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MODERN FOOD TECHNOLOGY: PRINCIPLES AND APPLICATIONS

MODERN FOOD TECHNOLOGY: PRINCIPLES AND APPLICATIONS



Editors :-

Dr. Ravi Kumar
Bharat Bansal
Dr. Tripti Verma
Dr. U. S. Rammiya
Dr. Sonia



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Preface

Food technology plays a vital role in ensuring food safety, quality, nutrition, and sustainability in an era marked by rapid population growth, changing consumer preferences, and increasing pressure on global food systems. Advances in processing technologies, preservation methods, packaging innovations, and quality assurance practices have transformed the way food is produced, stored, and delivered from farm to fork. A sound understanding of both the scientific principles and practical applications of food technology is therefore essential for addressing contemporary challenges in the food sector.

The book *Modern Food Technology: Principles and Applications* has been developed to provide a comprehensive and up-to-date overview of fundamental concepts and emerging trends in food technology. This volume brings together contributions from researchers, academicians, and industry experts to present a balanced integration of theory and practice. Emphasis has been placed on explaining core principles while highlighting their real-world applications in food processing and product development.

The chapters in this book cover a broad range of topics, including food processing and preservation techniques, thermal and non-thermal technologies, food safety and quality management, packaging systems, value addition, functional foods, nutraceuticals, food biotechnology, and regulatory frameworks. Special attention is given to sustainable processing methods, innovation in food product development, and technologies aimed at reducing post-harvest losses while maintaining nutritional quality.

This book is intended to serve as a valuable reference for undergraduate and postgraduate students, doctoral scholars, academicians, food technologists, quality control professionals, and researchers in food science and technology. It will also be useful for professionals in the food processing industry seeking scientifically grounded insights into modern technological applications.

The editors gratefully acknowledge the contributions of all authors for their scholarly inputs and dedication. Appreciation is also extended to the reviewers and the publishing team for their support in maintaining the academic quality of this volume. It is hoped that this book will contribute to strengthening knowledge, fostering innovation, and supporting sustainable growth in the food technology sector.

Editors

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CHAPTER-11

UNIT OPERATIONS IN FOOD PROCESSING

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Abstract

Unit operations are the foundational steps in food processing that transform raw materials into safe, nutritious, and shelf-stable products. This chapter provides a comprehensive overview of food processing unit operations, including mechanical, thermal, mass transfer, fluid flow, product-forming, and combined thermo-mechanical operations. Each operation such as size reduction, mixing, separation, pasteurization, drying, and extrusion is examined in terms of underlying principles, equipment, and effects on product quality and safety. Emphasis is placed on energy efficiency, process optimization, and integration of operations to achieve desired sensory, nutritional, and functional characteristics. Recent trends highlight non-thermal processing, process intensification, and digitalization, which enhance sustainability, product quality, and industrial productivity. The chapter underscores the importance of a systems-based approach, enabling modular process design, predictive modelling, and scale-up from laboratory to commercial production.

Keywords: Heat Treatments, Unit Operations, Packaging, Food Processing and Preservation.

Introduction

Food processing transforms raw agricultural materials into safe, stable, and value-added products. Unit operations are the fundamental physical steps involved in this transformation. Each unit operation performs a specific physical task such as heating, cooling, drying,

grinding, or separating which collectively determine the quality, safety, and shelf life of foods. Food manufacturing is built from a finite set of unit operations (cleaning, size reduction, heat transfer, mass transfer, separation, mixing, packaging, etc.) that are combined, sequenced and controlled to transform raw materials into finished products (Fellows, 2022).

These categories overlap and are often combined in sequences appropriate to the raw material and product goals; for example, vegetable canning. The grouping and selection of unit operations is guided by product quality targets, shelf-life requirements and economic constraints.

Unit operations form the *building blocks* of food manufacturing systems. Modern food factories rely on carefully designed sequences of these operations to ensure efficiency, product safety, and compliance with regulatory standards (Toledo et al., 2018). Each food product from milk to bread to fruit juice undergoes multiple unit operations to achieve desired sensory, nutritional, and functional characteristics.

1. Unit Operations

The concept of unit operations emerged to simplify complex processes in chemical and food engineering. Instead of studying each product-specific process individually, engineers classify steps based on the nature of physical change occurring. This rational approach improves process design, optimization, and scale-up (Geankoplis, 2018).

Definition

A unit operation is *a fundamental step involving physical transformations* such as heat transfer, mass transfer, fluid flow, mechanical processing, or product formation (Singh & Heldman, 2014). In other words, a unit operation is commonly defined as a single, physically distinct processing step in which a specific change

is imparted to the food material under controlled conditions. Each unit operation is described by a set of governing conservation laws, constitutive relations, and boundary conditions, these permit predictive models that scale from laboratory to industrial equipment. This systems-based view of processing facilitates modular process design and the substitution or optimization of individual steps without losing sight of the whole process.

