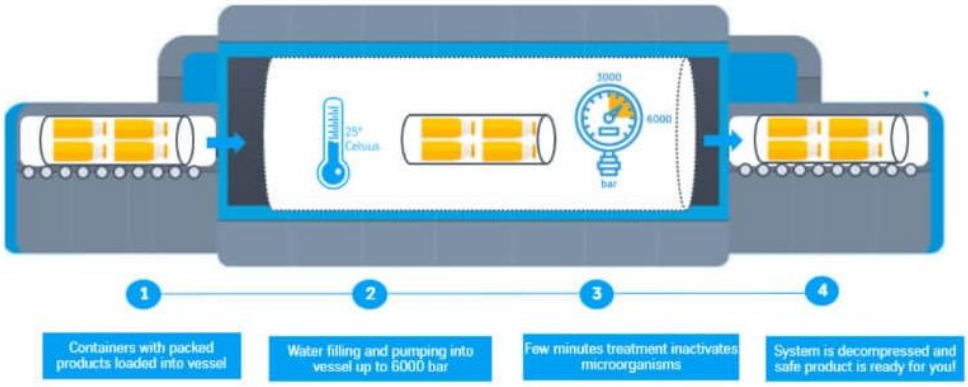

Figure 18: Principle of High-Pressure Processing (HPP)

An HPP system is mainly composed of a pressure vessel, a pressurization system, and auxiliary units such as heating or cooling elements (figure 19). The product is first packed in suitable materials, then placed inside the pressure vessel filled with a pressure-transmitting fluid, usually water because it is minimally compressible.

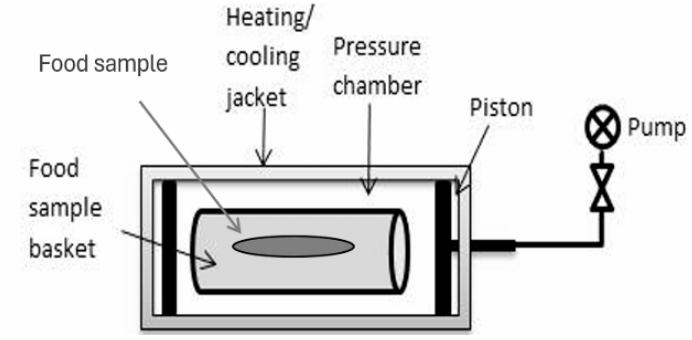

Figure 19: Schematic of high-pressure processing system.

II.1.2.2. Irradiation

Food irradiation is a preservation method sometimes called “cold pasteurization” because it destroys harmful bacteria without using heat. It helps reduce the number of pathogens and spoilage microorganisms, which can extend shelf life and reduce food waste.

The food is exposed to controlled gamma rays, usually from sources such as Cobalt-60 or Cesium-137. These rays penetrate the food quickly and produce little or no heat, so the treatment does not make the food radioactive. According to international expert evaluations, irradiation of food up to an average dose of 10 kGy has been considered safe, with no toxicological, nutritional, or microbiological problems reported. However, irradiated food still needs proper handling and good manufacturing practices, just like any other food (Figure 20).

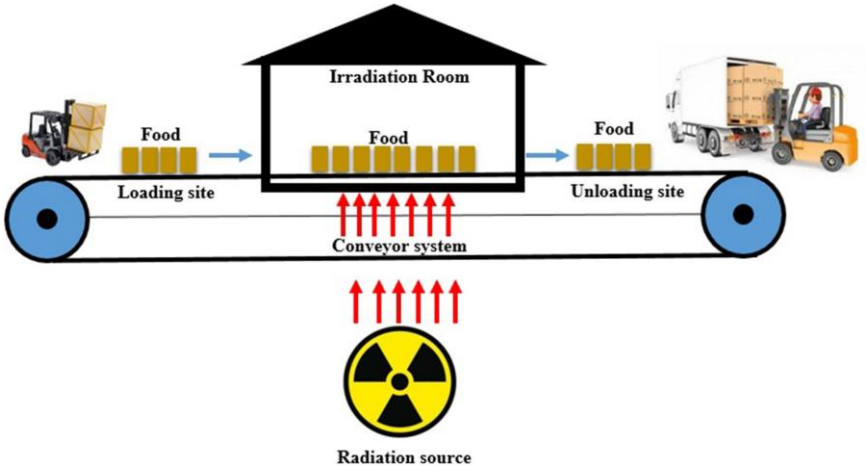

Figure 20: Process of food irradiation: The food is loaded on a conveyor system which transport it to irradiation room where it is exposed to the required amount of radiation for a certain period of time after which the conveyor takes it to the unloading site for removal and onward storage

This method is effective against common foodborne pathogens such as *Salmonella, E. coli,* and *Listeria*. It also helps reduce microbial contamination, insect infestation, and spoilage, while preserving most of the food’s quality. Food irradiation can slow down ripening and sprouting in fruits and vegetables by modifying the metabolism of plant cells. It also causes only limited changes in food because the treatment does not rely on heat. Table 8 displays different forms of irradiation.

Table 8: Different forms of irradiation.

Irradiation Treatment	Purpose of Application	Dose, kGy
Radicidation	To reduce viable non-spore-forming pathogenic bacteria	0.1–8.0
Radurisation	To kill viable spoilage organisms	0.4–10.0
Radappertisation	To eliminate both vegetative bacteria and spores	10.0–50.0

II.1.2.3. UV Treatment

Ultraviolet radiation, especially UV-C, is a non-thermal treatment used on fruits and vegetables to reduce microbial contamination and extend shelf life. UV-C is commonly used because it has a strong germicidal effect, mainly at 254 nm.

The principle of UV treatment is simple; the light damages the DNA or RNA of microorganisms on the surface of the product. As a result, bacteria, yeasts, and molds are inactivated, and the spoilage process is slowed down.

UV-C helps preserve the color, texture, and nutritional quality of fresh and fresh-cut produce. It can also reduce enzymatic browning by inhibiting enzymes such as PAL, PPO, and POD, which are involved in quality deterioration.

For fresh-cut fruits and vegetables, UV treatment helps reduce microbial contamination while maintaining quality. In some cases, it also improves firmness, slows browning, and preserves color and aroma better than chemical sanitizers (table 9).

Table 9: the effect of UV-C light on reduction of microorganisms in fresh-cut produce

Fresh-cut commodity	Microbiological organism	Number/UV lamp/power/fluence
Watermelon	Mesophilic, psychrophilic, and enterobacteria	15/LPM/36W
Cantaloupe Melon	Yeast, mold, *Pseudomonas* spp., mesophilic aerobes, Lactic acid bacteria	1.6, 2.8, 4.8, 7.2 kJ/m²1/LPM/N/A 0.0118 kJ/m²
Apple	*Listeria innocua* ATCC 33,090; *Escherichia coli* ATCC 11,229; and *Saccharomyces cerevisiae* KE 162	2/LPM/15 W 5.6 ± 0.3; 8.4 ± 0.5 and 14.1 ± 0.9 kJ/m²

II.1.2.4. Biopreservation

Biopreservation is a natural method of food preservation that uses beneficial microorganisms, their metabolites, or their derivatives to inhibit spoilage microorganisms and pathogens, thereby increasing shelf life and food safety. It is considered as an environmentally friendly and low-toxicity alternative to chemical preservatives.

The principle is based on the use of protective cultures or their antimicrobial compounds to modify the natural microbial ecosystem of the food. These competitive microorganisms can produce organic acids, bacteriocins, hydrogen peroxide, peptides, enzymes, exopolysaccharides, and other metabolites that inhibit microbial growth.

II.1.2.4.1. Fermentation

Fermentation is a food preservation process that uses the activity of bacteria, yeasts, and molds to transform food. During this process, microorganisms break down carbohydrates and produce compounds such as organic acids, carbon dioxide, alcohol, and other substances that help preserve the food and improve its characteristics. Fermentation helps preserve food, reduce spoilage, and produce foods with good sensory qualities and sometimes probiotic benefits. It is widely used for products such as yogurt, sauerkraut, fermented vegetables, and many traditional foods.

The main idea of fermentation is that microorganisms grow in the food under controlled conditions and change its composition. These changes can lower the pH, slow the growth of harmful microbes, and create flavors, textures, and aromas that are often desirable in fermented products.

The fermentation could be classified according to technology, type of microorganisms carrying out the fermentation, and product profile (figure 21):

Technology includes spontaneous fermentation, where fermentation occurs naturally using microorganisms already present on the product or in the environment; back-slopping, in which part of a previously fermented product is added to initiate a new fermentation; and fermentation with starter cultures, where selected microorganisms, either a single strain or a mixture of strains, are used to better control the process. The microorganisms involved may include bacteria, such as aerobic *Bacillus* species or anaerobic lactic acid bacteria (LAB), yeasts, which mainly contribute to alcohol, gas, and aroma production, and molds, which may also participate in certain fermentation processes. The product profile may be acidic or lactic acid-based, especially in fruits

and vegetables where LAB produce lactic acid, or alkaline, mainly in fermented legumes where fermentation can create a more alkaline environment.

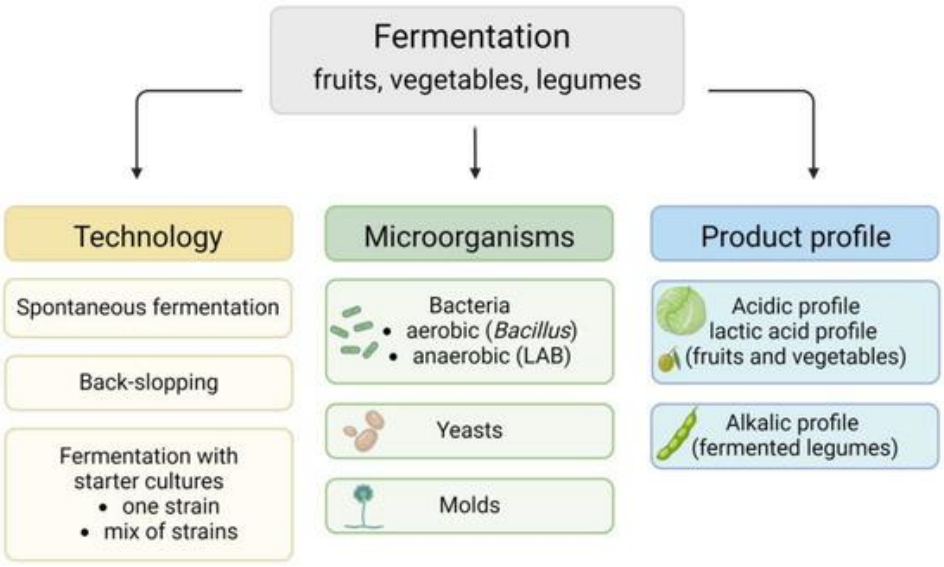

Figure 21: Fermentation classification according to technology, type of microorganisms carrying out the fermentation, and product profile.

➢ **Methods of fermentation used for fruits and vegetables** (Table 10)

1. Submerged fermentation

This method uses a liquid medium in which microorganisms grow freely. It is suitable for microbes that need a lot of moisture, especially bacteria and some yeasts. In this system, nutrients are dissolved in the liquid, and the microorganisms produce acids or other bioactive compounds in the broth.

2. Surface fermentation

In surface fermentation, microorganisms grow on the surface of the medium rather than inside it. This method is often used when the microorganism forms a visible layer or mycelial mat on top of the substrate. It is generally more suitable for small- or medium-scale production.

3. Solid-state fermentation

Solid-state fermentation is carried out on a solid material with little or no free water. The moisture needed for microbial growth is retained inside the solid substrate. This technique is especially

interesting for fruit and vegetable by-products because it can use peels, pulp, or plant residues as substrates.

Table 10: Types of fermentation and their advantages and disadvantages.

Fermentation type	Advantage	Disadvantage	Citric acid production
Surface fermentation	Less effort in operation, installation, and energy cost.	Very few surface microorganisms, large amount of heat generation, time-consuming, needs large area/space, sensitive to contamination by *Penicillia*, other *Aspergillus*, yeasts, and lactic acid bacteria.	Used in small/medium-scale industries.
Submerged fermentation	Sophisticated control mechanisms, lower labour cost, higher productivity and yield.	High-cost media, sensitive to trace metal inhibition, risk of contamination, high amount of post-recovery wastewater generation.	About 80% of the world's citric acid production.
Solid-state fermentation	Simple technology, higher yield, wide range of low-cost media, resembles the natural habitat for several microorganisms, better oxygen circulation, less susceptible to trace element inhibition, lower energy and cost requirements, low risk of bacterial contamination, less post-recovery waste.	Difficulties in scale-up, difficult control of pH, moisture, temperature, nutrients, and microbial growth, higher impurity products, higher recovery product costs.	Higher citric acid yields; economically efficient and industrially feasible process due to efficient utilization and value addition of wastes.

II.1.2.4.2. Probiotics

'Probiotics' is defined by the Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO) as "live microorganisms which when administered in adequate amounts confer a health benefit on the host"

Probiotics are an efficient class of microorganisms that can act as protective cultures in foods. Rather than just preserving and extending the shelf life of foods (figure 22, table 11), they also add to the nutritional profile of the foods by maintaining good gut health. Broadly speaking about probiotic preservation, a natural technique of enhancing the shelf life of food, there are two methods in which probiotics are applied. Biopreservation can be through the probiotic strains of organisms in the food or via metabolic products such as bacteriocins, postbiotics released or

externally added to the food. At the same time, this biological preservation can be either by externally added probiotic strains or by inherent microbiota in the food. Such foods can be broadly referred to as functional foods in the market due to their higher functionality in maintaining good human health

Figure 22: Extending of shelf life of fruits with probiotics

Table 11: Examples of probiotics used in biopreservation of vegetables, fruits, and other miscellaneous plant-based food items.

Food type	Product	Probiotic(s) used in biopreservation	Mode of biopreservation
Vegetable-based	Probiotic blanched cabbage	*Lb. paracasei* LMG P22043	Exclusion of pathogenic microorganisms
	Probiotic cabbage juice	*Lb. plantarum*, *Lb. rhamnosus*, *Lb. brevis*	Fermentation – low pH
	Probiotic beetroot juice	*Lb. casei* 431	Fermentation – low pH
	Probiotic tomato juice	*Lb. acidophilus*, *Lb. casei*, *Lb. plantarum*, *Lb. delbrueckii*	Fermentation – low pH
Fruit-based	Probiotic cut apple	*Lb. plantarum* 299v	Increased antioxidant activity; delayed oxidation
	Probiotic enriched	*Lb. plantarum* SICC	Production of antimicrobial

apple snacks		bioactive compounds
Probiotic apple juice	*Lb. paracasei* ssp. *paracasei*	Fermentation – low pH
Probiotic pineapple juice	*Lb. casei* NRRL B-442	Fermentation – low pH
Probiotic orange juice powder	*Lb. plantarum* 299v; *P. acidilactici* HA-6111-2	Production of antimicrobial bioactive compounds
Probiotic orange juice	*P. acidilactici* CE51	Fermentation – low pH
Probiotic cantaloupe juice	*Lb. casei* NRRL B-442	Fermentation – low pH
Probiotic pomegranate juice	*Lb. plantarum*, *Lb. delbrueckii*	Fermentation – low pH
Cut honeydew melon	*Lb. casei* NCIMB 4114	Increased antioxidant activity; delayed oxidation

II.2. Processed Products

Fruit and vegetable processing generates a vast and diversified range of commercial products, each demanding specific unit operations, quality control systems, and regulatory compliance frameworks. The transformation of raw produce into shelf-stable, safe, and nutritionally valuable products relies on the mastery of thermal, mechanical, biological, and physicochemical processes.

II.2.1. Juices and Beverages

Fruit and vegetable juices represent one of the most economically significant categories of processed horticultural products. Juices may be classified as single-strength (not concentrated), concentrated, or reconstituted; clarified (clear) or pulpy (cloudy); and thermally treated or minimally processed. The general production protocol is:

1. **Reception and sorting of raw materials**

Fruits or vegetables are received, inspected for maturity, and sorted to eliminate damaged, over-ripe, or contaminated units. Grading may be by size, color, or Brix value (°Brix).

2. **Washing and sanitization**

Produce is washed with potable water, often supplemented with approved sanitizing agents (chlorine at 50–200 ppm, or citric acid, peracetic acid). This step reduces the surface microbial load.

3. **Size reduction and extraction**

Depending on the fruit type, extraction is achieved by crushing/pressing (citrus, apple, grape) or by hot-break or cold-break methods (tomato). Cold-break processing (below 60°C) preserves aromatic volatiles and color. Hot-break (70–85°C) inactivates endogenous enzymes such as pectin methylesterase (PME) and polygalacturonase, stabilizing cloud and viscosity.

4. **Enzymatic treatment (depectinization)**

Pectinase and cellulase preparations are added (typically 0.01–0.05% w/w) at 40–50°C for 30–120 minutes to hydrolyze pectin and improve juice yield and filtration in clear juice production.

5. **Clarification and separation**

Clarification and separation of juices involve several key steps to achieve the desired clarity and stability. Fining agents such as bentonite, gelatin, or silica sol are used for clear juices to remove suspended particles. Centrifugation at 3,000–10,000 rpm removes coarse particles from the juice. Microfiltration or ultrafiltration, using membrane technology with 0.1–0.45 μm pore sizes, yields brilliant, haze-free juices by removing finer particles and microorganisms. For cloudy or pulpy juices like orange juice, homogenization is employed instead to ensure a stable suspension of particles, maintaining the desired turbidity and texture.

6. **Deaeration**

Dissolved oxygen is removed under vacuum (≤20 mbar) to prevent oxidative browning (Maillard reactions, ascorbic acid oxidation) and to stabilize color and flavor.

7. **Concentration (optional)**

Evaporation under vacuum (falling-film evaporator at 45–65°C) reduces water content to produce juice concentrates (65–70° Brix). Freeze concentration is an alternative that better preserves aroma.

8. **Thermal treatment**

- **Pasteurization (HTST – High Temperature Short Time)**

72–95°C for 15–60 seconds. Destroys vegetative pathogens and spoilage microorganisms. The product is distributed under refrigeration (shelf life: days to weeks). Preferred for NFC (not-from-concentrate) juices to maintain fresh sensory profile.