2. Classification of Unit Operations

Unit operations in food processing are usually grouped by the primary physical phenomenon they exploit. A practical classification used in textbooks and course modules (and adopted throughout this chapter) divides unit operations into six broad classes:

2.1. Mechanical Unit Operations - Size reduction, mixing, sieving/filtration, centrifugation and conveying.

2.2. Heat Transfer Unit Operations - Pasteurization, blanching, evaporation/concentration, cooling/freezing and sterilization.

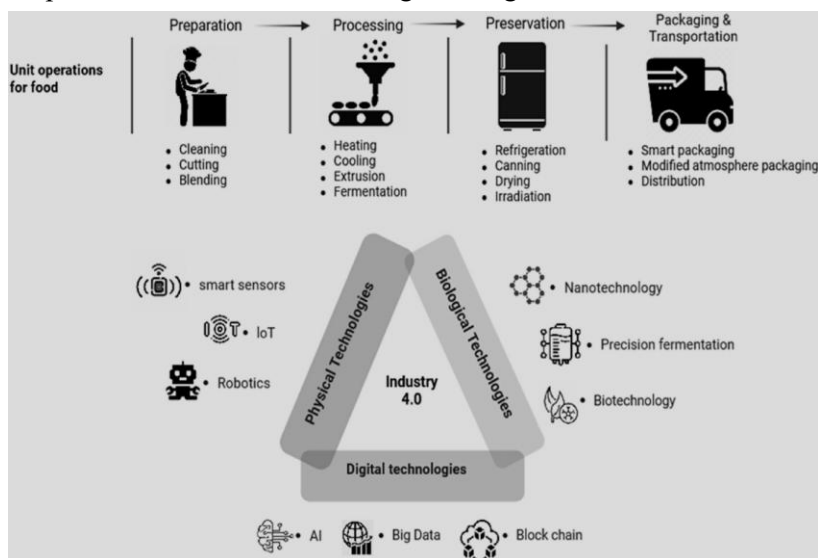


Figure 1.: Unit operations of food (Hassoun et al., 2024).

2.1. Mechanical Unit Operations

Mechanical unit operations involve physical processes that modify the form of food materials without changing their chemical composition. They are essential for preparing raw materials, controlling texture and particle size, and enhancing mass- and heat-transfer rates. Key examples include size reduction, mixing, homogenization, screening, filtration and centrifugation. Their effectiveness depends on material properties and the applied mechanical stresses. Proper selection and control optimize yield, sensory quality and energy use, while supporting efficient downstream processing in food manufacturing (Fellows, 2017).

2.1.1. Size reduction (comminution)

Size reduction (comminution) is the deliberate reduction of particle dimensions by cutting, crushing, grinding or milling to increase surface area, improve material homogeneity, aid extraction, and prepare solids for subsequent operations such as drying, sieving or heat treatment. The selection of cutting or milling equipment depends on material properties (brittleness, ductility, fibrousness), moisture content and the required product particle-size distribution. Common industrial devices include knife and cutter mills (shearing and cutting for fibrous materials), hammer and impact mills (high-energy impact for brittle materials), roller and roller-crushers (compression/attrition for granular materials), ball and stirred media mills (fine grinding), and colloid mills (high shear for pastes and emulsions. Theory for energy consumption and product size links fracture mechanics with empirical energy–size relationships: Rittinger’s law (energy proportional to new surface area; important for very fine grinding), Kick’s law (energy proportional to size reduction ratio; applicable to coarse crushing), and Bond’s law (intermediate, widely used for industrial estimates) (Rittinger, 1867; Kick, 1885; Bond, 1952; BIT Mesra module, 2021). Practical design balances energy efficiency,

heat generation (which can affect heat-sensitive foods), and product quality (particle shape, distribution, and presence of fines). Preconditioning (drying, freezing) is often used to change material fracture behaviour and reduce energy needs.

➤ **Types of Size Reduction in Food Processing**

Size reduction (also called **comminution**) involves breaking large food particles into smaller fragments using mechanical forces such as cutting, compression, impact, attrition, and shearing. The major types are:

i) Cutting

Cutting involves reducing food into smaller pieces using sharp blades through slicing, dicing, shredding, or chopping. It is widely applied to fruits, vegetables, cheese, and meats, enabling uniform shapes and improved cooking performance (Fellows, 2022). Examples: slicing apples, dicing meat, shredding cabbage. The main advantages of size reduction are uniform particle size, minimal heat generation and disadvantages is limited for very hard materials; blade wear occurs.

ii) Crushing

Crushing applies compressive forces to break large solid pieces into coarse particles. It is especially important for oilseeds, sugarcane, and cereal grains prior to further processing. This is a simple and energy-efficient operation whereas main drawback of this unit operation is production of non-uniform particle sizes; dust may form. Examples: crushing peanuts, crushing sugarcane, crushing malted barley (Toledo et al., 2021).

iii) Grinding

Grinding produces fine or semi-fine powders using impact and attrition mechanisms. Common equipment includes hammer mills, burr mills, and ball mills (Singh & Heldman, 2023). It creates fine, consistent particles. but generates heat that may degrade food quality.

Examples: grinding wheat for flour, grinding spices, grinding coffee beans.

iv) Milling

Milling refers to controlled fine size reduction achieved through abrasion, shearing, or impact under dry or wet conditions. It is essential in flour, rice, and corn processing. This operation has high precision, efficient separation of components but high energy demand; requires complex equipment. Examples: wheat flour milling, corn wet milling (Fellows, 2022).

v) Homogenization

Homogenization is an ultra-fine size reduction method in which liquids are forced through narrow valves at high pressure to disperse fat or solid particles uniformly. It improves stability and texture but expensive equipment; heating may occur. Examples: milk homogenization, homogenized sauces (Chandan & Kilara, 2019).

vi) Pulverization

Pulverization reduces materials into extremely fine powders, often below 100 μm , using high-speed impact or air-swept mills. It is ideal for instant and powdered foods. The main advantages are improved product uniformity and rapid dissolution and the drawbacks of this operation are generating heat and risk of nutrient loss. Examples: powdered sugar, instant coffee, fine spice powders (Toledo et al., 2021).

vii) Cutting–Shearing

Cutting–shearing combines slicing and tearing forces to reduce fibrous foods with tough structures, such as leafy vegetables and meat tissues. It is effective for fibrous textures and may not produce uniform particle size. Examples: shredding lettuce, cutting meat fibers (Fellows, 2022).

Table 1: Types of size reduction methods and its advantages & disadvantages.

Type of Size Reduction	Mechanism	Advantages	Disadvantages	Examples
Cutting	Shear	Quick, precise, maintains shape and nutritional quality	Not suitable for very hard foods; labour-intensive for large volumes	Vegetables, fruits, meat cubes, herbs
Crushing	Compression	Simple, energy-efficient, prepares material for downstream processing	Produces irregular particle sizes; may require further reduction	Sugarcane crushing, oil seeds, cereals
Grinding	Impact/attrition	Produces uniform powders, increases surface area for reactions	Generates heat, can affect heat-sensitive foods	Spices, coffee beans, grains into flour
Milling	Impact/shear	High precision, adaptable for dry or wet materials	Energy-intensive; risk of dust generation	Flour milling, wet corn milling
Homogenization	High pressure	Improves stability and texture, prevents phase separation	Requires specialized equipment; high energy cost	Milk, sauces, dressings

Pulverization	Impact	High surface area, fast solubility	Heat generation may affect flavors; not suitable for very hard materials	Powdered sugar, instant tea or coffee
Cutting–Shearing	Abrasion	Efficient for fibrous foods; maintains structure	Limited to fibrous materials; may not achieve very fine reduction	Meat fibers, leafy vegetables
Attrition	Cooling + impact	Produces smooth texture; suitable for viscous materials	Slow process; high wear of equipment	Colloid milling, nut butters, pastes
Extrusion-based size reduction	Abrasion	Uniform shape, simultaneous cooking possible	Limited to extrudable materials; high energy use	Noodles, pasta, snack pellets
Cryogenic grinding	Cooling + impact	Preserves aroma and nutrients; reduces heat damage	Expensive equipment and liquid nitrogen required	Spices, herbs, heat-sensitive foods

viii) Attrition

Attrition occurs when particles rub against one another or a surface to gradually wear down into smaller sizes. It is commonly used in colloid mills for paste formation. This unit operation helps to enable smooth, spreadable textures but its slow process and possible heat buildup is the main drawbacks. Examples: nut butter production, colloidal suspensions (Singh & Heldman, 2023).

ix) Extrusion-Based Size Reduction

Extrusion forces food dough through small dies under pressure, causing size and shape reduction as the material exits. It forms uniform shapes; continuous processing. In this process, thermal degradation occurs if temperature is not controlled. Examples: pasta, noodles, snack pellets (Riaz & Rokey, 2011).

x) Cryogenic Size Reduction

Cryogenic grinding uses liquid nitrogen to freeze materials, making them brittle and easier to pulverize without heat damage. This method helps to preserve flavour, color, and volatile compounds. This technique has high operating cost and requires specialized equipment. Examples: spices, herbs, heat-sensitive foods (Murthy & Bhattacharya, 2020).

2.1.2. Mixing and homogenization

Mixing blends components (liquids, powders, gas-liquid, or multiphase systems) to achieve uniform composition, accelerate heat and mass transfer, disperse phases, or create stable emulsions and suspensions. In food processing, mixing ranges from low-shear ribbon or paddle mixers (bulk powder blending, dough systems) to high-shear rotor-stator and homogenizers (emulsion formation, particle breakage, colloidal dispersions). Mixing performance is assessed by dimensionless groups and measurable quantities such as Reynolds number (flow regime), power number (power draw), Froude number

(when free surfaces matter), mixing time (time to reach specified homogeneity) and scale-up criteria (geometric similarity or constant tip speed/power per unit volume). Types of mixers used in food processing include static in-line mixers (no moving parts; continuous blending), top-entry and side-entry agitators (tank mixing), high-shear mixers and colloid mills (emulsification and cell disruption), and ultrasonic or membrane homogenizers (specialty nanoemulsions and particle size control). Homogenization (a subclass of mixing) uses intense shear and pressure differentials to reduce dispersed-phase droplet size and stabilize emulsions (e.g., milk homogenization), enhancing mouthfeel, stability and shelf life. Design must minimise undesirable effects such as over-shearing (which can damage texture) or heat generation that degrades sensitive ingredients (Fellow, 2017).