- **UHT (Ultra High Temperature)**

135–150°C for 2–10 seconds, followed by aseptic cooling and aseptic filling. Achieves commercial sterility; inactivates spores. Enables ambient storage for 6–12 months. Used for concentrates, purées, and beverage bases intended for long shelf life or export.

9. **Aseptic filling and packaging**

The product is filled into pre-sterilized containers under sterile conditions.

II.2.2. Purées and Pastes

Purées are homogenized preparations of comminuted fruit or vegetable flesh. Major commercial products include tomato paste (the world's largest processed tomato product category), apple sauce, and infant/baby food formulations. The Production protocol of tomato paste is as follow**:**

1. Raw material reception and inspection: Tomatoes are received at the plant, inspected for maturity, color, and freedom from mold.

2. Washing: Multiple-stage washing with potable water; flume washing or spray washing removes soil, debris, and surface microorganisms.

3. Sorting and trimming: Damaged, green, or moldy tomatoes are removed manually or by optical sorters.

4. Chopping / crushing: Whole tomatoes are crushed to facilitate juice extraction and heat transfer.

5. Hot-break or cold-break heating

a) Hot-break: Crushed tomatoes are heated rapidly to 85–95°C before pulping. This inactivates polygalacturonase and PME, resulting in a product with high viscosity and body, suitable for paste and ketchup.

b) Cold-break: Crushed tomatoes are heated to 65–70°C, preserving enzymes partially active; results in a more fluid product with brighter color, preferred for tomato juice.

6. Pulping and finishing: Heated pulp passes through finishers (sieves of 0.5–0.8 mm) to remove seeds and skin, yielding homogeneous tomato pulp/purée.

7. Evaporation / concentration: Multi-effect vacuum evaporation (50–65°C to protect lycopene and color) reduces water content to target °Brix: purée = 7–11° Brix; paste = 28–36° Brix; double concentrate = 36+° Brix.

8. **Pasteurization:** The concentrate is heat-treated at 95–100°C for 30–60 seconds.

9. **Filling and packaging:** Hot-fill into sterilized cans (tin-plated steel or BPA-free), glass jars, or aseptic bag-in-drum containers. Hot-fill temperature maintained at ≥85°C to ensure can lid sterility.

10. **Cooling and labeling:** Cans are cooled rapidly by water spray or immersion to below 40°C within 30 minutes to prevent thermophilic spoilage.

II.2.3. Jams, Jellies, and Marmalades

These are preserved fruit products whose structure and stability are governed by the formation of a pectin gel in the presence of sugar and acid. They are regulated under EU Directive 2001/113/EC relating to fruit jams, jellies, and marmalades intended for human consumption.

- **Jam:** Contains identifiable fruit pieces or fruit pulp, pectin, and sugar; minimum 35 g of fruit per 100 g finished product; minimum total soluble solids ≥60° Brix.
- **Jelly:** Prepared exclusively from clarified fruit juice; gel is clear and bright.
- **Marmalade:** Prepared from citrus fruit (pulp, juice, peel); minimum 20 g citrus per 100 g finished product.

II.3. Valorization of By-Products

The processing of fruits and vegetables generates enormous volumes of by-products (peels, seeds, pomace, stems, leaves) which currently represent a major sustainability challenge. Approximately one-third of global food production is lost or wasted annually, with fruit and vegetable residues accounting for about 22% of this total.

II.3.1. Composition and value of by-products

Fruit and vegetable by-products are valuable sources of nutrients and bioactive compounds that can be recovered and used in food, feed, nutraceutical, cosmetic, and pharmaceutical applications. Their main value comes from the presence of proteins, carbohydrates, dietary fiber, minerals, vitamins, polyphenols, flavonoids, pigments, fatty acids, and phytosterols (Table 12).

Table 12: composition and nutritional value of fruit and vegetables byproducts

Component	Nutritional / functional value	Examples of by-products mentioned
Protein	A source of protein that can be used in food products, animal feed, supplements, and functional ingredients.	Grape pomace, mango peel, papaya peel and seed, pineapple peel and pomace, tomato skins and seeds, banana peel.
Carbohydrates	Provide energy and can be used as substrates for fermentation and food formulation.	Apple pomace, orange peel, pear pomace, potato peel, onion skin, carrot pomace, pomelo peel.
Dietary fiber	Supports digestive health and can be used to enrich biscuits, bread, pasta, and other functional foods.	Apple pomace, cactus pear peel and seeds, mango peel, pomegranate peel, strawberry pomace, potato peel, melon peel.
Minerals	Contribute to enzymatic activity, fluid balance, and bone health.	Broccoli leaves, cabbage outer leaves, carrot peel, potato peel, tomato waste, pineapple peel, banana peel, papaya peel and seeds.
Vitamins	Important for food fortification and nutraceutical applications.	Broccoli leaves and stems, cabbage outer leaves, beetroot peel, citrus peels, pumpkin seeds, tomato waste, pomegranate peel, watermelon rind.
Polyphenols	Strong antioxidant, antimicrobial, and anti-inflammatory compounds.	Apple pomace, avocado peel, banana peel, carrot waste, eggplant peel, onion skin, grape pomace, citrus peels, mango peel, pomegranate peel, strawberry residues, tomato waste.
Flavonoids	Increase antioxidant capacity and functional value of foods.	Apple pomace, cucumber waste, eggplant peel, onion skin, orange peel, grapefruit waste, grape skin, mango peel, banana peel, strawberry by-products.
Pigments / carotenoids	Useful as natural colorants and functional compounds.	Tomato pomace, carrot residues, beetroot peel, avocado seed, watermelon rind, mango peel, pomegranate peel.
Fatty acids / phytosterols	Valuable for edible oils, cosmetics, and pharmaceutical uses.	Mango seed kernel, pumpkin seed, avocado seed, cactus pear seed.

II.3.2. Extraction technologies

Conventional solvent extraction is being progressively replaced by green, non-thermal extraction methods that better preserve thermolabile bioactive compounds:

II.3.2.1. Ultrasound-Assisted Extraction (UAE)

Ultrasound-assisted extraction (UAE) uses high-frequency sound waves, typically in the range of 20 kHz to 100 MHz, to generate acoustic cavitation. This process creates microscopic bubbles in

the solvent that grow and collapse violently, producing strong mechanical effects that disrupt plant cell walls and improve mass transfer.

The main principle of UAE is cavitation. When ultrasound passes through a liquid containing plant material, alternating compression and rarefaction cycles form bubbles that implode, creating shock waves, microjets, turbulence, and shear forces. These effects increase solvent penetration and help release intracellular compounds more efficiently (Figure 23).

UAE is widely used to extract bioactive substances such as polyphenols, flavonoids, anthocyanins, polysaccharides, pectins, proteins, peptides, essential oils, pigments, and other natural compounds. The method has been successfully applied to materials such as flaxseed, papaya leaves, rye bran, orange peel, eggplant peel, mung bean peel, sunflower heads, and passion fruit peel.

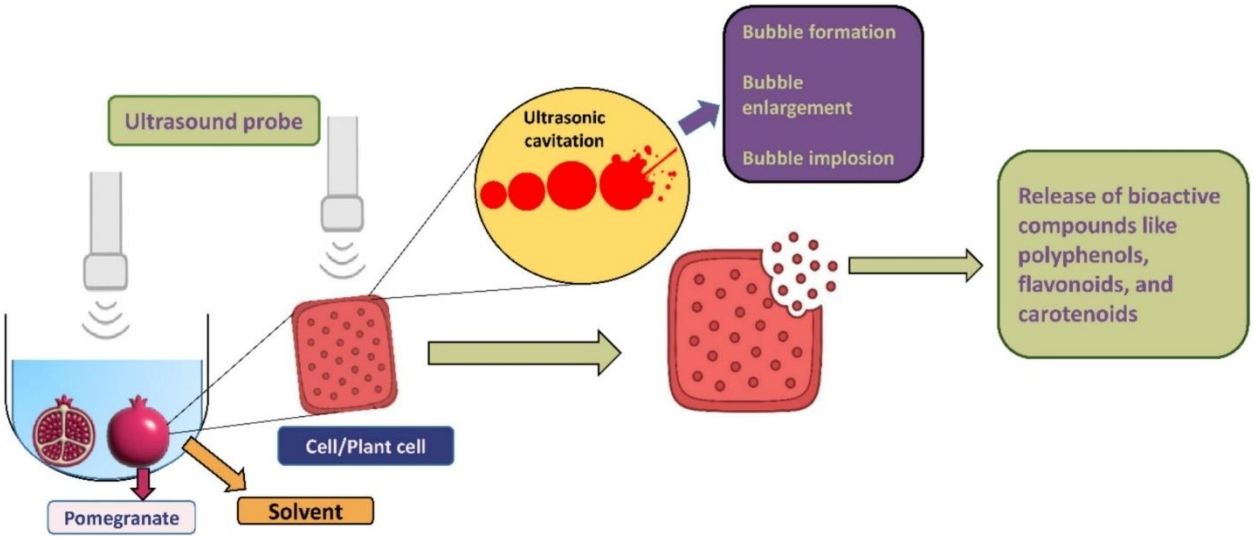

Figure 23: mechanism of Ultrasound-Assisted Extraction

II.3.2.2. High Hydrostatic Pressure (HPP) extraction

High Hydrostatic Pressure is a non-thermal preservation method that uses high pressure to reduce microorganisms, extend shelf life, and improve extraction from plant tissues while maintaining food quality. HPP disrupts plant cell integrity, enhances solvent penetration and mass transfer, and facilitates the release of bioactive compounds. As a non-thermal technology, it helps retain the texture, flavor, color, nutrients, and antioxidant compounds of foods more effectively than conventional heat treatments.

II.3.2.3. Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction (SFE) is a recent extraction technique, and it is based on the use of the critical point of the solvent during the extraction. The combination of gas mass transfer and liquid solvation properties allows a high transfer mass (diffusion coefficients) than working below critical point. The majority of SFE studies have focused on the use of CO_2 due to its characteristics (non-toxic and cheap and can be easily removed after extraction).

II.3.2.4. Enzyme-Assisted Extraction

Enzyme-assisted extraction depends strongly on operating conditions such as pH, temperature, and the surrounding environment. Under optimal conditions, the enzyme binds to the plant cell wall, changes its conformation, and weakens cell wall bonds, which helps release the active compounds (Figure 24).

This technique uses several enzymes, including cellulase, xylanase, amylase, pectinase, hemicellulase, papain, and trypsin. It is especially useful for extracting bioactive compounds in a more selective and efficient way.

Enzymatic hydrolysis is widely used to obtain bioactive peptides because it is fast, specific, and able to produce peptides with reproducible molecular weight and composition. Depending on the enzyme used, these peptides may show different biological activities, such as antihypertensive or antioxidant effects.

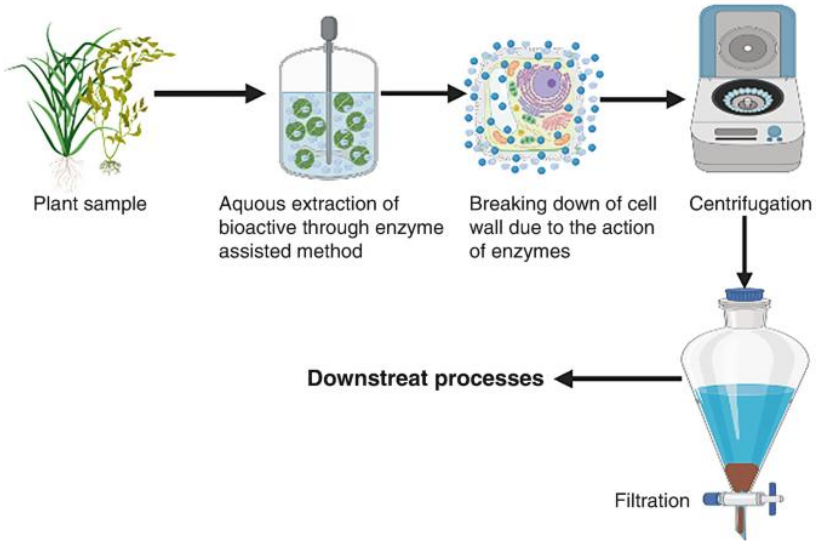

Figure 24: Principle of Enzyme-Assisted Extraction

II.3.2.5. Pulsed Electric Field (PEF)

Pulses Electric Fields (PEF) consist of subjecting the selected material to the intermittent application (<300 Hz) of electric fields at moderate-high intensity (0.1–20 kV/cm) and short duration (μs to ms). The main characteristic is the application of electric field pulsing on plant matrices that induces electro permeabilization (formation of located pores in cell membranes of cells), and the effect mainly depends on medium composition. PEF technology has been defined as technology which requires fewer resources to produce nutritional with optimal sensory characteristics and longer shelf lives of products such as hummus, smoothies and juices. Related to recovery bioactive compounds from fruits and vegetables by-products, it enhances the specific recovery of bioactive intracellular compounds without increasing temperature or/and damaging the structure of the matrix. The obtained result depends on treatment intensity, physicochemical properties of the matrix and the tissues and cells composition. If the combination of the variables is optimized, reversible electroporation could occur (the membrane can return to its original state once the electric field application has finished). It is important to highlight that recent study indicated that pulsed electric field (PEF) treatment needs an optimization for more selective, quicker, and sustainable bio-active compounds extraction in the food industry.

III. Packaging Technologies

III.1. Packaging Materials

Packaging is the final protective barrier between the product and external deteriorating factors, and plays a fundamental role in maintaining quality, extending shelf life, ensuring safety, and enabling commercial distribution. Packaging for fruits and vegetables is essential for reducing post-harvest losses, preserving quality, and extending shelf life. Key functions include protecting produce from mechanical damage and contaminants, managing moisture loss to prevent wilting, and controlling atmospheric gases for optimal storage

III.1.1. Key barrier properties

The key barrier properties of packaging describe its ability to limit exchanges between the food product and the external environment. For fruits and vegetables, these properties are essential for reducing postharvest losses, slowing moisture loss and wilting, controlling gas exchange, and maintaining quality during storage and distribution.

a) Oxygen Transmission Rate (OTR): indicates how much oxygen passes through the packaging material over time. A low OTR helps reduce oxidation, enzymatic browning, and quality loss in oxygen-sensitive produce.

b) Water Vapor Transmission Rate (WVTR): measures the passage of water vapor through the package. This is critical for preventing excessive dehydration and wilting, while also avoiding condensation that can promote microbial growth.

c) Carbon Dioxide Transmission Rate (CO_2TR): describes how much carbon dioxide can pass through the material. It is important in modified-atmosphere packaging because it helps balance the respiration of fresh produce.

d) Aroma barrier: limits the loss of desirable volatile compounds and prevents the absorption of outside odors, helping preserve sensory quality.

III.1.2. Fruit and Vegetable Packaging types

III.1.2.1. Conventional packaging materials

a) Metal cans

Metal cans, usually made of tinplate or aluminum, are widely used for thermally processed fruits and vegetables. They are hermetically sealed, so they prevent the entry of oxygen, moisture, and light, which makes them ideal for sterilized products with long shelf life. Their main advantages are excellent protection, durability, and high recyclability, but they are heavier and less suitable for products that need to be seen by the consumer.

b) Glass jars and bottles

Glass is a classic material for products such as jams, juices, sauces, and preserves. It is chemically inert, meaning it does not react with the food, and it is also impermeable to gases and moisture. Glass is transparent, which helps with product visibility, and it is fully recyclable. Its disadvantages are weight and fragility, which increase transport cost and risk of breakage.

c) Rigid plastics

Rigid plastics such as PET, HDPE, PP, and PVC are very common in fresh and processed produce packaging. They are lightweight, easy to shape, and can be transparent or opaque depending on the application. Their barrier properties vary depending on the polymer, so they are selected according to the product's needs. They are often used for fresh juices, sauces, condiments, and minimally processed vegetables.

d) Flexible films and laminates

Flexible packaging materials such as PE, PP, PA, and EVOH multilayers are especially important in modified atmosphere packaging. Their major role is to control the transfer of oxygen, carbon dioxide, and water vapor, which helps slow spoilage and maintain product quality. Laminated and multilayer structures are often used because they combine several properties in one material, such as strength, sealability, and gas selectivity.

e) Corrugated board and wood

Corrugated board and wooden containers are mainly used as secondary or transport packaging for whole fruits and vegetables. They provide cushioning, stacking strength, and support during handling and distribution. These materials are not usually in direct contact with the food for long periods, but they are essential for logistics, retail display, and protection during transport.

III.1.2.2. Biobased and biodegradable materials

a) Polylactic acid (PLA)

PLA is a biobased polymer produced from starch fermentation. It is transparent, compostable under appropriate conditions, and increasingly used for fresh produce containers, trays, and films. PLA is attractive because it combines a renewable origin with a modern appearance, although its barrier and thermal properties may still need improvement for some applications.

b) Starch-based films

Starch-based films can be edible or non-edible and are valued for their low cost and renewable origin. However, they generally have poor moisture barrier properties, which limits their use for highly humid products. They are more suitable for dry or semi-dry foods, or as components in composite packaging systems.

c) Cellulose-based materials

Cellulose-based materials include paper, cardboard, and cellophane. They are renewable, recyclable, and widely available, making them environmentally attractive. Their main weakness is limited resistance to moisture, so they are often used where high-water barrier performance is not required or where coatings are added.

d) Chitosan and seaweed-based films

Chitosan and seaweed-derived films are especially interesting because they can provide antimicrobial and antioxidant activity in addition to acting as physical barriers. They are often used as edible coatings or active packaging films for fresh and fresh-cut fruits and vegetables. These materials are promising for extending shelf life while also reducing the need for synthetic preservatives.

III.2. Innovative Processes

Packaging technologies for fruits and vegetables have evolved well beyond passive containment. Modern innovations focus on active interaction with the product and real-time quality monitoring.

III.2. 1.Modified Atmosphere Packaging (MAP)

Gas flushing with defined $O_2/CO_2/N_2$ mixtures or equilibrium MAP (EMAP) where the film permeability is matched to the produce respiration rate; suppresses aerobic microorganisms, delays senescence, and reduces enzymatic browning.

III.2. 2. Active Packaging

Active packaging interacts with the internal environment of the package to improve preservation:

a) Oxygen scavengers (iron-based, enzymatic) eliminate residual O_2 to prevent oxidation and aerobic microbial growth.

b) CO_2 emitters or absorbers to maintain optimal gas concentrations during transit.

c) Ethylene absorbers (zeolites, permanganate, palladium catalysts) to delay ripening and senescence in climacteric fruits.

d) Antimicrobial packaging: films incorporating essential oils, plant extracts, organic acids, or bacteriocins with controlled release to inhibit surface pathogens.

III.2.2.1. Intelligent (Smart) Packaging

Intelligent packaging does not only protect food; it also monitors and communicates product condition. It may include indicators of freshness, temperature history, humidity, leakage, or spoilage, helping both distributors and consumers track product quality:

a) Time-Temperature Indicators (TTIs): Visual, irreversible labels that change color in response to temperature-time history; indicate cold chain integrity.

b) Freshness Indicators: Colorimetric sensors responding to volatile metabolites (CO_2, H_2S, amines, ethanol) produced during microbial spoilage or ripening.

c) RFID and QR-based traceability: Enable full supply chain transparency from farm to consumer.

d) Biosensors: Detect specific analytes (pesticides, mycotoxins, pathogens) in situ; integrated into packaging for real-time safety monitoring.

III.2.2.2. Edible Coatings

Edible coatings are thin protection layers that are directly applied to the product surface and can be consumed along with it. They are made from natural film-formers that adhere to the product surface, creating a protective layer that can help to prolong the shelf-life by reducing or inhibiting natural chemical, biochemical or microbiological degradation processes caused by gas contact, gas diffusion or water transfer (figure 25).

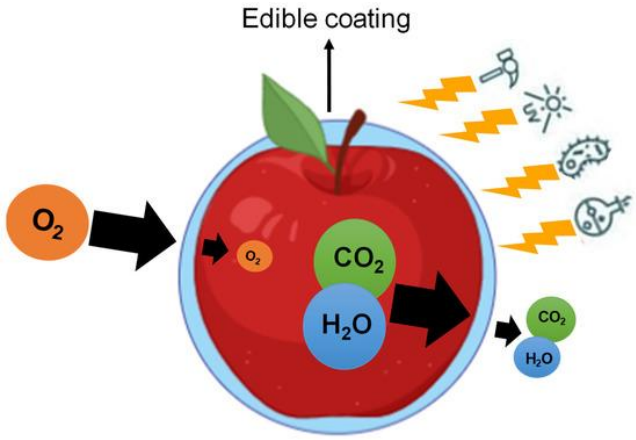

Figure 25: Main functions of edible coatings on fruits and vegetables.

Essential properties of an edible coating include adhesiveness to the product, an invisible and uniform surface appearance, neutral or positive sensory attributes, a defect-free cover, and a composition that conforms to food regulations. The main materials used for edible coating are summarized in table 13.

Table 13: Summary of diverse structural materials frequently used for edible coating.

Material	Main matrices	Positive points	Negative points
Polysaccharide	Starch, chitosan, alginate, cellulose and its derivatives, pectin	Good gas and mechanical barrier properties	Poor moisture barrier due to hydrophilic nature
Lipid	Animal and vegetable waxes and resins, vegetable oil, fatty acids	Good moisture barrier properties with a shiny appearance	Poor mechanical and gas barrier properties
Protein	Gelatin, casein, whey protein, zein, soy protein, myofibrillar protein, quinoa protein	Good gas barrier properties without anaerobic conditions	Brittle and susceptible to cracking
Composite	Combination of polysaccharide and/or protein with lipids	Good moisture and gas barrier properties	Formation of non-homogeneous emulsion

III.2. 2.3. Nanotechnology in packaging

Nanotechnology is used in fruit and vegetable packaging to improve shelf life, quality, and safety. Fresh produce is highly perishable because it contains a lot of water, continues to respire after harvest, and is easily damaged, so conventional packaging is often not enough to prevent losses. Nanotechnology offers a more advanced solution by improving barrier properties, active protection, and monitoring functions (Figure 26).

Nanoparticles can make packaging materials denser and reduce pore size, which helps limit the movement of oxygen and water vapor. Materials such as nanocellulose and nano-chitosan have been shown to improve oxygen and moisture barrier performance and reduce weight loss and respiration in fruits and vegetables.

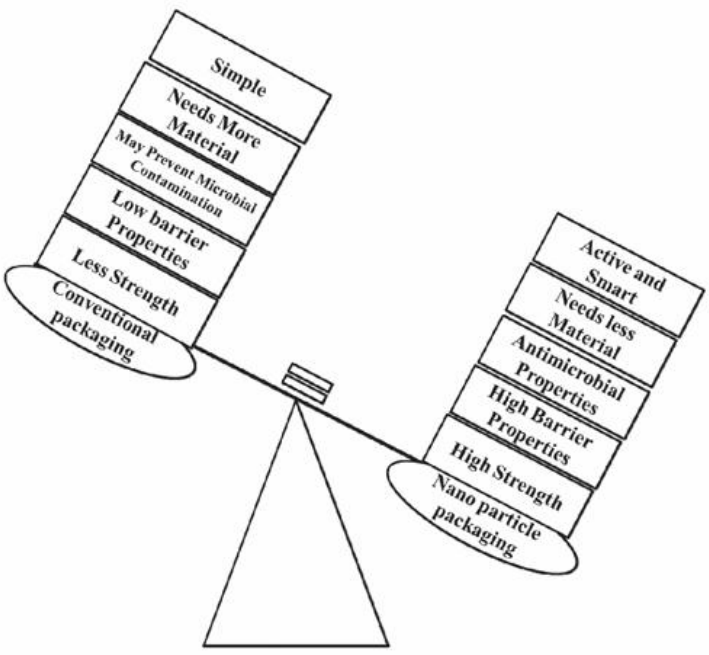

Figure 26: Advantage of nanopackaging over conventional packaging

Some nanoparticles, especially silver, zinc oxide, titanium dioxide, and copper-based particles, have strong antimicrobial effects. When incorporated into packaging films or coatings, they can inhibit spoilage and pathogenic microorganisms, helping to extend shelf life and improve food safety. Nano coatings can be applied directly to fruits and vegetables or to packaging surfaces, where they act as protective layers that reduce moisture loss, slow respiration, delay browning, and may also carry antioxidants, flavors, nutrients, or antimicrobials. This makes them useful for both whole produce and fresh-cut products. In addition, nanoparticles such as nanoclays can improve the mechanical strength and thermal stability of packaging materials, which is important because fruits and vegetables are delicate and need packaging that protects them during transport and storage without breaking or losing function. Nanotechnology also supports active packaging and smart packaging systems: active systems may use ethylene scavengers, oxygen absorbers, or antimicrobial agents, while smart systems can include sensors that monitor freshness, temperature abuse, or cold-chain failure.

IV. Quality Control and Safety

IV.1. Physicochemical Analyses

Physicochemical analyses of fruits and vegetables provide objective and quantitative data on their chemical composition and physical properties, which makes it possible to assess their quality, authenticity, and compliance with regulatory standards. They are also useful for sanitary control, internal quality control, and the measurement of parameters such as nutritional value, contaminants, pH, acidity, water activity, sugars, minerals, and chemical residues.

IV.1.1 Water content / Dry matter

The water content of fruits and vegetables is correlated with their shelf life. This empirical observation led to the drying or brining of foods to increase their preservation. Gradually, science has demystified the role of water, with major benefits for the food industry, enabling it to better control the stabilization of food matrices.

Gravimetric method (oven drying at 105°C); fundamental for product characterization and shelf-life prediction; influences texture, browning reactions, and microbial stability.

This analysis is important because water content strongly influences product texture, firmness, shriveling, enzymatic and non-enzymatic browning, respiration rate, and microbial stability.

In gravimetric method, the sample is weighed, then dried (usually for a prescribed period of time under specific conditions of temperature and often under vacuum) and weighed again. The moisture content is calculated based on the initial and final weights of the sample, which assumes that all weight loss is due to the removal of water and ignores the loss of other volatiles. The sample preparation and drying conditions (e.g. time, temperature, type of oven, humidity, and pressure) influence the efficiency of moisture removal and the resulting drying time required to complete a test can vary from hours to days.

IV.1.2. Water activity (aw)

The notion of water activity has been significantly applicable in preservation of food and on this regard various methods have been productively modified and novel products have been tailored. Water is termed as the universal solvent since it is vital for metabolism, multiplication, and to sustain various chemical reactions happening in food substances. Free water in food product is the kind of water obtainable for biochemical processes to occur, to gear up microbial growth, and to transport components within the medium. Whereas, the water in bound phase is confronted to take

part in the biochemical processes as it gets restricted using various soluble ingredients say salt, sugars, and through the surface impact of the substrate binding medium.

Minimum water activity values for the growth and toxin production of microorganisms of public health concern are an important criterion in food safety, especially for low-moisture products. In general, the critical water activity range for most foods is around 0.6–0.7, below which microbial growth becomes increasingly limited. Pathogenic bacteria are usually inhibited when aw*aw* falls below 0.85–0.86, although the exact threshold may vary depending on the species and environmental conditions. Yeasts and molds are generally more tolerant and may still grow at lower water activity values, typically below 0.80, but no microbial growth occurs when aw*aw* is below 0.60 (figure 27). Therefore, controlling water activity is essential to prevent spoilage and reduce the risk of toxin production in dried, concentrated, and shelf-stable foods.

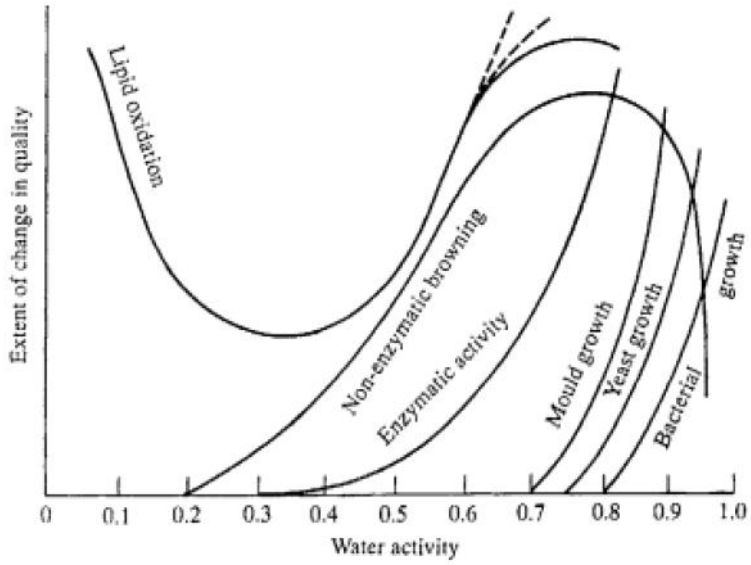

Figure 27: Extent of change of quality as a function of water activity

Many methods and instruments are available for laboratory measurement of water activity in foods. Methods are based on the colligative properties of solutions. Water activity can be estimated by measuring the following:

- Vapor pressure
- Osmotic pressure
- Freezing point depression of a liquid
- Equilibrium relative humidity of a liquid or solid

- Boiling point elevation
- Dew point and wet bulb depression
- Suction potential, or by using the isopiestic method
- Biothermal equilibrium
- Electric hygrometers
- Hair hygrometers

IV.1.3. Soluble Solids Content (SSC/°Brix)

Soluble solids content (SSC) in fruits refers to the total content of substances dissolved in fruit juice, including sugars (such as glucose, fructose, and sucrose), organic acids, and minerals. Since sugars dominate this composition, SSC is commonly referred to as soluble sugar content. The level of soluble sugar content is one of the core indicators for evaluating fruit sweetness, maturity, and overall quality. By measuring SSC, it is possible to assess fruit sweetness, maturity, and storability, providing scientific guidance for harvesting, storage, and processing.

SSC was traditionally determined by destructive methods such as juice chemical analysis, Abbe refractometry, and handheld refractometry, which provide accurate results but require sample destruction and are therefore unsuitable for rapid on-line fruit grading. non-destructive alternatives such as near-infrared spectroscopy, hyperspectral imaging, computer vision, electronic nose, X-ray CT, Raman spectroscopy, and other sensing methods are actually more used.

IV.1.4. Visible and Near-Infrared Spectroscopy Technology

Visible and near-infrared (Vis/NIR) spectroscopy is a popular non-destructive technique for detecting fruit sugar content. It uses electromagnetic radiation from 380 to 2500 nm. Vis light (380–700 nm) and NIR light (780–2526 nm) interact with fruit samples through reflection, transmission, or absorption, producing spectra that reveal physical and chemical properties. Vis/NIR spectroscopy is favored for its ability to detect signals from most organic compounds' structures and functional groups, with stable spectral features (figure 28).

IV.1.5. Hyperspectral Imaging Technology

Hyperspectral Imaging Technology, a non-destructive method blending computer imaging and spectroscopy, captures the spatial and spectral data of objects. By splitting light into many

contiguous bands via an imaging spectrometer, it forms a 3D data cube where each pixel has a unique spectral curve, like a fingerprint. This reflects internal physical and chemical changes, enabling qualitative and quantitative analysis of fruit traits such as sugar, acidity, and water content.

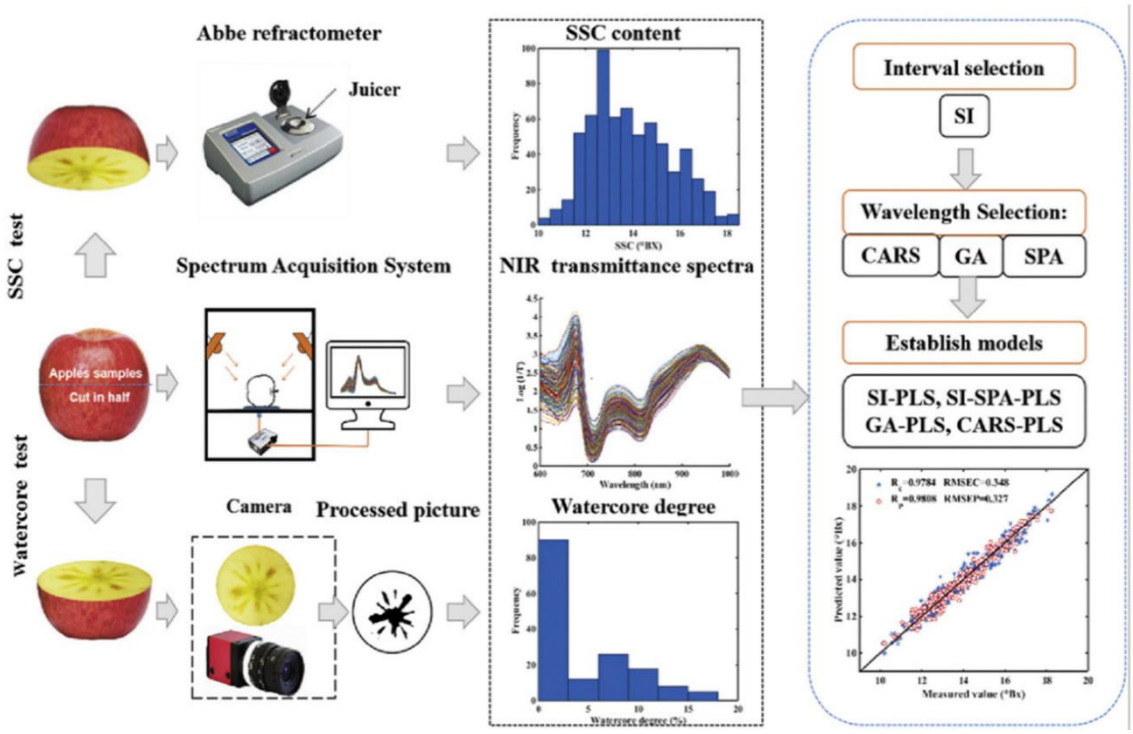

Figure 28: Flowchart of the near-infrared system for detecting apple soluble solids content and water core severity

IV.1.6. Titratable Acidity (TA)

Potentiometric or colorimetric titration with NaOH is commonly used to determine the titratable acidity of fruits and vegetables, which is then combined with soluble solids content (SSC, expressed as °Brix) to calculate the Brix/acid ratio, an important maturity index. In this method, a known volume of fruit juice or homogenized extract is titrated with a standard sodium hydroxide solution until the end point is reached. In colorimetric titration, the endpoint is identified visually by the color change of a suitable pH indicator, while in potentiometric titration, the endpoint is determined more accurately by measuring the change in pH or electrical potential with a pH electrode. The amount of NaOH required to neutralize the organic acids present in the sample is

used to calculate titratable acidity, usually expressed as a percentage of citric acid or another dominant acid. This value is then compared with SSC to obtain the Brix/acid ratio, which reflects the balance between sweetness and acidity. A higher ratio generally indicates advanced ripeness and better eating quality, especially in fruits such as citrus, grapes, tomatoes, and mangoes, where flavor depends strongly on sugar–acid equilibrium.

IV.1.7. pH

pH is commonly measured by potentiometry and is a critical physicochemical parameter in fruits and vegetables. It is especially important for heat process design, because products are classified as high-acid or low-acid foods according to their pH, and the safety boundary of pH 4.6 is widely used to assess the risk of *Clostridium botulinum* growth and botulism in processed foods. pH also affects the color stability of anthocyanins, since these pigments change color and degrade more rapidly depending on acidity, which influences the visual quality of many fruit products. In addition, pH plays a major role in pectin gelation, particularly in jams, jellies, and fruit preserves, where the correct acidity is necessary to promote gel formation and obtain the desired texture. For these reasons, pH measurement is essential not only for quality control but also for processing, preservation, and product safety.