➤ **Types of Mixing and homogenisation**

i) Mechanical Mixing

Mechanical mixing involves physically blending ingredients using blades, paddles, or agitators to achieve uniform composition. It is widely used in batter, dough, and liquid formulations. It is a simple, cost-effective and suitable for a wide range of viscosities. It may introduce air unintentionally and can be energy-intensive for highly viscous. Example: Mixing cake batter using a planetary mixer.

ii) High-Shear Mixing

High-shear mixing uses rapid rotation and intense mechanical force to disperse, emulsify, or break down particles in liquids. It is suitable for creating fine emulsions or suspensions. This method produces uniform particle size and stable emulsions but consumes high energy and possible heat generation which can affect sensitive ingredients. Example: Mayonnaise production using high-shear mixers.

iii) Static Mixing

Static mixers use stationary elements in a pipe to mix fluids as they flow, without moving parts. Mixing occurs due to turbulence and flow splitting. The static mixer has low maintenance, continuous operation, and energy-efficient operation. It is limited to low to medium viscosity fluids and less effective for solid inclusions. Example: Blending liquid flavorings into beverages.

iv) Ultrasonic Homogenization

Ultrasonic homogenization employs high-frequency sound waves to break particles and emulsify immiscible liquids at a micro or nano scale. This method helps to produce very fine emulsions, enhances stability, and preserves heat-sensitive nutrients but the main drawback of this method is limited throughput for large-scale operations and expensive equipment. Example: Production of nano-emulsions in fruit juices.

v) Rotor-Stator Homogenization

Rotor-stator homogenizers use a rotating rotor within a stationary stator to generate shear forces that reduce particle size and produce uniform mixtures. It is efficient for high-viscosity fluids, scalable, and produces consistent particle size but used high energy and possible heat buildup during processing. Example: Homogenization of milk and dairy products.

2.1.3. Separation

Separation operations remove or classify phases and are central to clarifying liquids, concentrating solids, and sizing particulate products. Screening (sieving) is a mechanical size-classification method that separates particles by aperture; common industrial screens include vibrating screens, rotary sieves and trommels for coarse classification and scalping. Separation processes are essential in food processing to isolate, purify, or remove components based on physical or chemical properties. These operations improve product

quality, shelf life, and safety. Separation can be broadly classified into mechanical, physical, and chemical methods. Each method has specific applications depending on particle size, density, solubility, and other properties. Key selection criteria include particle size and density difference, feed solids concentration, throughput, required dryness of cake or clarity of centrate, and shear sensitivity of the product. Modern practice increasingly integrates membrane and centrifugal technologies for energy-efficient, high-throughput separations while considering cleaning, fouling control and product integrity (Lamichhane et al., 2018).

i) Solid–Solid Separation

Solid–solid separation involves separating one type of solid particulate from another based on physical properties such as size, shape, density or magnetic susceptibility. It does not involve liquid. Typical methods include sieving (screening), gravity and density separation (via vibrating decks/air-flow), or magnetic separation when removing metal contaminants. Examples: In flour milling, sieves separate fine flour particles from larger bran pieces. In grain processing, gravity separators remove stones, dirt, or other heavier foreign materials from cereals/seeds by density difference.

ii) Solid–Liquid Separation

This separation removes solid particles suspended in a liquid (or slurry) solids are retained, and liquid (filtrate/clarified liquid) passes through. Methods include filtration (through porous media) and sedimentation (letting solids settle under gravity). Examples: Clarification of fruit juices by filtration to remove pulp or suspended matter; clarification of beverages like wine or beer by sedimentation or filtration; removal of insoluble solids in syrups or oils.

iii) Density-Based Separation by Centrifugation

Uses centrifugal force to separate components of different densities. It is especially useful when density differences are small or when rapid separation is required. Centrifugation can separate solids from liquids, or separate two immiscible liquids based on density. Examples: Separating cream (fat) from milk in dairy processing; clarifying olive oil by separating oil from water and solid residues after pressing; separation of pulp or fine solids from juices or syrups.

v) Membrane Separation

Membrane separation uses semi-permeable membranes to separate components based on molecular size or weight. Smaller molecules (e.g., water, salts) pass through the membrane pores, while larger ones (proteins, macromolecules) are retained. This allows separation at the molecular or colloidal level rather than just particles. Examples: In dairy industry ultrafiltration to concentrate milk proteins or produce whey concentrates; microfiltration for removing bacteria or fine suspended matter in milk or juices; reverse osmosis or membrane concentration to concentrate fruit juices without heat, preserving flavor and nutrients.

vi) Liquid–Liquid Separation

Separation of two immiscible (or poorly miscible) liquid phases based on density or solubility differences. It may involve allowing the phases to settle (gravity), using centrifugation, or using a solvent to extract one component selectively. In food processing, this helps recover oils, fats, solvents, or concentrate certain soluble. Examples: Separation of vegetable oil from water after oilseed pressing; recovering oil from aqueous mixtures; using solvent extraction to isolate flavors, oils or bioactive compounds from plant materials; using membrane-assisted extraction (e.g. perstraction) for sensitive components.