IV.1.8. Color measurement

Color measurement is an important quality parameter because it reflects maturity, appearance, and consumer acceptability. Spectrophotometry measures the absorbance spectrum of extracted pigments or the sample surface, using the principle that pigments absorb light at specific wavelengths; this is useful for quantifying chlorophylls, carotenoids, and anthocyanins. Colorimetry expresses color in the CIE L*a*b* system, where L∗*L*∗ indicates lightness, a∗*a*∗ the red-green axis, and b∗*b*∗ the yellow-blue axis, allowing standardized and comparable color evaluation across samples.

Computer vision systems use digital image capture and processing to estimate color attributes automatically; they are widely applied to fruit and vegetable grading because they can reproduce color information with good reliability and support rapid, on-line inspection. Compared with visual scoring, these methods reduce subjectivity, improve repeatability, and make color assessment suitable for research and industrial quality control.

IV.1.9. Texture analysis

Textural parameters of fruits and vegetables are perceived with the sense of touch, either when the product is picked up by hand or placed in the mouth and chewed. Texture Profile Analysis (TPA), puncture tests, and compression tests are widely used to assess fruit and vegetable texture in an objective way. TPA is usually based on a double-compression cycle that simulates biting and provides parameters such as firmness/hardness, cohesiveness, springiness, gumminess, and chewiness, while puncture or penetrometer tests measure the force required for a probe to penetrate the sample and are commonly used as indicators of firmness. Compression tests deform the sample under a controlled force and are useful for evaluating resistance to deformation, elasticity, and structural integrity.

These texture properties are closely related to the cell wall structure and pectin composition of the tissue. As fruits ripen, cell wall polysaccharides such as pectin are modified, solubilized, or depolymerized, which weakens tissue cohesion and reduces firmness. Therefore, lower puncture resistance or lower compression force generally reflects softer tissue, loss of cell wall integrity, and changes in pectin-related bonding. TPA is especially useful because the second compression gives information on recovery and internal structure, so it can reflect not only firmness but also cohesiveness and springiness, which are important indicators of ripeness and eating quality.

IV.1.10. Enzymatic activity

In fruit and vegetable products, enzymatic activity is a major determinant of quality during processing and storage.

- Peroxidase (POD) is widely used as an indicator of blanching efficiency because of its relatively high heat stability, and its oxidation of phenolic compounds can contribute to browning, chlorophyll degradation, and, in some tissues, cell-wall cross-linking and texture improvement. In plant samples, POD oxidizes substrates such as pyrogallol or guaiacol in the presence of H_2O_2, generating a yellow or red reaction product whose absorbance increases over time. The activity is then calculated from the change in absorbance, usually at 420 nm or 532 nm, depending on the assay reagent system used
- Polyphenol oxidase (PPO) is the principal enzyme responsible for enzymatic browning, catalyzing the conversion of phenols to o-quinones that polymerize into brown melanins, thereby reducing visual quality and sometimes affecting flavor. activity is usually determined by

a spectrophotometric assay that monitors the formation of o-quinones from phenolic substrates such as catechol or chlorogenic acid. The reaction is followed by the increase in absorbance at a suitable wavelength, often around 410 nm for catechol-based methods, and the initial rate of absorbance change is used to calculate enzyme activity.

- Pectinmethylesterase (PME), on the other hand, is closely associated with juice cloud instability because it de-esterifies pectin, promoting calcium-mediated aggregation and phase separation in fruit juices and concentrates; thus, PME inactivation is essential for maintaining cloud stability, especially in citrus products. The activity is commonly determined by measuring the methanol released during pectin demethylation or by acid-based titration of the free carboxyl groups formed during the reaction.

IV.1.11. Vitamin C

The precise amount of vitamin C in a specific food varies according to the season of harvesting, transport, storage time before use, and processing practices. Even minor operations related to the processing of fruit and vegetables, such as peeling, cutting, or crushing, can change the matrix structure and activate ascorbic acid oxidase, which contributes to the oxidation of L-ascorbic acid, resulting in the huge loss of this valuable vitamin. The main analytical methods used for its determination are high-performance liquid chromatography (HPLC) and spectrophotometric or titrimetric methods based on 2,6-dichlorophenolindophenol (DCPIP) (Figure 29). HPLC is considered the more accurate, precise, and specific technique because it can quantify ascorbic acid with minimal interference from other compounds and can also be adapted for oxidized forms of vitamin C. In contrast, the DCPIP method is simple, rapid, and inexpensive, making it useful for routine analyses, although it is less specific and may overestimate vitamin C in complex food matrices because of interference from other reducing substances.

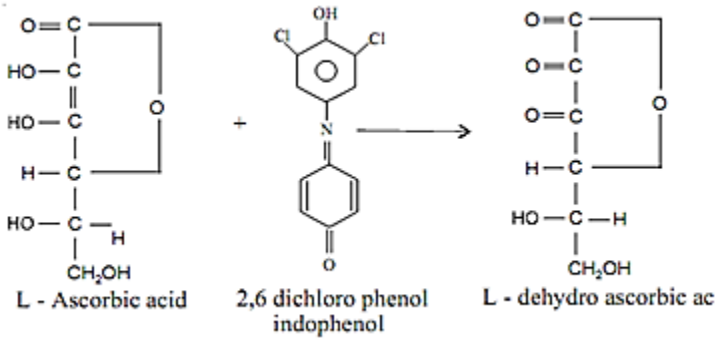

Figure 29: Conversion of ascorbic acid to dehydro ascorbic acid using 2,6-dichlorophenolindophenol

IV.1.12. Phenolic compounds and antioxidant capacity

Phenolic compounds and antioxidant capacity are frequently evaluated in fruits, vegetables, and derived products. These methods are important for functional food and nutraceutical labeling because they help characterize the nutritional and bioactive quality of plant-based products. They are commonly used to compare raw and processed foods, evaluate losses during storage, and support claims related to antioxidant richness. However, results from different assays are not always directly comparable because each method measures a slightly different chemical property.

a) Folin–Ciocalteu assay

The Folin–Ciocalteu method estimates total phenolic content. In this assay, phenolic compounds reduce the Folin reagent under alkaline conditions, producing a blue complex that is measured spectrophotometrically. The result is usually expressed as mg gallic acid equivalents (GAE) per 100 g or per 100 mL. Although it is widely used as a proxy for total polyphenols, the method is not perfectly specific because other reducing compounds may also react with the reagent.

b) DPPH assay

The DPPH test measures the ability of antioxidants to donate hydrogen or electrons to the stable purple DPPH radical. When DPPH is reduced, its color fades from purple to yellow, and the decrease in absorbance is measured, usually around 517 nm or in some protocols with adapted wavelengths. This assay is especially useful for screening the radical-scavenging ability of plant

extracts, fruit juices, and functional ingredients.

c) ABTS assay

The ABTS assay is based on the decolorization of the ABTS radical cation. Antioxidants in the sample reduce the blue-green radical, causing a decrease in absorbance, commonly measured at 734 nm. This method is useful for both hydrophilic and lipophilic antioxidants, and it is often considered more versatile than DPPH because it works well in a broader range of food matrices.

d) FRAP assay

The FRAP method measures the reducing power of antioxidants by their ability to reduce ferric ions Fe3+Fe3+ to ferrous ions Fe2+Fe2+, forming a colored complex. The reaction is usually monitored at 593 nm. Unlike DPPH and ABTS, which are radical-scavenging assays, FRAP reflects electron-donating capacity and is therefore a useful indicator of overall reducing potential in foods.

IV.1.13. Near-Infrared Spectroscopy (NIR/NIRS)

Near infrared spectroscopy (NIR), which covers approximately 780 to 2500 nm, has many applications in the fruit and vegetables industry without sample preparation, and can be used to measure moisture, soluble solids content, water content, stiffness or presence of internal damage, among other parameters. The principle is that when near-infrared light interacts with the sample, different chemical components in the sample will absorb particular wavelengths of near-infrared light selectively through the quantized energy level transition mechanism due to their unique molecular vibration frequencies. After the characteristic response of the interaction between light and matter is captured by the detector, the spectral information reflecting the composition characteristics of the sample can be obtained through analysis. Three types of optical sensing systems used for fruit or crop inspection: a portable device, an online system, and a vehicle-mounted system (Figure 30).

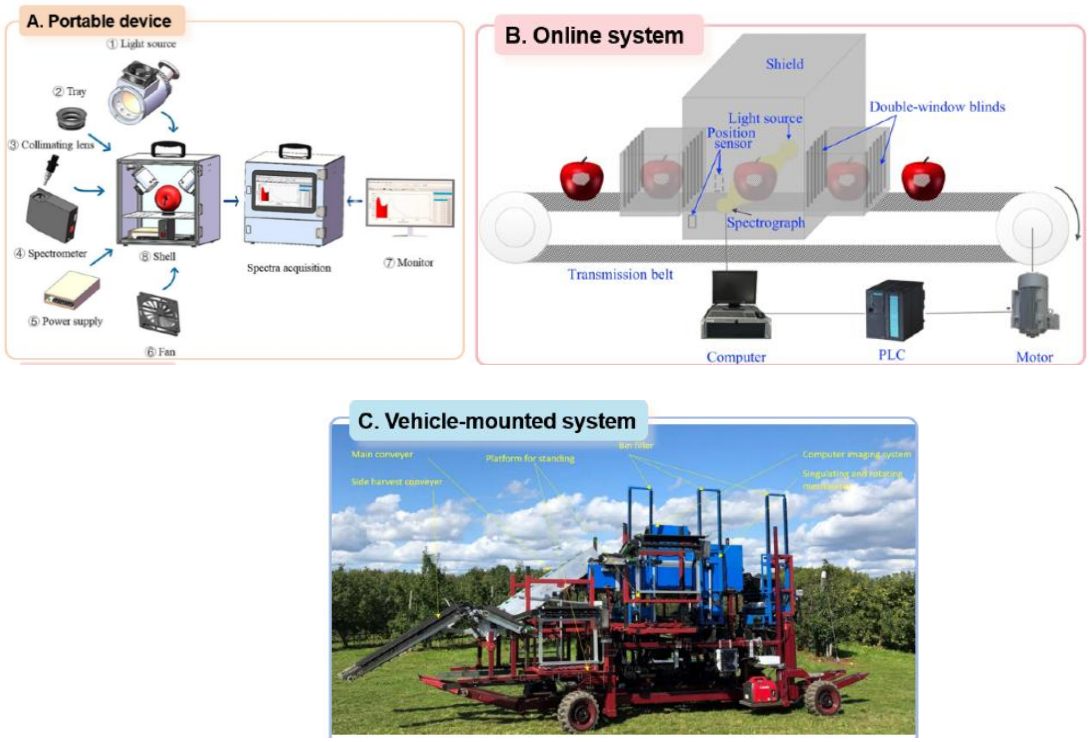

Figure 30: Schematic diagrams of three typical Vis/NIR spectroscopy system configurations for fruit quality detection. (A) Portable device. (B) Online system. (C) Vehicle-mounted system

IV.1.14. Pesticide residues

Pesticides are present in fruits and vegetables in trace and ultra-trace amounts, with concentrations ranging from a few ng/kg or ppt to a few mg/kg or ppm. Each pesticide has its own unique physicochemical properties, making simultaneous analysis of all pesticides impossible. Furthermore, once present in food, some molecules can bind strongly to the food matrix, further complicating analysis. Due to the wide variety of physicochemical properties and their low concentrations in fruits and vegetables, pesticide quantification is generally challenging. It requires prior development, optimization, and validation steps for the entire procedure.

a) Main Analytical Steps

Pesticide analysis in fruits and vegetables generally involves several steps:

- Representative batch sampling.
- Sample homogenization.
- Residue extraction.
- Purification/cleaning of the extract.

- Preconcentration if necessary.
- Instrumental separation and quantification.
- Compound identification and confirmation.
- Method validation by recovery, repeatability, LOD, LOQ, and linearity.

b) Extraction and Preparation Methods

The most widely used method today is QuEChERS (Quick, Easy, Cheap, Rugged, Effective, and Safe), often combined with a purification step by d-SPE (dispersive solid-phase extraction). This approach is very popular because it is fast, inexpensive, simple to implement, and compatible with GC or LC analyses. It is particularly well-suited to fruit and vegetable matrices, although adjustments may be necessary depending on the water, pigment, sugar, or fat content.

Other extraction methods can also be used depending on the nature of the pesticide and the matrix:

- LLE: Liquid-Liquid Extraction.
- SPE: Solid-Phase Extraction.
- SPME: Micro-Extraction on Solid Phase.
- MSPD: Matrix Dispersion on Solid Phase.
- GPC: Gel Permeation Chromatography.

c) Instrumental methods of quantification

Pesticides in fruits and vegetables are primarily quantified by GC-MS/MS for volatile and stable compounds, and by LC-MS/MS for polar or heat-labile compounds. ELISA and EC are complementary methods, while characterization relies on identification by MS/MS and validation by LOD, LOQ, recovery, and precision.

IV.2. Microbiological Analyses

Microbiological safety is a critical quality attribute for both fresh and processed fruits and vegetables because contamination can occur at any stage of the chain, from soil and irrigation water to harvesting, processing equipment, packaging, and storage. Fresh-cut and minimally processed products are especially vulnerable because they are handled more, stored under refrigeration, and often consumed without a cooking step. The major microbiological hazards are bacterial pathogens, spoilage organisms and mycotoxins (Table 14).

Table 14: The major microbiological hazards of fruits and vegetables

Hazard group	Main examples	Main concern	Typical source or condition	Control focus
Bacterial pathogens	*Listeria monocytogenes*	Growth at refrigeration temperatures; serious safety risk	Minimally processed and ready-to-eat produce	Hygiene, cold chain, sanitation
	Salmonella spp.	Foodborne illness	Soil, water, manure, handling	Good agricultural practices, clean water
	E. coli O157:H7 and STEC	Severe infection risk	Fecal contamination of raw produce	Field sanitation, worker hygiene
	Clostridium botulinum	Toxin production in low-acid foods	Low-acid canned or anaerobic products	Proper thermal processing, acidification
	Yersinia enterocolitica	Cold-tolerant survival	Refrigerated produce and contaminated water	Cold-chain control, sanitation
Spoilage organisms	Molds, yeasts, aerobic spoilage bacteria	Off-flavors, visual spoilage, losses	Poor storage, damaged produce, humid conditions	Storage control, rapid turnover
Mycotoxins	Aflatoxins, patulin, ochratoxin A	Toxic, heat-stable contamination	Mold growth during storage	Source control, mold prevention

Standard microbiological methods are used to evaluate the hygienic quality, shelf life, and safety of fruits and vegetables. They are especially important because fresh produce can carry microorganisms from soil, water, workers, equipment, and packaging surfaces. In routine food control, culture-based ISO/NF methods remain the reference tools because they are standardized, comparable, and accepted in regulatory and industrial laboratories.

IV.2.1. Total Viable Count (TVC / TPC)

The Total Viable Count (TVC), also called Total Plate Count (TPC) or Aerobic Plate Count, measures the total number of viable microorganisms that grow under aerobic conditions, usually at 30°C. It is a general indicator of hygiene quality, process cleanliness, and expected shelf life. In fruits and vegetables, a high TVC usually suggests poor handling, temperature abuse, or advanced spoilage, although it does not identify a specific pathogen.

IV.2.2. Enterobacteriaceae count

The Enterobacteriaceae count is a useful indicator of hygienic status and possible contamination from fecal matter, soil, water, or poor sanitation. These bacteria are not all pathogens, but their presence often signals unfavorable processing conditions or insufficient cleaning. ISO 21528 methods are commonly used for detection and enumeration of Enterobacteriaceae in food and environmental samples, especially when assessing hygiene in the food chain.

IV.2.3. Detection of specific pathogens

Specific ISO methods are used when a defined pathogen must be confirmed. ISO 11290 is used for *Listeria monocytogenes*, which is highly relevant in refrigerated ready-to-eat produce because it can grow at low temperatures. ISO 6579 is the standard for *Salmonella* spp., a major pathogen associated with raw produce and environmental contamination. ISO 16649 is used for β-glucuronidase-positive *E. coli*, which is important as an indicator of fecal contamination and potential STEC risk.

IV.2.4. Mold and yeast count

The mold and yeast count is especially relevant for fruits, jams, fruit juices, and fruit-based beverages because these products are rich in sugars and often exposed to air and moisture. Yeasts can cause fermentation, gas production, turbidity, and off-flavors, while molds can produce visible spoilage and may also be associated with mycotoxin formation under poor storage conditions. For this reason, yeast and mold enumeration is important in quality control and shelf-life evaluation of fruit products.

IV.2.5. Molecular methods

PCR, qPCR, and MALDI-TOF MS are rapid methods used for specific detection and identification of microorganisms. They are faster than culture methods and are very useful when quick confirmation is needed, especially for pathogens such as *Listeria* and *Salmonella*. However, culture-based ISO methods remain the official reference in many regulations, while molecular methods are often used as complementary or confirmatory tools.

IV.3. Sensory Analysis

Sensory analysis is the scientific study of human perception of food through sight, smell, taste, touch, and hearing. It is essential for evaluating the quality of fruits and vegetables because it provides information for consumers that instrumental methods cannot fully replace. In practice, sensory analysis helps determine whether a product is appealing, acceptable, and marketable.

IV.3.1. Types of Sensory Tests

IV.3.1.1. Discriminant Tests

Discriminant tests are used to determine if two samples show a perceptible difference. Common examples include the triangle test, the duo-trio test, and the A-not-A test. These tests are useful for evaluating the effect of a change in the manufacturing process, storage conditions, packaging system, or a difference in cultivar. They generally require a panel of trained or semi-trained tasters and a sufficient number of replicates to achieve adequate statistical reliability.

IV.3.1.2. Descriptive Analysis

Descriptive analysis aims to describe and quantify the sensory attributes of a product. Methods such as quantitative descriptive analysis, aroma profiling, and texture profiling use trained panels, typically composed of 10 to 15 panelists, who evaluate defined attributes like sweetness, acidity, firmness, aroma, and off-flavors on structured intensity scales. This results in a sensory profile that can be presented as a table, radar chart, or spider diagram for product comparison.

IV.3.1.3. Hedonic Testing

Hedonic or affective testing measures consumer appreciation and acceptance. It is generally conducted with untrained consumers, often with 60 to 200 respondents, using a 9-point hedonic scale or a preference ranking system.

V. Innovations and Sustainability

V. 1. Sustainable Production and the Circular Economy

The fruit and vegetable sector faces growing pressure to reduce environmental impact, minimize waste, and adopt sustainable production models. Sustainability encompasses three interrelated dimensions: environmental (reduction of greenhouse gas emissions, water and energy use), economic (profitability, value creation from waste), and social (food security, employment,

consumer health).

The “cleaner” food production that is integrated with the environment is based on the principle that losses must be reduced and reused/recycled, with the aim at valorizing these by-products and the waste produced (Figure 31), as well as executing innovative processes and developing products that work collaboratively with the environment, always aiming for quality, safety and efficiency

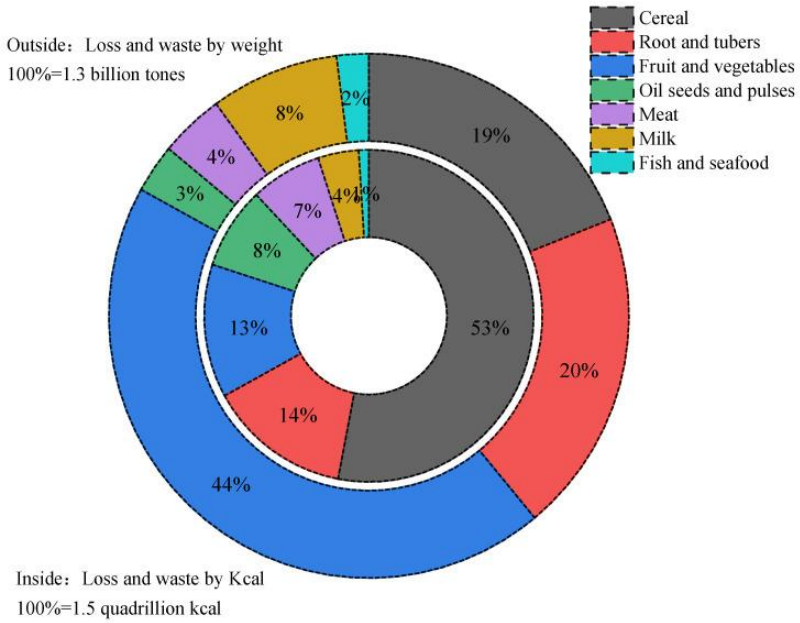

Figure 31: Global food loss and waste by different calculations.

V. 2. Circular economy principles

The EU Circular Economy Action Plan and Farm-to-Fork Strategy set targets for waste reduction and resource efficiency. The circular economy replaces the traditional "extract-produce-discard" model with a system where materials are used for as long as possible, waste is minimized, and residual biomass is repurposed as a secondary resource. In the fruit and vegetable processing sector, this means that peelings, seeds, pomace, pulp residue, and unsold produce can be transformed into ingredients or industrial inputs instead of being discarded. Valorization of fruit and vegetable by-products into food additives, functional ingredients, biofuels, bioplastics, and cosmetics replaces a linear "take-make-dispose" model with a circular, zero-waste biorefinery approach.

Fruit and vegetable wastes are promising ingredients for animal feed and food nutrition because they contain valuable nutrients and bioactive compounds such as vitamins, minerals, fiber,

phenolics, and carotenoids. Their valorization supports sustainable feed production, reduces competition with human food, and improves the environmental and economic performance of food systems (Figure 32).

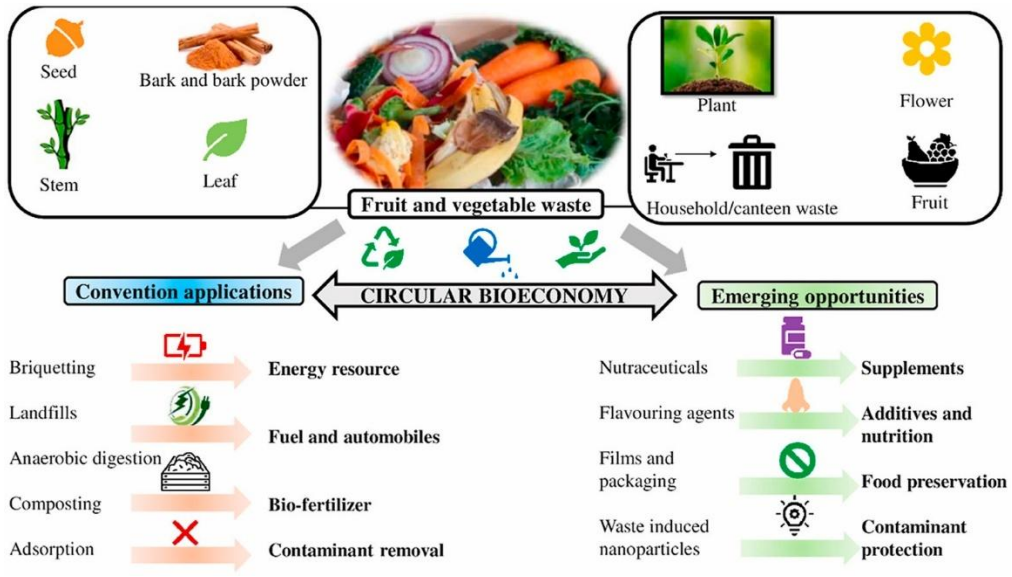

Figure 32: Utilization of fruit and vegetable waste to produce value-added products

V.3. Different Techniques for Fruits and Vegetable Waste Valorization

Bioremediation is a sustainable and efficient way to convert fruit and vegetable waste into valuable bioproducts. It uses natural biological processes such as microbial degradation, enzymatic bioconversion, aerobic and anaerobic digestion, and composting to break complex organic materials into useful compounds (figure 33). During this process, microorganisms can produce biosolvents: for example, *Clostridium acetobutylicum* can convert plant sugars into acetone and butanol, while *Saccharomyces cerevisiae* can produce ethanol. The efficiency of biosolvent production depends on factors such as pH, temperature, oxygen supply, and the composition of the waste. This process can be further improved through genetic engineering and metabolic pathway modification of microorganisms, which increases biosolvent yield.

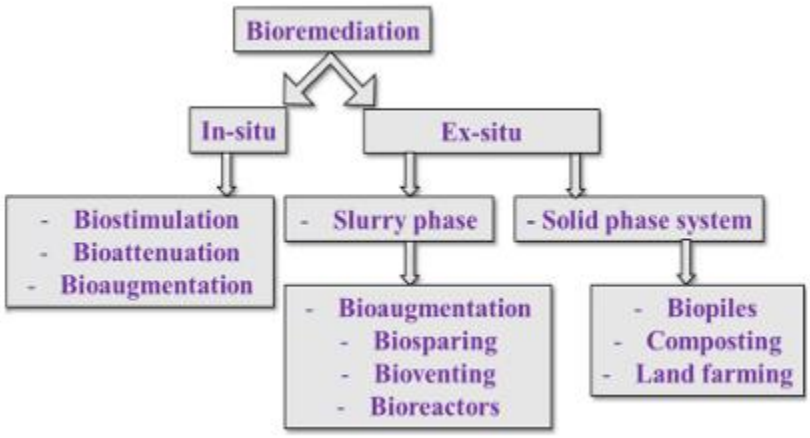

Figure 33: General techniques of bioremediation for waste management

V.3. 1. Microbial Degradation

This method uses microorganisms to break down fruit and vegetable waste into simpler compounds. It is especially useful for producing value-added products such as biogas, bioethanol, biosolvents, and organic acids. It is effective because fruit and vegetable waste is rich in carbohydrates and other nutrients that support microbial growth.

V.3. 2. Enzymatic Bioconversion

Enzymatic bioconversion uses enzymes to convert complex materials in waste into useful compounds. It is applied to produce eco-enzymes and to release fermentable sugars that can later be used for fermentation. Enzyme immobilization and enzyme cocktails can improve efficiency, stability, and reuse.

V.3. 3. Anaerobic Digestion

Anaerobic digestion decomposes organic waste in the absence of oxygen. This process produces biogas and a nutrient-rich digestate that can be used as fertilizer. It is one of the most important techniques for converting fruit and vegetable waste into renewable energy (figure 34).

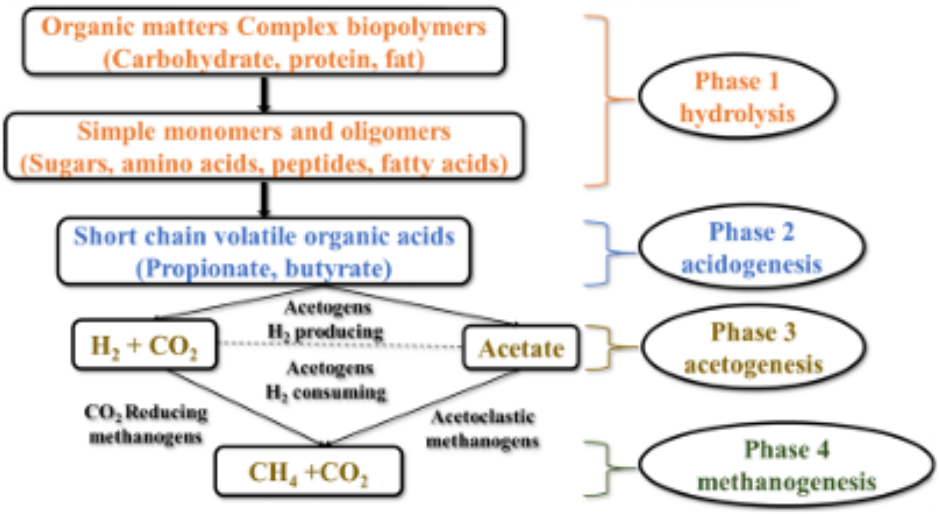

Figure 34 : Anaerobic digestion pathway for fruits and vegetable waste management.

V.3. 4. Aerobic Digestion

Aerobic digestion occurs in the presence of oxygen and results mainly in carbon dioxide, water, and stable compost. It is faster than anaerobic digestion and produces less odor, but it does not generate biogas. It is a practical stabilization method for organic waste.

V.3. 5. Composting

Composting uses microorganisms to decompose fruit and vegetable waste into nutrient-rich compost. It is a well-established and low-cost technique for improving soil quality and reducing the volume of waste sent to landfills (Figure 35). It plays an important role in sustainable agriculture and waste management.

V.3. 6. Vermicomposting

Vermicomposting uses earthworms together with microorganisms to convert organic waste into high-quality vermicompost. It is faster than conventional composting and produces a more nutrient-dense final product. It is a simple and effective method for treating green waste.

Figure 35: Composting process and the changes in soil properties of organic waste management.

V.3. 7. Fermentation for Biosolvents

Fermentation converts sugars from fruit and vegetable waste into biosolvents such as ethanol, butanol, acetone, and lactic acid. These biosolvents are considered green alternatives to petroleum-based solvents. This approach supports both waste valorization and green chemistry.

V.3. 8. Biochar Production

Biochar is produced by pyrolyzing waste at high temperature in the absence of oxygen. It can be used as a soil conditioner, for carbon sequestration, and in water filtration. It is a valuable route for converting waste into a useful carbon-rich product.

V.3. 9. Biodiesel Production

Oil-rich fruit and vegetable waste can be converted into biodiesel through transesterification. This provides a renewable fuel source that can replace part of conventional fossil fuel use. A common example is biodiesel produced from avocado seed oil.

V.3. 10. Single-Cell Protein Production

Fruit and vegetable waste can serve as a substrate for microbial growth to produce single-cell protein. This protein can be used in animal feed and, in some cases, human nutrition. This method turns waste into a protein-rich resource.

V.3. 11. Bioplastic Production

Carbohydrate-rich waste can be used to produce biodegradable plastics such as polylactic acid-based materials. This reduces dependence on petroleum-based plastics and supports circular economy goals. It is a promising high-value application.

V.3. 12. Pigment Extraction

Natural pigments such as carotenoids, anthocyanins, and chlorophyll can be recovered from fruit and vegetable waste. These pigments are useful as natural colorants in food, cosmetics, and textiles. Pigment extraction is an important co-product recovery strategy.

Part 3. Meat and Fish Technology

I. Overview of the Composition and Structure of Meat

I.1. General Information on the Raw Material

I.1.1. Definition

Meat is defined, in a technological sense, as the entirety of the striated skeletal muscle tissues of a slaughter animal (bovine, ovine, caprine) or poultry, consumable by humans. Its final quality is the result of a chain of complex interactions between the animal's genetics, its breeding method, its diet, the slaughter conditions, and post-mortem technological treatments. Meat is defined by the Codex Alimentarius as "all parts of an animal that are intended for, or have been judged as safe and suitable for human consumption," and is comprised of three major components: muscle cells, connective tissue, and fat.

I.1.2. Classification of Meat Animals

Meats can be classified according to, animal, the edible parts, color and lipid content (Table 15).

Table 15: Meat Classification

Classification Criterion	Categories	Detailed Description
Animal	Cattle	Bull, steer, cull cow, heifer, veal. Difference between beef breeds (Charolais, Limousin, Blonde d'Aquitaine) versus dairy breeds. Determines conformation, degree of fat cover, and meat quality.
	Sheep	Lamb, mutton, cull ewe. Meat characterized by high intramuscular fat content and specific flavor (branched-chain fatty acids).
	Poultry	Chicken, turkey, duck, guinea fowl, quail. Muscles with predominantly white fibers (breast) and red fibers (thighs).
The edible parts	Flesh	Main muscular part of the animal.
	Offal	Internal organs and other non-muscular edible parts.
	Charcuterie products	Processed and prepared meats (sausages, hams, pâtés, etc.).
Color	Red meat	Meat from an adult bled animal with meat that has undergone maturation.
	White meat	Meat from a young animal or poultry.
	Dark meat	Meat from a wild animal that has not been bled.
Lipid content	Lean meat	≤ 5% fat.
	Intermediate meat	5 to <15% fat.
	Fatty meat	> 15% fat.

I.1.3. Factors Influencing Raw Material Quality

Meat quality depends on a range of parameters that act before, during, and after slaughter. These parameters include genetics, diet, age, sex, farming system, pre-slaughter stress, slaughter conditions, as well as meat storage and maturation (Table 16). They can be grouped into intrinsic factors related to the animal and extrinsic factors related to farming and processing practices. These factors modify the main characteristics of the meat: pH, color, water retention capacity, tenderness, juiciness, flavor, processing yield, and suitability for processing.

Table 16: Factors influencing on meat quality

		Effect on meat quality
Extrinsic factors	Feeding	Affects growth, intramuscular fat, fatty acid profile, color, and flavor.
	Rearing system	Influences physical activity, stress level, carcass composition, and sensory quality.
	Fasting before slaughter	Too short or too long may reduce quality and favor PSE or DFD meat.
	Transport	Causes stress, weight loss, injuries, and pH changes.
	Lairage / waiting before slaughter	Poor rest conditions increase stress, fighting, and meat defects.
	Stunning and slaughter conditions	Affect post-mortem metabolism, blood spots, and the occurrence of PSE meat.
	Storage and ageing	Influence tenderness, juiciness, color, and shelf life.
Intrinsic factors	Breed / genotype	Influences post-mortem pH decline, intramuscular fat content, tenderness, and technological quality.
	Major genes (RYR1, RN)	Can cause defects such as PSE or acid meat, with reduced water-holding capacity and poorer sensory quality.
	Sex	May affect ultimate pH and odor, especially in entire males.
	Age and slaughter weight	Increase collagen content, color intensity, and marbling, but may reduce tenderness.

I.2. Meat Composition and Structure

I.2.1. Structure

Meat corresponds to the various muscles composed of muscle fibers and connective tissue protecting them (Figure 36).

The muscle is composed of:

a) **Protein constituents**: Muscle proteins are mainly divided into myofibrillar proteins (about 50%, mainly actin and myosin), sarcoplasmic proteins (25–35%, such as myoglobin and glycolytic enzymes), and connective tissue proteins (10–15%, such as collagen and elastin).

b) **Muscle fibers**: A muscle fiber is made up of myofibrils, and several fibers form a bundle. The actin-myosin complex in the myofibrils is responsible for muscle contraction. There are two main fiber types: type I or red fibers, which contain more myoglobin and lipids, and type II or white fibers, which contain less.

c) **Connective tissue**: Connective tissue holds muscle bundles together and supports oxygenation and nutrition. It includes fat cells, elastin, and collagen. Elastin does not dissolve during cooking, while collagen is important for meat tenderness because it can be converted into gelatin around 60°C in water. The collagen/protein ratio is used to judge the amount of connective tissue in meat: a high ratio means tougher meat, lower nutritional value, and longer cooking time. A ratio of about 8% is considered low in collagen and is used as a quality criterion for minced meat and cold cuts.

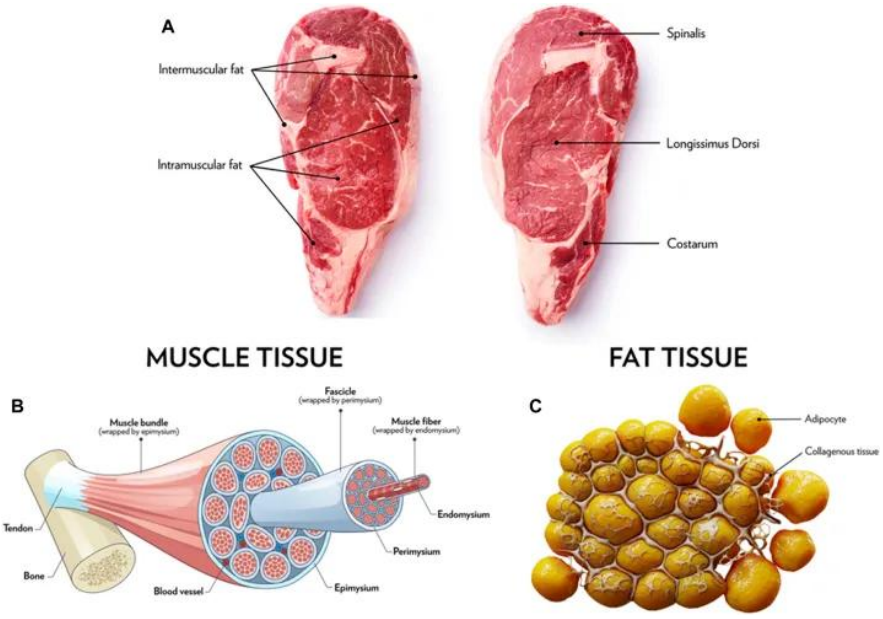

Figure 36: Photograph of a typical ribeye steak **(A)** and illustrations of the anatomical features it comprises of–muscle tissue **(B)** and fat tissue **(C)**.