Table 2.: Various types of separation methods used in food processing.

Separation Type / Method	Principle / Basis	Common Applications	Advantages	Disadvantages
Filtration	Size-based sieving through porous medium	Clarifying juices, removing solids from suspensions	Gentle, low-energy, preserves heat-sensitive compounds	Filter clogging, limited to solid-liquid separation
Centrifugation	Density-based separation using centrifugal force	Cream separation, oil-water separation, slurry dewatering	Fast, efficient, effective for fine particles or immiscible liquids	High energy, equipment cost, possible damage to delicate food components
Membrane separation (MF, UF, NF, RO)	Size/charge-based selective	Concentration & clarification of milk, juices; demineralization;	Non-thermal, selective, preserves quality, scalable	Membrane fouling/clogging, cost, limited throughput

	permeability of membranes	whey protein concentration		
Sedimentation (Gravity/Solid–Solid/Solid–Gas separation)	Density/weight difference under gravity or fluid flow	Cleaning grains, removing impurities, air/dust removal, bulk separation	Simple, cheap, low-energy, good for preliminary cleaning or bulk processing	Slow, not precise, not suitable for fine separations
Solvent Extraction (Crystallization, Distillation, Evaporation)	Solubility / volatility / phase behavior differences	Oil extraction, sugar crystallization, concentrating juices, extracting flavors, alcohol separation	Effective for dissolved solutes or concentration, good selectivity	Heat or solvent exposure may damage food quality; higher energy or safety concerns

2.1.4. Heat Transfer Unit Operations

Heat is transferred by three main methods i.e. conduction, convection, radiation and its combination of these three methods. Conduction is the transfer of heat through a solid or between solids in direct contact, without bulk movement of matter heat flows by molecular vibration and collision from high-temperature regions to lower temperature ones. Convection is transferring the heat through the movement of a fluid (liquid or gas). In this mode, warmed fluid moves away from the heat source, carrying energy with it, while cooler fluid replaces it creating circulation that transports heat. Radiation transfers heat in the form of electromagnetic waves (such as infrared, microwaves) heat can travel through vacuum or air, without requiring a material medium. In food processing, radiant heat warms the surface of food directly. In practice, food-processing often uses a combination of heat transfer modes (conduction + convection + radiation) or specialized systems (e.g. heat exchangers) to optimize heating/cooling. Heat transfer is central to food preservation and transformation: it inactivates spoilage and pathogenic microorganisms, triggers desirable chemical and physical changes (e.g., gelatinization), and enables concentration and drying. The main heat transfer operations include:

i) Pasteurization and sterilization

Pasteurization is the process of heating food to a specific temperature for a defined time to kill pathogenic microorganisms without significantly affecting taste or nutritional value (Rahman, 2017). It is widely used in milk, fruit juices, and liquid eggs.

Pasteurization (mild heat) reduces pathogenic load while preserving sensory and nutritional quality; sterilization (higher temperature/pressure, e.g., commercial retort) achieves commercial sterility for shelf-stable products. Heat penetration, lethality calculations (F-values, D- and z-values) and appropriate heat transfer

equipment (plate, tubular, or scraped-surface exchangers) are design cornerstones.

Table 3: Types of pasteurisations.

Method	Typical temperature & time (for milk)
Low-Temperature Long-Time (LTLT) (also called Batch or Vat pasteurization)	63 °C for 30 minutes (some sources: 63-65 °C)
High-Temperature Short-Time (HTST) (also called Flash or Continuous-flow pasteurization)	~72 °C for 15 seconds (or around 71.7-75 °C for 15–20 s depending on product)
Ultra-High Temperature (UHT) (or Ultra-Heat Treatment/Ultra-pasteurization)	~135 °C (or up to ~140-150 °C depending on protocol) for 1-5 seconds

Table 4: Different methods of heat transfer used in food industry.

Heat transfer methods	Advantages	Disadvantages	Examples in Food Processing
Pasteurization	- Improves food safety- Retains nutritional quality- Extends shelf life	- May not kill all microorganisms- Some loss of flavor or vitamins	Milk pasteurization, fruit juice pasteurization
Blanching	- Prevents enzymatic browning- Reduces microbial load- Preserves color and texture	- Nutrient loss (water-soluble vitamins)- Requires energy	Blanching of spinach, peas, and potatoes
Evaporation (Concentration)	- Reduces volume and storage cost- Increases shelf life	- Risk of overheating- Loss of volatile compounds	Fruit juice concentration, milk powder production

Sterilization (UHT Processing)	- Long shelf life without refrigeration- Safe for consumption	- Can affect taste and texture- High energy consumption	Canned vegetables, UHT milk
Cooking /Baking/Roasting	- Improves palatability- Enhances digestibility- Destroys harmful microorganisms	- Nutrient degradation- Uneven cooking if not controlled	Baking bread, roasting coffee beans
Freezing (Cooling or heat removal)	- Preserves food quality- Extends shelf life- Minimizes chemical changes	- High energy requirement- Ice crystal formation can damage texture	Frozen vegetables, ice cream production

ii) Blanching, cooking and frying

Blanching involves brief heating of vegetables or fruits in hot water or steam to inactivate enzymes that cause spoilage and discoloration. It also reduces microbial load and improves texture and color retention. Blanching inactivates enzymes pre-processing (e.g., prior to freezing or drying). Frying is a coupled heat/mass transfer phenomenon where oil and moisture exchange simultaneously, producing unique texture and flavor but also driving complex chemical reactions; control of temperature, product residence and oil quality determines safety and sensory attributes (Heldman & Hartel, 2014).

iii) Evaporation and concentration

Evaporation removes water from food by heating, concentrating solids and reducing water activity. It is widely used in fruit juice concentration, milk powder production, and sugar processing. Evaporation concentrates liquid foods (e.g., fruit juices, milk) by removing water; multiple-effect evaporators and mechanical vapor recompression are used to improve energy efficiency while minimizing thermal damage. Heat transfer theory (conduction, convection, radiation) and heat exchanger design underlie the

practical implementation of all these operations (Potter & Hotchkiss, 2012).

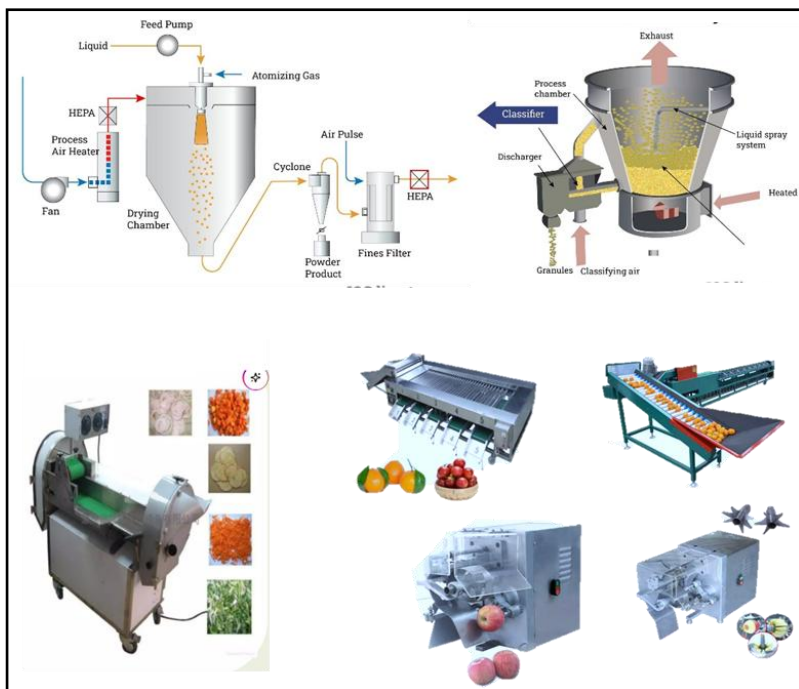


Figure 2. Instruments and machinery used for unit operations in the food processing industry, including dryers, cutting machines, sorters, and graders.

2.1.5. Mass Transfer Unit Operations

Mass transfer operations move components (water, solutes, volatiles) between phases or within porous structures, and they include drying, distillation, extraction and osmotic dehydration.

i) Drying and dehydration

Drying removes water to extend shelf life and reduce transport costs. Air-drying, vacuum drying, spray drying and freeze drying are chosen according to product sensitivity and desired quality. Drying kinetics are governed by internal diffusion and external convective mass

transfer; modeling these mechanisms is essential for process control and energy optimization.

ii) Sun (or Solar) Drying

The oldest and most traditional method. Food items fruits, vegetables, grains, etc. are spread out under direct sunlight (or placed in a simple solar dryer) to dry, using solar heat and ambient air circulation. This type of drying no fuel or electricity needed, very low cost, minimal infrastructure, environmentally friendly. The main limitations are highly dependent on weather (sunshine, low humidity), takes a long time (days), risk of contamination (dust, insects), uneven or inconsistent drying.

iii) Shade Drying

Sometimes used for herbs, spices, or delicate produce: food is placed on racks/trays in a well-ventilated, shaded area so ambient air circulates and removes moisture slowly. Slower and more controlled than sun drying, with reduced risk of contamination compared to direct sun. But still depends on ambient conditions (air flow, humidity), and may take a long time. These are often used in small-scale, rural, or low-resource settings for example drying fruits, vegetables, herbs, spices, grains, etc.

iv) Hot-Air & Mechanical Drying Methods

When more control, speed and consistency are needed especially for commercial production “mechanical” drying methods are preferred. These use heated air, controlled airflow, humidity and other parameters.