I.2.2. Composition of meat

Meat is mainly composed of water and dry matter; for good-quality meat, the ratio of dry matter to water should not fall below 1:3. The dry matter contains the main nutritive components: proteins, lipids, carbohydrates, minerals, and vitamins (table 17).

Table 17: Chemical composition of the meat of various species

Constituent	Lean beef	Lamb meat	Chicken breast	Technological role
Water	72–76%	64–70%	74–75%	Water-holding capacity, juiciness
Proteins	18–22%	17–20%	22–24%	Structure, water retention, emulsification, gelation
Lipids	3–8%	8–20%	1–3%	Flavor, juiciness, lipid oxidation
Carbohydrates	< 1%	< 1%	< 1%	Glycogen → lactic acid post-mortem
Minerals	0.8–1.2%	0.8–1.1%	0.9–1.1%	Heme iron, zinc, phosphorus

II. The First Transformation: Slaughtering

II.1. Cattle and Sheep Slaughtering Operations

The slaughterhouse constitutes the first link in the chain of transforming the animal into meat. The slaughtering operations must simultaneously meet the requirements of animal welfare, food hygiene, personnel safety, and the technological quality of the carcass. The figure 37 summarize the slaughter operation of cattle.

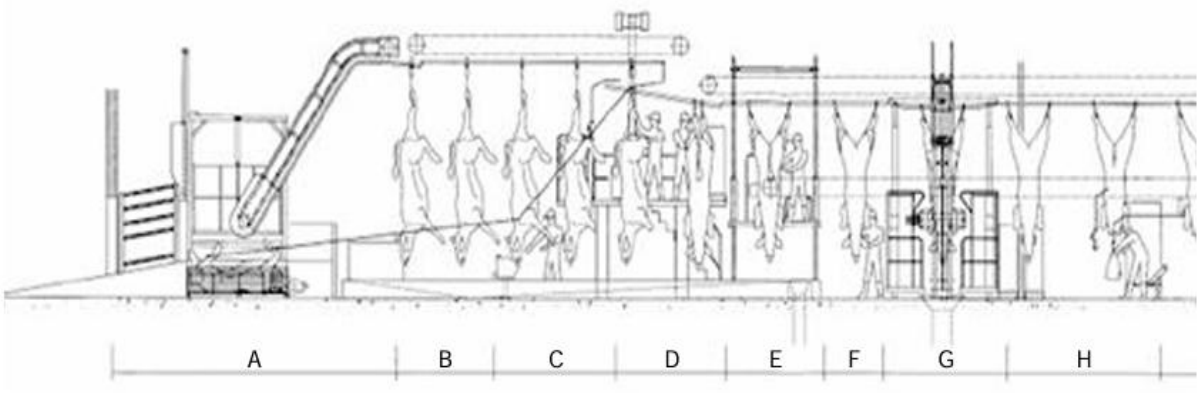

Figure 37: Cattle slaughter line and dressing operations: stunning, sticking, bleeding, removal of feet and horns, pre-dedhiding, evisceration, and head removal

II.1. 1.Reception and preslaughter handling

Cattle are first received at the slaughterhouse and kept in lairage or holding pens before processing. This stage reduces stress, allows resting, and helps ensure the animals are fit for slaughter after veterinary inspection. Good preslaughter handling is important because stress can affect both animal welfare and meat quality.

II.1.2. Stunning

Stunning is used to render the animal immediately unconscious and insensitive to pain before bleeding. In cattle, the most common method is the penetrating captive bolt, while electrical stunning may also be used in some systems. A correct stun is essential for humane slaughter and for smooth processing of the carcass.

II.1.3. Bleeding

After stunning, the animal is shackled and bled by cutting the major blood vessels in the neck or thoracic region. This step, also called sticking or exsanguination, removes blood from the carcass and helps prevent microbial growth and discoloration. Efficient bleeding is also important for carcass quality and shelf life.

II.1. 4. Head removal and handling

The head is removed after bleeding, and this requires careful handling to avoid contamination. In cattle slaughter, the spinal cord may be cut during this process, so hygiene is critical to prevent

cross-contamination. The head is then cleaned and inspected according to sanitary rules.

II.1.5. Hide removal

Hide removal, also called skinning or dehiding, is the process of separating the skin from the carcass. This step is necessary so that the edible carcass is exposed for inspection and further dressing. It must be done carefully to prevent dirt, hair, or microorganisms from contaminating the meat.

II.1.6. Evisceration

Evisceration is the removal of the internal organs, including the stomach, intestines, and other viscera. This is one of the most critical hygiene stages because any rupture of the digestive tract can contaminate the carcass. The operation is performed under sanitary control, and the organs are usually inspected separately.

II.1.7. Carcass splitting

The carcass is split lengthwise into two halves, usually down the backbone. This makes chilling, transport, inspection, and later cutting easier. Splitting is an important fabrication step because it prepares the carcass for classification and commercial cutting.

II.1.8. Inspection and trimming

After splitting, the carcass undergoes post-mortem meat inspection and trimming. Inspection ensures that the meat is safe and suitable for human consumption, while trimming removes contaminated or damaged tissues. These actions improve both food safety and visual quality.

II.1.9. Washing and chilling

The carcass is washed if necessary and then moved to chilling rooms. Chilling lowers the temperature quickly, usually to around 0–4°C or the required legal storage temperature, to slow bacterial growth. Rapid cooling also helps stabilize the carcass before fabrication into retail cuts.

II.1.10. Weighing, classification, and quartering

Finally, the carcass is weighed and classified, then divided into quarters or primal cuts. These steps determine commercial value and prepare the meat for distribution or further processing. This is the final stage before the meat enters the cutting and packaging chain.

II.2. Poultry Slaughter Operations

Poultry slaughter is highly mechanized in modern industrial slaughterhouses, enabling very high line speeds, often ranging from 5,000 to 15,000 birds per hour. The process is designed to maximize efficiency while maintaining hygiene, product quality, and animal welfare standards (Figure 38).

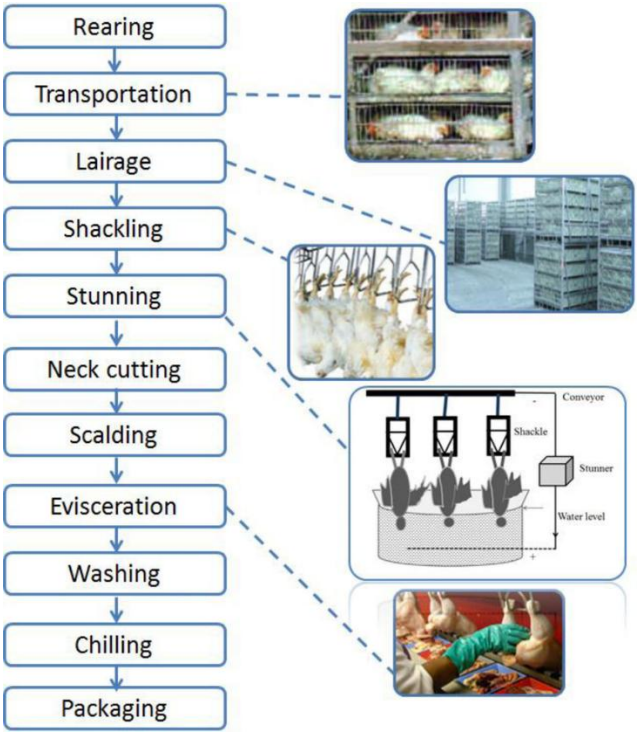

Figure 38: Typical events in the commercial production of poultry meat.

II.2.1. Reception and feed withdrawal

the hens arrive in crates or modules and are held under feed withdrawal for about 8–12 hours before slaughter. This fasting period reduces gut fill, lowers the risk of fecal contamination during evisceration, and helps improve sanitary conditions.

II.2.2. Shackling

The hens are hung by the legs on shackles attached to the slaughter line. This stage can be stressful and may cause bruising or breast meat defects, so it should be carried out carefully, preferably under dim light or red light to reduce agitation.

II.2.3. Electrical stunning in a water bath

The hens' heads pass through a water bath carrying an electric current, usually 50–200 mA at 50 Hz, which induces reversible unconsciousness. The main critical factors are current intensity, frequency, and immersion time; if the current is too low, birds may remain conscious, while excessive current can cause hemorrhages in the breast muscles and wing tips. As an alternative, controlled-atmosphere stunning with CO2 can improve animal welfare and reduce muscular damage.

II.2.4. Bleeding

Bleeding is performed either automatically, using a rotating knife, or manually by cutting the carotid arteries and jugular veins. The bleeding time is usually around 90–120 seconds, and a bleeding tunnel is often used to confine blood and improve hygiene.

II.2.5. Scalding

The carcasses are immersed in hot water to loosen the feathers. Two main scalding regimes are used: soft scalding at about 51–53°C for 120 seconds, which preserves the skin and gives a better appearance, and hard scalding at about 56–58°C for 90 seconds, which is used for yellow-skinned chickens or ducks.

II.2.6. Defeathering

Feathers are removed mechanically using rotating rubber-finger pluckers. Several passes are usually required to remove large feathers, small feathers, and down, and any remaining defects may be corrected manually.

II.2.7. Singeing and polishing

Residual feathers and filamentous feathers are removed by flaming with gas burners or infrared systems. This step improves the final appearance of the carcass and helps eliminate remaining feather fragments.

II.2.8. Automated evisceration

The abdominal cavity is opened and the viscera are removed automatically. The liver, gizzard, and heart are collected separately as edible offal, while the carcass undergoes internal and external washing with pressurized water. Post-mortem inspection of the carcass and viscera is also carried out at this stage.

II.2.9. Chilling

Two main chilling systems are used. Immersion chilling uses ice-cold water baths at 0–4°C and is common in the United States, but it may create cross-contamination risks and cause water uptake of up to 4% of carcass weight. Air chilling uses cold-air tunnels and is more common in Europe; it avoids water absorption and offers better control of cross-contamination, with the carcass generally required to reach 4°C or below within 4 hours.

III. By-Product Treatment: Valorization of the Fifth Quarter

III.1. Definition and Composition of the Fifth Quarter

The traditional "four quarters" of noble meat correspond to the classic division of a butcher's carcass (beef, veal, etc.) into: right forequarter, left anterior quadrant, right posterior quadrant and left hindquarter.

These quarters group together the so-called "noble" cuts of meat, that is, the main muscles of the carcass. The fifth quarter refers to all products obtained during slaughter that are not part of the carcass itself, which is divided into the four main quarters. It includes edible and inedible by-products such as offal, hide, blood, fat, bones, horns, hooves, and other residual materials (Figure 39). In a bovine, it can represent more than 50% of the live weight before slaughter and therefore constitutes an important source of economic value for the meat industry.

III. 2. Categories of the Fifth Quarter

III. 2. 1. Offal, edible viscera

Offal, or edible viscera, is directly consumed in many cultures and must be handled and refrigerated within the required time limits, typically with rapid chilling at temperatures at or below 3°C. This group includes red offal such as the liver, heart, lungs, kidneys, spleen, tongue, and brain. It also includes white offal such as the stomach compartments of cattle, intestines, caul fat,

feet, head, and tail.

III. 2. 2. Food coproducts

Food coproducts include blood, bones, fat, horns, and hooves. Blood accounts for about 3–4% of live weight and is rich in proteins such as albumin, fibrinogen, and globulins. Bones and fat are important components of the fifth quarter, while horns and hooves are keratin-rich materials.

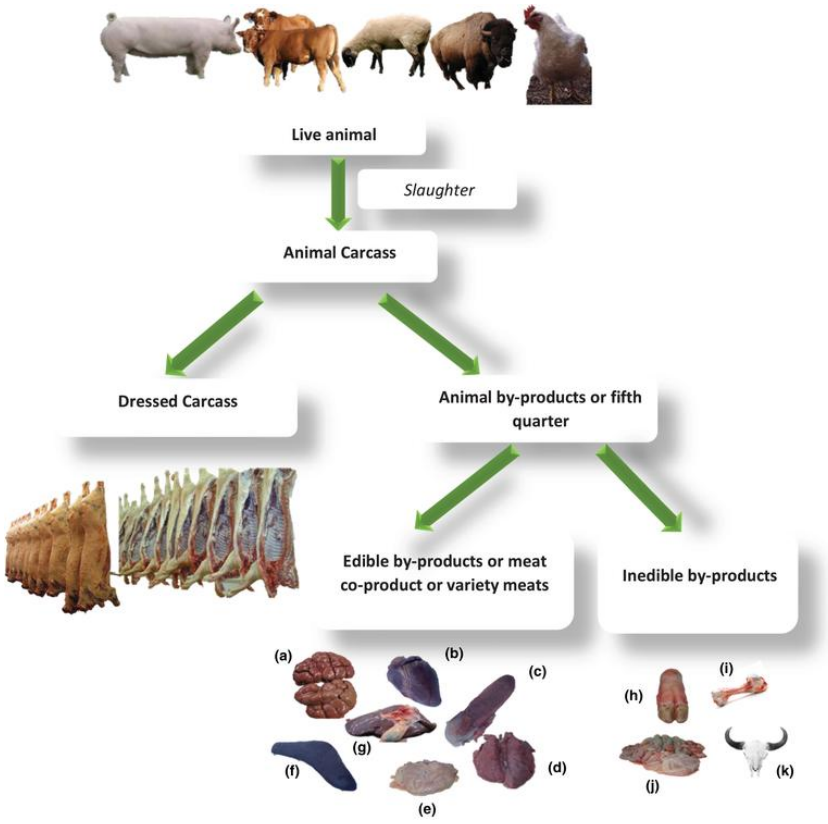

Figure 39: The classification of the fifth quarter with common names used to describe them; Selected fifth quarter labeled as (a) kidney, (b) heart, (c) tongue, (d) lung, (e) stomach, (f) spleen, (g) liver, (h) hoof, (i) bone, (j) digesta in gut, and (k) skull.

III. 2. 3. Hides and skins

Hides and skins represent about 5–8% of bovine live weight. They are a major component of the fifth quarter because of their large mass and high commercial importance. Careful flaying is necessary to preserve the integrity of the skin.

III. 2. 4. Non-food by-products

Non-food by-products include bile, endocrine glands, and natural casings. Bile contains bile acids, while endocrine glands include the pancreas, pituitary, and thyroid. Natural casings are also part of this category.

III. 3. Classification of Animal By-Products

Regulation (EC) No. 1069/2009 classifies animal by-products into three categories according to the level of sanitary risk they present.

III. 3.1. Category 1 (high risk): specified risk materials such as bovine brain and spinal cord from animals older than 12 months with respect to bovine spongiform encephalopathy, as well as animals suspected of transmissible diseases. These materials must be disposed of by incineration.

III. 3.2. Category 2: by-products from animals that died other than by slaughter for human consumption, manure, and digestive tract contents. These materials may be processed into meat and bone meal or fats for energy purposes, or into fertilizers after pressure sterilization at 133°C for 20 minutes at 3 bar.

III. 3.3. Category 3: by-products derived from healthy animals slaughtered and declared fit for human consumption. They may be converted into processed animal proteins (PAPs) and animal fats for pet food, detergents, gelatin, cosmetics, and related uses; they account for about two-thirds of the treated by-products.

III. 4. Use of By-Products

Meat by-products can be used in several sectors, including food, animal feed, pharmaceuticals, and technical products (Figure 40).

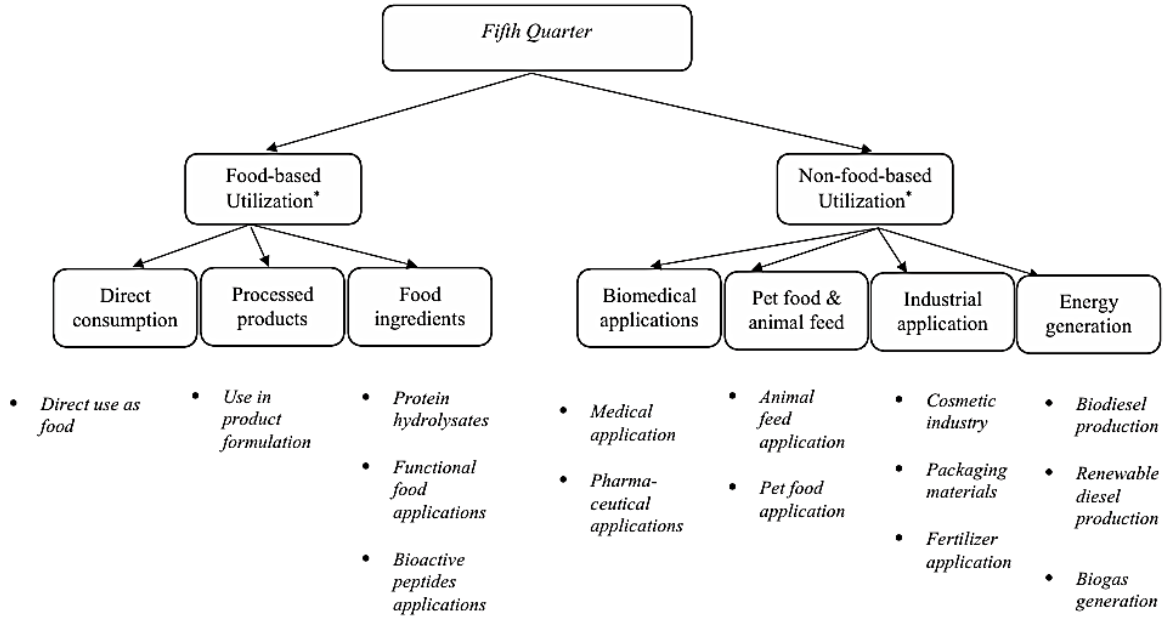

Figure 40: Potential Uses of Fifth Quarter By-Products

III. 4.1. Blood

Blood can be processed into food additives, stabilizers, emulsifiers, natural colorants, blood meal, and feed ingredients (Figure 41). Blood processing generally includes stabilization, defibrination, fractionation, coagulation, and drying.

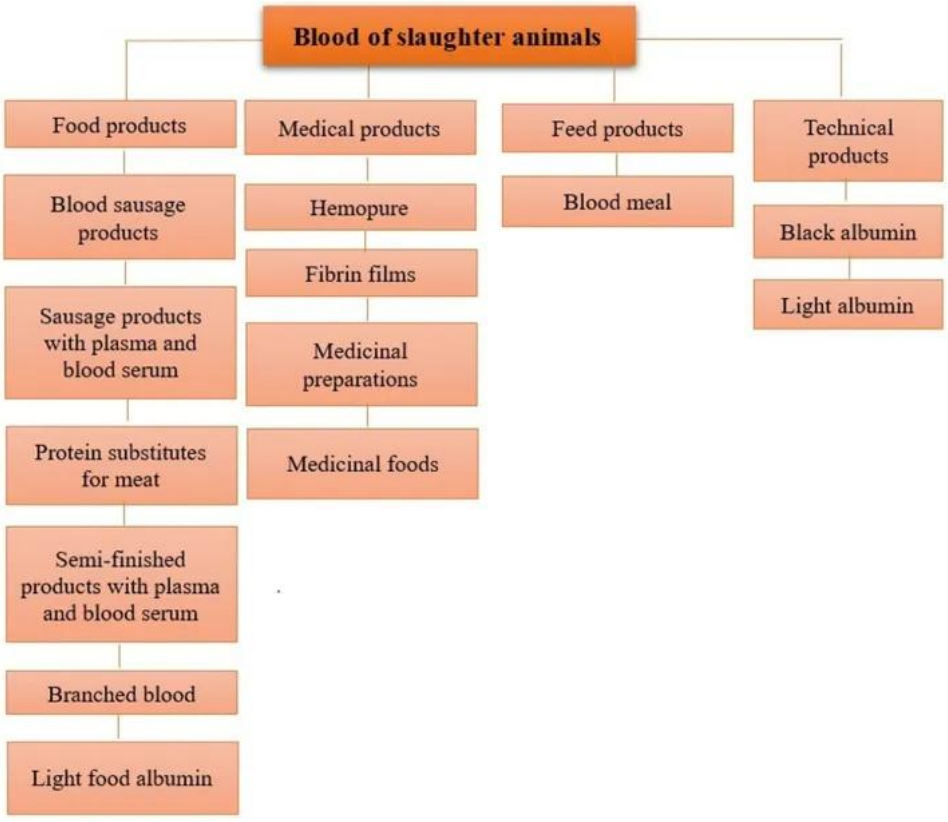

Figure 41: Application of waste blood.

Stabilization prevents clotting and preserves valuable proteins, while defibrination removes fibrin. Fractionation separates blood into plasma and cellular components, improving industrial utilization. Spray drying is commonly used to produce blood meal, a protein-rich product suitable for animal nutrition.

III. 4.2. Bone

Bones are used to produce bone meal, broth, phosphates, hydroxyapatite, glue, and fertilizers, while skin and other collagen-rich tissues are converted into gelatin, collagen hydrolysates, and bioactive peptides. Bones are processed through thermal and mechanical methods to obtain bone meal, bone extracts, and hydroxyapatite.

III. 4.3. Collagen-rich materials

Collagen-rich materials such as skin, tendons, and connective tissues are transformed into gelatin or collagen hydrolysates by controlled hydrolysis. Enzymatic and biotechnological methods are also used to produce bioactive peptides, which have antioxidant, antimicrobial, and

antihypertensive properties. These products are used in food formulations, health products, animal nutrition, and technical applications.

III. 4.4. Animal fats

Animal fats are also valuable for food applications, soap making, biodiesel production, and other industrial uses. Animal fat is typically processed by wet rendering or dry rendering. After extraction, it is purified by heating, settling, and separation to remove water and impurities. The resulting fat can be used in food production, soap manufacturing, energy applications, and biodiesel.

IV. Fish

V.1. Composition of Fish

Fish are aquatic vertebrate animals that live in fresh or salt water. They are characterized by gill respiration, the presence of fins for locomotion, and a body that is generally covered with scales. They are cold-blooded animals, or poikilothermic, and reproduce mainly by laying eggs, so they are oviparous.

Fish flesh, unlike meat, has some specific characteristics (figure 42). It contains short muscle fibers organized into lamellae called myotomes, which makes the flesh more tender. It also has a low content of connective tissue, which is why fish must usually be cooked quickly to remain tender.

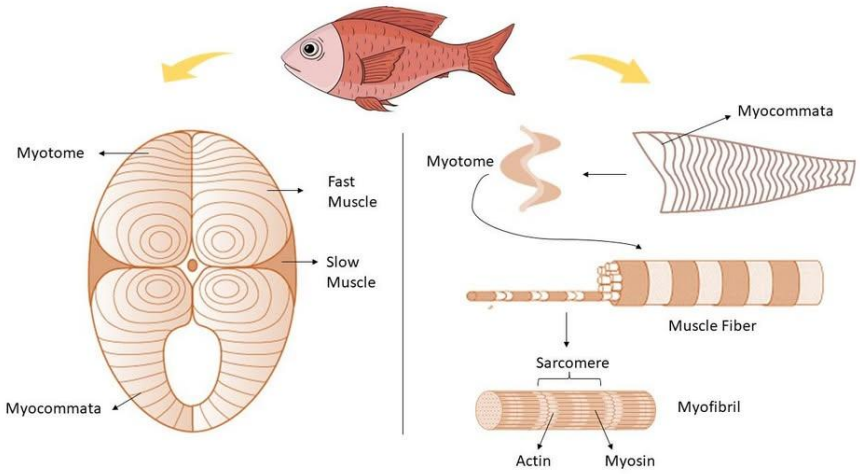

Figure 42: muscle structure of a fish

The chemical composition of fish (Table 18) varies considerably according to species, season, fishing area, and the physiological state of the animal, especially during the spawning period. This composition determines the nutritional properties, shelf life, and the technological processes that can be applied.

Table 18: Composition of fish

Constituent	Lean fish (cod, hake)	Fatty fish (sardine, salmon)	Nutritional / technological role
Water	78–85%	60–75%	Water activity, texture
Proteins	16–22%	16–20%	Structure; gelling ability, especially in surimi
Lipids	0.5–2%	8–25%	Source of omega-3 fatty acids (EPA, DHA); oxidation susceptibility
Carbohydrates	< 0.5%	< 0.5%	Almost absent
Minerals	1–2%	1–2%	Iodine, selenium, calcium from bones

V.1.1. Water

Water is the most abundant component of fish flesh, usually ranging from 60% to 85%. Lean fish contain more water than fatty fish, and water content is inversely related to fat content. Fish muscle contains both bound water and free water, with free water representing the larger fraction. A high-water activity makes fish highly susceptible to microbial growth.

V.1. 2. Lipids

Fish lipids are made mainly of triglycerides and phospholipids, plus a smaller unsaponifiable fraction. Fatty fish contain more lipids than lean fish, and these lipids are rich in long-chain unsaturated fatty acids, especially omega-3 fatty acids such as EPA and DHA. Because of their high unsaturation, fish lipids are highly prone to oxidation.

V.1. 3. Nitrogenous compounds

Proteins are the major nitrogenous compounds in fish and usually account for about 15% to 20% of the muscle such as actomyosin, myosin, actine…etc. Their proportion is generally stable, but it can vary with season, diet, and sexual cycle. Fish also contain non-protein nitrogen compounds such as trimethylamine oxide, urea, ammonia, free amino acids, and nucleotide bases. These compounds contribute strongly to the characteristic flavor of fish and vary by species and size.

V.1.4. Carbohydrates

Carbohydrates are present in very small amounts, mainly as glycogen. Their level is usually low in fish muscle, though it may be higher in mollusks. Glycogen is found especially in red muscle and is affected by species, age, season, and capture method. Stress during capture can reduce glycogen reserves.

V.1. 5. Minerals

Fish contain several important minerals, especially calcium, sodium, potassium, magnesium, phosphorus, iron, copper, selenium, and iodine. Iodine is one of the elements that distinguishes fish muscle from mammalian muscle. Minerals may be present either dissolved in the cellular environment or bound to proteins. In many species, fish are considered a good dietary source of iodine, selenium, and phosphorus.

V.1. 6. Vitamins

Fish contain both fat-soluble vitamins and water-soluble vitamins. The main fat-soluble vitamins are A, D, E, and K, while the main water-soluble vitamins include B1, B2, B6, B12, and C. Vitamins A and D are especially abundant in fatty fish and are often stored in the liver. Fish is also recognized as an important source of vitamin B12.

V.1. 7. Enzymes

Fish muscle contains many enzymes that are involved in postmortem degradation and spoilage. These include glycolytic enzymes, ATPase, adenylate kinase, AMP deaminase, proteases, and trimethylamine N-oxidase. Their activity contributes to texture changes, freshness loss, and the development of spoilage odors. Enzyme activity is therefore important in fish preservation and processing.

V.2. Nature of Fish

Fish play a crucial role in human nutrition, particularly for coastal populations, where they represent a major source of high-quality proteins, essential fatty acids, and micronutrients. Their biological diversity allows them to be classified according to several scientific and technological criteria.

V.2.1. Classification by Habitat

Fish can be classified based on their natural environment:

a) Freshwater fish: live in rivers, lakes, and ponds. Examples: carp, catfish.

b) Marine fish: inhabit seawater environments. Examples: sardine, red mullet, sole, sea bass.

c) Migratory (diadromous) fish: migrate between freshwater and seawater during their life cycle. Example: salmon.

V.2.2. Classification by Skeletal Structure

The skeletal structure reflects the evolutionary history of fish:

a) Cartilaginous fish: characterized by a skeleton made of cartilage; they are among the earliest fish to appear. Examples: sharks, rays, dogfish.

b) Bony fish: possess an ossified skeleton and are more evolutionarily advanced and diverse. Examples: anchovy, salmon.

V.2.3. Classification by Body Shape

Fish can also be categorized according to their morphology:

a) Round fish: spindle-shaped body adapted for active swimming. Example: whiting.

b) Elongated fish: long and slender body. Examples: dogfish, salmon.

c) Flat fish: laterally flattened body adapted to bottom-dwelling life. Example: sole.

V.2.4. Classification by Lipid Content

Lipid content is an important criterion in nutrition and food technology:

a) Lean fish (lipids < 2%): cod, hake, sole, sea bass, sea bream, whiting. Lipids are mainly stored in the liver (e.g., cod liver).

b) Semi-fatty fish (2–8%): trout, carp, red mullet.

c) Fatty fish (lipids > 8%): sardine (8–18%), mackerel (10–20%), herring (10–20%), salmon (12–18%), bluefin tuna (8–25%). Lipids are distributed throughout the muscle tissue.

V. Cold treatment of Meat and Fish

Cold is the most widely used method for preserving meat and fish because it slows biochemical, enzymatic, and microbial reactions according to the Arrhenius law, so a 10°C decrease typically reduces reaction rates and microbial growth by a factor of about 2 to 3. It also helps preserve the nutritional and sensory qualities of foods better than cooking or dehydration, since it causes fewer structural and compositional changes. Temperature and water activity are key factors in spoilage; fresh meat and fish have very high-water activity, which makes them highly perishable, while refrigeration mainly limits psychrotrophic bacteria such as *Brochothrix thermosphacta*, *Pseudomonas fluorescens*, and *Shewanella putrefaciens*.

The cold chain is the uninterrupted sequence of cooling, storage, transport, and retail conditions from slaughter or capture to the consumer, and any break in this chain can sharply reduce shelf life and increase food safety risks from pathogens.

IV. 1. Refrigeration

IV.1.1. Principle of Refrigeration and Preservation Objectives

Refrigeration involves lowering and maintaining the temperature of a food above its freezing point, in order to significantly slow down spoilage reactions without forming intracellular ice. The main objective is to extend the shelf life while preserving the "fresh" organoleptic characteristics of the product color, texture, odor, juiciness which would be deteriorated by the crystallization of the water inherent in freezing. Refrigeration works by slowing down bacterial growth, reducing endogenous enzymatic activity, and limiting lipid oxidation reactions.

IV.1.2. Optimal temperatures for red meat, poultry, fish

European regulations (Regulation EC No 853/2004) set precise maximum temperatures for meat storage: beef and lamb carcasses below 7 °C, offal below 3 °C, and poultry carcasses with an internal temperature below 4 °C (Table 19).

Table 19: Optimal temperatures of refrigeration of meats and fish

Product	Maximum Temperature	Necessary Conditions
Red meat (beef/lamb carcasses)	< 7 °C	Continuous cold chain (0 to +4 °C), immediate post-slaughter refrigeration, avoid freezing.
Red meat (offal)	< 3 °C	Isolated storage, continuous monitoring, no cold chain breaks.
Chicken (poultry carcasses)	< 4 °C (internal)	Strict cold chain (0 to +3 °C), ventilated transport and storage.
Fresh fish (sea products)	0 to 2 °C (melting ice)	Near 0 °C without freezing, controlled humidity, airtight packaging.

IV. 1.3. Relative humidity and air velocity in cold rooms

In cold storage rooms, relative humidity (RH) and air velocity complement temperature to preserve the quality of meats and fish. An RH that is too low causes superficial desiccation (dry crust, weight loss, commercial spoilage), while excessive RH promotes condensation and microbial growth; 85-90% is recommended for red meats, 90-95% for fish/poultry. Air speed (0.5-2 m/s) homogenizes the temperature and accelerates cooling, but increases evaporation if too high, requiring a compromise depending on the facilities.

IV.1.4. Refrigeration storage times for main meats and fish

The shelf life in refrigeration depends on the species, the packaging, and the temperature (Table 20)

Table 20: Shelf life of meat and fish under refrigeration

Product	Storage condition	Shelf life	Main factors affecting shelf life	Main quality losses
Beef	Aerobic refrigeration	5–7 days	Species, packaging, temperature, initial microbial load	Microbial spoilage, color change, texture softening
Poultry	Aerobic refrigeration	2–3 days	High water activity, rapid microbial growth, temperature	Off-odors, slime formation, microbial deterioration
Beef	Sous vide at 0 °C	Up to 12 weeks	Vacuum packaging, low temperature, low oxygen availability	Slower spoilage, but possible quality loss if cold chain is broken
Lamb	Sous vide at 0 °C	About 5 weeks	Vacuum packaging, strict temperature control	Microbial growth if temperature rises, changes in flavor and texture
Fatty fish (herring, mackerel)	On ice at about 0 °C	5–7 days	High fat content, enzymatic activity, microbial load	Rancidity, TVB-N increase, odor deterioration
Lean fish	On ice at about 0 °C	15–30 days if gutted and cooled quickly	Rapid chilling, gutting, hygienic handling	Texture and color changes, spoilage if handling is delayed

IV. 2. Freezing

IV.2.1. Principle of Freezing: Freezing Point and Storage Temperature

Freezing is the process by which the temperature of a food is lowered below its freezing point, causing a significant portion of the water to turn into ice. The freezing point of meats is generally between −1 and −2 °C, and that of fish is between −0.8 and −1.4 °C depending on the species and the content of salt and proteins. For long-term storage, the target temperature is −18 °C or lower, a threshold below which most pathogenic and spoilage microorganisms are unable to multiply. At −10 °C, about 80% of the water in the products is converted into ice, which drastically reduces water activity and inhibits microbial growth. Freezing thus improves the shelf life well beyond the limits of refrigeration, but is accompanied by qualitative changes that must be controlled.

IV.2.2. Physico-Chemical Effects of Freezing on Meats and Fish

During freezing, free water first crystallizes extracellularly, cryo-concentrating solutes (salts, proteins) in the residual liquid, lowering its freezing point and causing biochemical disturbances; the volumetric expansion (~9%) ruptures membranes and myofibrils. Rapid freezing forms small intracellular crystals that are less damaging than the large extracellular crystals formed during slow freezing.

Drip loss (juice loss during thawing) results from these cellular ruptures, worsened by long storage and large crystals; it reduces water content (chicken: 73.8% → 63.5%; fish: 74.3% → 70.1%). Tenderness improved by myofibrillar fragmentation, but dryness and loss of juiciness during cooking.

Frozen storage denatures proteins (myosin: aggregation, ↓ water retention, post-cooking hardening; more sensitive in fish), causes oxidation of polyunsaturated fatty acids (fatty fish: rancidity, ↓ color/protein solubility); mitigate by glazing, vacuum, exclusion of O_2/light.

IV. 2.3. Freezing method

Freezing method choice depends on the product, required quality, and cost.

IV. 2.3.1. Air blast freezing

Air blast freezing is the most widely used method in the food industry. It uses high-speed refrigerated air (1–5 m/s) around products placed on racks or hung in a tunnel or freezer cabinet. Air temperatures are usually between −25 and −40 °C. This method is versatile and suitable for many product shapes and packaging types. Its main drawback is that freezing is relatively slow for thick pieces, which can lead to larger ice crystals and greater quality loss than cryogenic methods.

IV. 2.3.2. Contact freezing (plates)

Plate freezing is based on direct contact between the product and metal plates cooled by a circulating refrigerant. It is especially suitable for regular-shaped products such as vacuum-packed fish fillets or blocks of minced meat. Direct heat transfer by conduction is more efficient than air convection, so freezing is faster and product quality is better preserved. Plate freezers can be horizontal or vertical, depending on the type of product and industrial setup.