a) Hot Air Drying / Convection Drying

Heated air circulates around or through food products (on trays, belts, in chambers), evaporating the moisture. This is one of the most widely used industrial methods, for fruits, vegetables, dehydrated foods. Types: batch systems (like tray or cabinet dryers), or continuous systems (tunnel dryers, belt dryers, conveyor dryers). This is the faster

than natural methods, more uniform and reliable results, scalable for large volumes. It is energy consuming (electricity/fuel) method and potential for heat damage (nutrients, colour, flavour) if not optimally controlled. Variants of hot-air or controlled-air drying. For example: tray/cabinet dryers where food is placed on shelves/trays and heated air circulated around; belt or tunnel dryers continuous drying along conveyors; kiln or stack-type dryers for larger pieces or bulk drying. These methods are used depending on scale, product type, and required throughput.

v) Specialized & Advanced Dehydration Methods

For foods or materials that are sensitive to heat, or when high-quality retention (nutrients, flavor, structure) is needed advanced dehydration techniques are used.

a) Vacuum Drying

In vacuum drying, atmospheric pressure is lowered inside a drying chamber. This makes water evaporate at much lower temperatures than under normal pressure. Useful for heat-sensitive materials (herbs, medicinal plants, delicate fruits), helps preserve colour, flavour, nutrients, and reduces oxidation.

b) Freeze Drying (Lyophilization or Cryodesiccation)

Probably the most sophisticated dehydration method. The process: product is frozen first, then under vacuum the frozen water sublimates (ice to vapor) without passing through liquid phase. This preserves structure, shape, colour, flavor, and nutritional content extremely well. This method has excellent retention of original characteristics (texture, taste, nutrients), very good rehydration, suitable for high-value foods, and heat-sensitive items. This is very expensive, requires specialized freeze-drying equipment, high energy consumption, longer process times compared to simpler methods.

c) Spray Drying

Used especially for liquid foods, purees, juices, milk basically for things that can be atomized into small droplets. In spray drying, the liquid is sprayed into a hot-air chamber; the droplets dry almost instantly, turning into powders. Widely used for milk powder, instant coffee, fruit powders, etc. spray drying is very fast, able to process large volumes, good for low-viscosity liquids, produces powders with good rehydration properties. It is not suitable for high-viscosity substances (e.g., thick purees), may cause thermal damage to heat-sensitive nutrients if not managed carefully.

d) Drum (Roller Drying or Heated-surface Drying)

Here, liquid food or puree is spread as a thin layer over a heated rotating drum (or heated surface). As the drum rotates, heat transfers quickly via direct contact, moisture evaporates, and the dried product is scraped off as flakes or powder. Used for viscous purees, sauces, baby-foods, tomato products, etc. It is efficient heat transfer method and good for viscous materials that cannot be spray-dried, high production capacity. High surface temperatures (risk of nutrient / flavour loss), limited to materials that can be formed into thin layers, possible thermal damage.

vi) Osmotic Dehydration

A relatively gentle and non-thermal pretreatment method: food (typically fruits or vegetables) is immersed in a hypertonic (high concentration) solution of sugar or salt. Due to osmosis, water moves out from the food into the solution, partially dewatering the product before subsequent drying. This method reduces drying time when combined with conventional drying, helps preserve colour, texture, flavour; less thermal stress; can improve final product quality (better organoleptic properties). It usually removes only part of the water (partial dehydration), often needs follow-up drying (e.g. hot-air), may alter taste (e.g. sugar or salt uptake), and is more complex than simple

drying. Osmotic dehydration (OD) is a low-temperature mass transfer method where water migrates from cellular food into a hypertonic solution; OD retains texture and color better than direct hot drying and is often used as a pretreatment prior to drying or freezing. Recent advances vacuum-assisted, ultrasound-assisted and pulsed-field-assisted OD—seek faster kinetics and improved quality.

vii) Combination & Other Modern Techniques

There are also hybrid or advanced methods combining different drying principles for example combining convective (hot-air) drying with other techniques to optimize speed, energy use, and product quality. Some lists also mention methods like microwave drying, fluidized-bed drying, vacuum-belt drying, foam-mat drying, superheated steam drying, etc., depending on the material and product requirements.

2.1.6. Extraction and distillation

Solvent extraction and steam distillation separate valuable soluble compounds (oils, flavors) from the food matrix. Process design balances selectivity, solvent toxicity and energy demand; continuous counter-current extraction cascades are common in industrial practice.

2.1.7. Combined (Thermo-Mechanical Operations)

Operations such as extrusion, frying and freeze-drying couple mechanical work with thermal or mass transfer effects.

i) Extrusion

Extrusion is a high-shear thermo-mechanical process used for snacks, texturized vegetable proteins and pasta. The combination of pressure, shear and temperature causes starch gelatinization and protein texturization; process variables (screw speed, barrel temperature, moisture) control product structure and expansion. Extrusion is prized for continuous, high-throughput manufacture and for its flexibility in producing diverse product forms.

ii) Freeze-drying (lyophilization)

Cooling or freezing removes heat from food to slow microbial growth and chemical reactions, thereby extending shelf life. This is critical for perishable foods like meat, fish, and dairy products (Fellows, 2020). Freeze-drying removes ice by sublimation under reduced pressure and preserves heat-sensitive components (bioactives, flavors) at the cost of high energy and capital. It is used for specialty foods, instant coffee and high-value ingredients.