IV. 2.3.3. Cryogenic freezing

Cryogenic freezing uses very low-temperature agents such as liquid nitrogen (−196 °C) or solid CO_2, also called dry ice (about −78 °C). These methods produce extremely fast freezing, creating very fine ice crystals, reducing cell damage, and improving final quality in texture, color, and water retention. They are often used for shrimp, premium fish fillets, and high-value fresh products. The main disadvantages are the high cost of cryogenic agents and the need for specialized ventilation and equipment.

IV.3. Flash Freezing

IV.3.1. Definition

Flash freezing is an ultra-rapid freezing technique regulated by European legislation (Directive 89/108/EEC, transposed into national laws), which requires that the core temperature of the product be reduced from +20 °C to −18 °C as quickly as possible, and that the product be continuously maintained at −18 °C or lower until it is sold to the consumer. The essential difference with conventional freezing lies in the cooling speed; "ordinary" freezing can be slow (several hours), while flash freezing requires an ultra-rapid passage thru the maximum crystallization zone (between approximately −1 and −7 °C), which leads to the formation of very fine ice microcrystals. Classic freezing lowers the core temperature between −12 and −18 °C without speed constraints, while flash freezing is legally defined by this requirement for rapid temperature descent (figure 43).

IV.3.3. Advantages of flash freezing for meat and fish

The benefits of flash freezing compared to slow freezing are numerous and documented: reduction of drip loss and maintenance of better water retention capacity after thawing, preservation of texture and juiciness, limitation of protein denaturation and lipid oxidation. For aquatic products, cryogenic freezing (an extreme form of quick freezing) results in significantly lower juice loss and protein denaturation compared to conventional air-blast freezing. The shelf life of frozen products stored at −18 °C is comparable to that of conventionally frozen products, but their quality upon thawing is significantly superior.

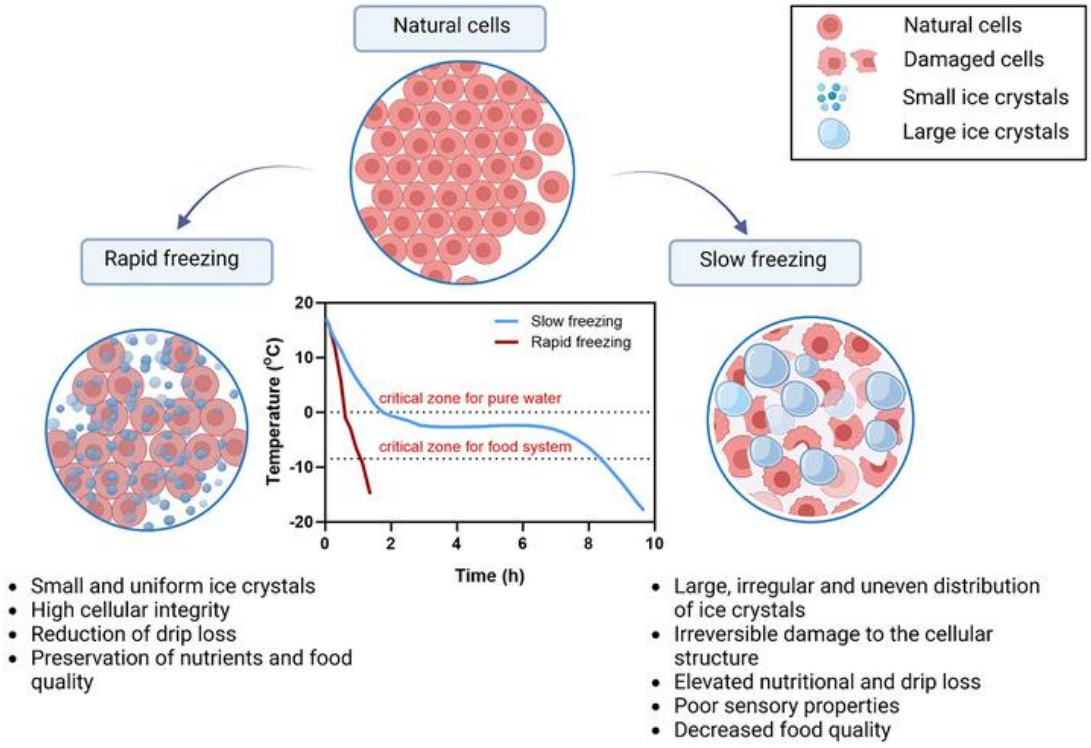

Figure 43: The cellular structure and changes that occur during rapid and slow freezing

IV.3.4. Equipment and Processes Used

Industrial freezing equipment mainly includes air blast freezing tunnels (with continuous conveyor or carts), fluidized bed freezers (particularly suitable for small products like shrimp, vegetables, or small pieces of meat, especially for the production of individually quick-frozen products, IQF — Individually Quick Frozen), plate freezers, and cryogenic freezers using liquid nitrogen or CO_2. The IQF (Individually Quick Frozen) technology is particularly used for shrimp, fish filets, scallops, and nuggets because it produces high-quality, non-clumped products. Cryogenic tunnels offer the fastest freezing speeds but come with high operational costs due to the price of cryogenic fluids.

VI. Products of the Third Meat Processing

VI.1. Technologies Used in Algeria: Cooking, Grinding, Curing

The third transformation encompasses all operations that confer technological, gastronomic, and commercial added value to meat cuts or meat mixtures. In Algeria, the main technologies applied are cooking, mincing, and curing, in a context of respect for religious prescriptions (Halal).

VI.1.1. Mincing

The term “Minced Meat” refers to a reduction in particle size of raw meat pieces that have been cut by a mechanical knife, sharp blades or a grinder plate. The resulting product is a smaller (1–12.5 mm) version of mainly intact muscle structures that have drastically increased the surface area of the product. Other names, like ground and comminuted meat, are synonymous in meaning.

This process disrupts muscle structure, releases myofibrillar proteins, and increases the surface area of the meat. As a result, it improves binding and emulsifying properties, which is important for the structure of many processed meat products.

However, minced meat presents a higher microbiological risk because surface bacteria are dispersed throughout the product mass. For this reason, strict hygiene and temperature control are required, especially during grinding, when the meat should remain at low temperature. Common Algerian minced-meat products include merguez, kefta, halal burgers, fricandeau, and fresh minced meat

VI.1.2. Curing and Salting

Curing consists of adding salt, and sometimes other curing ingredients, to meat in order to preserve it and develop specific technological and sensory properties. Salt plays several important roles:

- It lowers water activity, which inhibits microbial growth.
- It solubilizes myofibrillar proteins, improving water binding and emulsification.
- It contributes to the characteristic texture of cooked cured products through heat-induced gel formation.

Three main curing methods are used:

a) Dry salting

Dry salting consists of applying salt directly to the surface of the meat, sometimes mixed with spices or other curing ingredients. The salt then penetrates gradually into the tissue by diffusion and osmosis, while water moves out of the meat, leading to partial dehydration.

This method is simple and traditional, and it is suitable for large cuts such as hams and certain artisanal cured products. However, it is slower than the other methods because salt penetration depends on thickness, temperature, and contact time.

b) Brine immersion

Brine immersion involves soaking meat in an aqueous salt solution called brine. In this method, salt diffuses from the brine into the muscle, producing a more uniform and usually faster curing effect than dry salting.

This technique can be used for whole cuts, smaller pieces, or products intended for smoking or cooking. It provides good control of salt content, flavor, and processing uniformity, but strict hygiene and temperature control are required.

c) Brine injection

Brine injection is a rapid industrial method in which brine is injected directly into the muscle using multi-needle systems. This allows salt and curing agents to penetrate quickly and ensures a more homogeneous distribution throughout the meat.

It is especially useful for large products or industrial production where fast, standardized, and reproducible curing is needed. Injection can be used alone or combined with immersion to improve curing uniformity.

VI.1.2.1. Technological role of salt

Salt plays several key roles in meat products; it lowers water activity, which limits microbial growth; it helps solubilize some muscle proteins; and it contributes to the final texture of the product. In processed meats, it also supports firmer and more stable structure after cooking.

In Halal contexts, nitrite-free formulations are often preferred. In Western meat processing, nitrites are used for antimicrobial protection, especially against *Clostridium botulinum*, and for the characteristic pink color of cured meats. In Algerian Halal formulations, alternatives such as sodium lactate and acetate are often used instead.

VI.1.3. Cooking

Cooking performs several functions at once; it destroys pathogens, denatures proteins, develops texture, enhances flavor, and improves digestibility.

Key thermal changes include:

a) Myofibrillar protein denaturation, generally between 60 and 70 °C.

b) Collagen conversion into gelatin above about 65–70 °C.

c) Inactivation of pathogens such as *Listeria monocytogenes* at around 70 °C for 2 minutes, depending on the time-temperature combination.

Industrial cooking processes include steam cooking, mold cooking for products such as cooked ham, smoke-cooking, tunnel oven cooking, and autoclave sterilization for shelf-stable products.

VI.2. Structuring of Fine Meat Pastes (Pâté, Cachir)

Fine meat batters, or emulsified meat pastes, represent a critical category of processed meat products. Their manufacture relies on the formation of a stable meat–water–fat emulsion driven by the functional properties of salt-soluble myofibrillar proteins, particularly myosin. These proteins act as natural emulsifiers, stabilizing fat droplets within a continuous aqueous protein matrix.

VI.2.1. Principle of fine meat emulsion formation

An emulsion is a heterogeneous colloidal system consisting of two immiscible phases, where fat droplets are dispersed within a continuous aqueous phase. In fine meat pastes, fat droplets are stabilized by an interfacial protein film formed by soluble myofibrillar proteins extracted through the addition of sodium chloride.

The stability of meat emulsions depends on several critical physicochemical and processing parameters: Salt concentration (1.5–2.5%), Cutter temperature (< 12°C), Meat/fat/water ratio and Meat pH (5.4–6.0)

VI.2. 2. Manufacturing Process

The industrial production of fine meat pastes involves a sequence of unit operations:

a) Selection and Preparation of Raw Materials

Lean meat (typically beef or poultry) and firm fats (backfat or poultry skin) are selected based on formulation requirements. Ice water, salt (NaCl), phosphates (optional), and spices are incorporated to facilitate protein solubilization and flavor development.

b) Cuttering (Comminution & Emulsification)

This is the core technological operation, performed in a bowl cutter equipped with a rotating bowl and high-speed rotating knives (1,500–3,000 rpm). During cutting:

- Muscle fibers are mechanically sheared, disrupting myofibrillar structures;
- Salt and phosphates enhance ionic strength, promoting the extraction and solubilization of myosin and actomyosin;
- Fat is progressively reduced into fine droplets and stabilized by the protein film;
- A smooth, viscoelastic, homogeneous batter is obtained.

Critical control point: Bowl temperature must remain below 12°C (ideally 0–4°C) to prevent protein denaturation and fat phase separation.

c) Stuffing or Molding

The batter is transferred into:

- Natural or artificial casings (e.g., collagen, cellulose) for cachir and emulsified sausages;
- Trays, molds, or cans for pâté and liver pastes.

d) Thermal Processing

Cooking induces protein gelation, forming an irreversible three-dimensional network that immobilizes fat and water, ensuring product cohesion. Simultaneously, heat treatment ensures:

- Pasteurization (70–80°C core temperature) for refrigerated products;
- Sterilization ($F_0 \geq 3$ min, 121°C) for shelf-stable canned products.

VI.2.2.1. Cachir

Cachir is one of the most emblematic products of Algerian halal charcuterie. It is an emulsified sausage manufactured primarily from beef or poultry meat, characterized by a high-water content and the incorporation of starch as a binder and extender.

a) Typical Formulation

The formulation of cachir is based on a balanced mixture of meat, water, binders, salt, spices, and texturizing agents. Each ingredient plays a specific role in the development of the final product, contributing to its structure, stability, flavor, and overall quality (Table 21).

Table 21: Typical formulation of cachir

Ingredient	Proportion (%)	Functional Role
Lean beef / poultry meat	40–60	Protein source, emulsion base
Water / ice	20–30	Continuous phase, cooling medium
Starch (corn, potato, or wheat)	5–10	Binder, water retention, cost reduction
Salt	1.5–2.5	Protein extraction, flavor, preservation
Spices (cumin, coriander, pepper)	0.5–2.0	Flavor, antimicrobial properties
Texturizing agents (carrageenan, soy protein)	0.3–1.0	Water binding, emulsion stabilization

b) Technological Challenges

The primary challenge in cachir production is maintaining emulsion stability during thermal processing. This requires:

- Strict control of cutter temperature to prevent fat coalescence;
- Prevention of syneresis (weeping), which is the expulsion of water from the gel network due to poor protein–water binding or excessive starch retrogradation.

VI.2.2.2. Pâté

Pâté is a meat product based on liver (liver pâté) or finely emulsified lean meat, thermally processed in terrines or cans. The key steps in the preparation of pâté preparation are:

a) Meat Selection

Algerian pâté primarily uses beef, chicken, turkey, or other poultry. The meat must be halal certified, an essential criterion for the majority of local consumers and for export. Specialized butchers play a central role in selecting the appropriate cuts.

b) Seasoning

The addition of spices such as Espelette pepper, black pepper, or local herbs gives Algerian pâté its unique character. Espelette pepper, although of Basque origin, is increasingly used to enhance the flavor and meet the demands of consumers seeking novelty.

c) Mincing and Mixing

The meats are finely minced and then mixed with spices, salt, and sometimes vegetables or eggs, depending on the regional recipe. This homogeneous mixture guarantees the typical texture of Algerian pâté.

d) Cooking

Cooking is traditionally done by steaming or in a bain-marie, but the industry also uses steam ovens for larger volumes. This step is crucial to ensure food safety and product preservation.

e) Packaging

The pasta is then vacuum-packed or jarred, depending on its intended use (butcher shop, supermarket, export). Packaging affects shelf life and presentation on restaurant menus or during direct sales.

VII. Fish Preserves (Sardines, Tuna...)

Fish preserves are an important form of canning that makes it possible to obtain a product that is stable at room temperature, microbiologically safe, and shelf-stable for several years. This process relies on the combination of severe heat treatment and hermetic packaging, without the need for chemical preservatives. It preserves a large part of the fish proteins, omega-3 fatty acids, and sensory qualities, although some nutritional and organoleptic changes may occur depending on the processing conditions.

VII. 1. Importance of fish preserves

Canning offers several major advantages. It ensures the microbiological stability of the product by destroying pathogenic and spoilage microorganisms, including spore-forming organisms when the thermal schedule is properly applied. It greatly extends shelf life while allowing storage without refrigeration, which facilitates distribution and marketing. It also offers a wide variety of recipes thanks to the choice of covering medium: oil, tomato sauce, salted water, marinade, or other preparations.

VII. 2. Raw material

The quality of the preserve first depends on the freshness of the fish when it arrives at the plant. The raw material may be fresh or frozen, depending on the species and the organization of the supply chain. For sardines, the catch is often seasonal and processing must be rapid to limit post-capture spoilage. For tuna, supply is often in the form of frozen whole fish, especially for tropical species such as skipjack and yellowfin tuna.

Freshness control relies on sensory and analytical tests, notably TVB-N, the K value, histamine, and observation of the fish's overall condition. These checks are essential because poor raw material leads to a lower-quality final product, even after sterilization.

VII. 3. Manufacturing steps

VII. 3.1. Reception and washing

Upon receipt, the fish is inspected and then washed with cold water to remove mucus, dirt, scales, and surface contaminants. This step is essential to reduce the initial microbial load and prepare the fish for the following operations.

VII. 3.2. Cleaning and trimming

The fish then undergoes heading, gutting, and, depending on the product, cutting or tail removal. For sardines, these operations are usually quick and can be manual or mechanical. For tuna, partial thawing is often carried out, followed by heading, gutting, and then whole cooking before skin and bone removal.

VII. 3.3. Pre-cooking

Pre-cooking is a major step in the process. It may be carried out by steaming, boiling, or frying,

depending on the type of preserve desired. It reduces muscle moisture, removes part of the fat, inactivates enzymes, and develops the typical aromas of the final product. In the case of tuna, steaming is common; for some traditional sardine products, oil frying may be applied before canning.

VII. 3.4 Filling and seasoning

The fish is then placed in metal cans or glass jars, whole, filleted, in pieces, or flaked, depending on the final product. The covering medium plays an important role in flavor, lipid contribution, and preservation: olive oil, sunflower oil, salted water, tomato, or marinade. Salt dosage must be carefully controlled to meet regulatory and nutritional requirements.

VII. 3.5. Seaming

Seaming is the critical step that ensures hermetic closure of the can. A double seam between the lid and the can body creates a tight barrier that prevents any recontamination after filling. Dimensional checks of the seam are necessary because any loss of tightness compromises the commercial sterility of the product.

VII. 3.6. Sterilization

The hermetically closed cans are then treated in an autoclave at a temperature above 100 °C, generally between 115 and 121 °C under pressure. The objective is to achieve commercial sterility, especially by destroying *Clostridium botulinum* and other pathogenic spore-forming microorganisms. Time/temperature schedules are specific to each fish species, can size, covering medium, and filling method. The current trend is to use shorter high-temperature treatments in order to better preserve omega-3 fatty acids, color, and texture.

VII. 3.7. Cooling

After sterilization, the cans are rapidly cooled to stop cooking and prevent overcooking of the product. Cooling is often done with water, by spray or injection, until a temperature suitable for handling is reached. The cans are then dried and held in quarantine before labeling and shipping.

VII. 4. Quality control

Fish preserve quality control includes several aspects.

a) Microbiological controls

The absence of commercial sterility defects is checked by incubation at 37 °C and 55 °C to detect any remaining mesophilic and thermophilic microorganisms. Can swelling and vacuum retention are also checked.

b) Physicochemical controls

The main parameters monitored are pH, TVB-N, histamine, salt content, drained net weight, and fat content. Histamine is particularly important for scombroid fish because its level is regulated. TVB-N remains a classic indicator of freshness and spoilage.

c) Organoleptic controls

Sensory evaluation focuses on color, odor, texture, taste, and the appearance of the covering liquid. A good preserve should retain an appealing appearance, proper texture, and a flavor profile consistent with the recipe.

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