iii) Fluid Flow and Product-Forming Operations

a) *Fluid flow (pumping, sedimentation, piping)*

Fluid transport and handling are essential for continuous processing. Pumps, pipes, valves and separators must be chosen to match fluid rheology, minimize shear damage (important for emulsions and particulate foods), and ensure hygienic cleanability. Sedimentation and clarification rely on Stokes-law principles for particle settling and are often combined with flocculation or centrifugation for improved efficiency.

b) *Product forming and packaging*

Product-forming (molding, cutting, sheet forming) imparts the final shape and microstructure; packaging finalizes product protection and shelf life. Packaging decisions integrate barrier properties, aseptic or modified atmosphere requirements, and sustainability metrics.

2.1.7. Process Integration, Modeling and Optimization

Unit operations are not isolated they must be integrated into sequences that preserve quality, minimize waste and meet economic goals. Transport phenomena analogies (momentum, heat, mass transfer) allow unified modeling approaches; process simulation tools and experimental design (RSM, DOE) are widely used to optimize coupled operations (e.g., osmotic dehydration prior to air-drying). Energy recovery (heat integration, vapor recompression) and life-cycle thinking are increasingly important in modern plant design.

2. Recent Trends and Innovations

Key contemporary directions include: advanced pretreatments (ultrasound, pulsed electric fields) to enhance mass transfer and reduce thermal load; process intensification (integrated multitask equipment such as continuous pasteurizer–filler lines); digitalization and process control (sensors, PAT, model-predictive control); and sustainability-driven redesign (reduced water/energy, valorization of by-products). Osmotic dehydration and hybrid drying methods, for example, show active research and industrial interest for energy-sensitive products.

3. Emerging and non-thermal unit operations

To reduce quality loss and energy use, non-thermal methods are increasingly adopted: high-pressure processing (HPP), pulsed electric fields (PEF), ultraviolet (UV) and cold plasma treatments can inactivate microorganisms while retaining sensory and nutritional qualities. Membrane separations, supercritical CO₂ extraction and ohmic heating are examples of hybrid or novel unit operations that address consumer demand for minimally processed foods. These technologies require careful validation, regulatory approval and cost–benefit assessment for industrial adoption.

4. Process integration, design and scale-up considerations

Designing an industrial food process requires integrating unit operations into an optimal sequence and defining operating conditions that meet safety, quality and economic targets. Key engineering tasks include:

- Mass and energy balances across each unit operation and the whole plant.
- Heat and mass transfer calculations (e.g., convective coefficients, boundary resistances) for dryers, heat exchangers and coolers.

- Residence time distribution and mixing analysis to ensure uniformity and control reaction/thermal exposure.
- Hygienic equipment design and cleanability (CIP systems) to prevent cross-contamination and simplify sanitation.
- Scale-up rules from lab to pilot to commercial scale, retaining similar dimensionless groups (Reynolds, Peclet, Biot numbers) wherever possible for predictable behaviour. Robust process control relies on sensors (temperature, pH, conductivity, Brix), automation, and hazard analysis (HACCP) to maintain critical limits and document compliance.

5. Quality, safety and regulatory aspects

Unit operations directly impact microbial lethality, chemical safety and nutritional retention. Thermal treatments are validated against target pathogens (e.g., *Clostridium botulinum* in low-acid cans), while non-thermal alternatives must demonstrate equivalent or superior safety. Process validation, traceability, and conformity with local and international regulations (Codex Alimentarius, national food safety authorities) are required for market access.

6. Sustainability, energy efficiency and process intensification

Energy use and water consumption in unit operations draw increasing scrutiny. Strategies to reduce environmental footprint include: heat integration (economizers, multiple-effect evaporation), waste-heat recovery, process intensification (combining operations or using continuous instead of batch), and water recycling. Lifecycle thinking assessing raw material sourcing, processing, packaging and distribution helps designers prioritize interventions that reduce overall environmental impact.

Conclusions

Unit operations remain the backbone of modern food manufacturing, enabling controlled transformation, preservation, and quality

enhancement of diverse products. Classical operations cleaning, heating, drying, separation, and packaging continue to be essential, while innovative non-thermal, hybrid, and digitalized approaches offer improved energy efficiency, safety, and nutritional retention. Effective process integration, modeling, and optimization ensure product consistency, regulatory compliance, and sustainability. Future developments will increasingly rely on interdisciplinary collaboration, advanced control systems, and sustainable design strategies to meet consumer demand for safer, healthier, and environmentally responsible foods. Unit operations remain the backbone of the food industry. While classical operations (cleaning, heating, drying, freezing, separation) continue to be essential, the future is shaped by energy-efficient design, non-thermal preservation methods, membrane and separation technologies, and digitalization (sensors, process modelling, AI for process optimization). Interdisciplinary collaboration between food scientists, chemical/mechanical engineers and data specialists will accelerate innovation and help meet demands for safer, healthier and more sustainable foods.

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