International Institute of Refrigeration

Technical Guides

Recommendations for Chilled Storage of Perishable Produce

5th edition



International Institute of Refrigeration

Recommendations for chilled storage of perishable produce

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International Institute of Refrigeration

⁄ IIR and the Decade of Science



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The cold chain is essential to preserve the quality and safety of perishable products, which includes food and horticulture products. Reliable cold chain practices help to reduce food loss and waste, therefore contributing to food security and the well-being and economic development of all those involved in the supply chain, from producers to consumers.

The 5th edition of the IIR Guide on "Recommendations for Chilled Storage of Perishable Produce", offers practical, user-oriented guidance on the cooling and storage of perishable foods for professionals working in chilled food management.

This publication is issued under the United Nations Decade of Science (2024–2033), coordinated by UNESCO, as part of the IIR's Science-Policy Alignment through Research and Knowledge-exchange (SPARK) initiative. In line with the Decade's objectives, the handbook aims to equip the global community with reliable, internationally relevant technical knowledge on the storage of perishable products.

Concise and practically oriented, the guide is designed to be easy to apply in operational settings, providing actionable knowledge for professionals and stakeholders involved in chilled food management.

⁄ Disclaimer

The information provided in this publication is based on the current state of the art and is designed to assist engineers, scientists, companies and other organisations. It is a preliminary source of information that will need to be complemented prior to any detailed application or project. Whilst every care has been taken in the production of this document, the IIR, its employees, officers and consultants cannot accept any liability for the accuracy or correctness of the information provided nor for the consequences of its use or misuse.

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International Institute of Refrigeration

The **International Institute of Refrigeration** (**IIR**) brings together a unique global network of leading refrigeration scientists and experts, who serve on its Science and Technology Council, ensuring scientific excellence and strategic guidance across all areas of refrigeration. The Council is distinguished by its ability to provide independent, evidence-based information and guidance. Its intergovernmental status further guarantees neutrality, credibility, and alignment with international priorities.

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Foreword

Recommendations for chilled storage of perishable produce

5th edition



The term "*chilled foods*" includes a wide variety of food types which are often further processed. This book considers the chilling, storage and handling of chilled foods.

This is the fifth edition of "*Recommendations for chilled storage of perishable produce*" published by the International Institute of Refrigeration (IIR); the first four editions being published in 1959, 1967, 1979 and 2000. The book was therefore due an update to account for new technologies and initiatives that have occurred over the past 25 years and the exponential increase in the global trade of fresh produce and agricultural products which are dependent on a seamless cold chain from farm to point of sale.

There has been a proliferation of processed chilled food since the first book was published. This market is currently reported to be worth $0.85 trillion in 2025 and is forecast to reach $1.15 trillion by 2030 (Mordor Intelligence, 2026). This is driven by consumers wanting convenient, fresh-tasting prepared foods that align with busy lifestyles, urbanisation and the demand for quality and health-conscious chilled food options. In particular, there have been developments in ready-to-eat food, packaging and some processing/storage technologies which have been incorporated into the new book. New chapters have been added on egg storage and brewing/juice processing/storage methods.

The aim of the book has always been to provide a balanced knowledge-based review of chilled product techniques and technologies as well as good background supporting information. We appreciate that some readers may feel that there are too many details, whereas others may find that there are too few. The overall aim is to provide a sound basis and introduction to chilled foods which readers can use as a guide.

We have tried our best to cover the variety of food from different countries and regions as well as differing process methods. However, it is impossible to cover every species, variety or cultivar in great depth. We have therefore tried to provide guidance on best practices and general recommendations for readers. The figures given, such as the storage life under different storage conditions (temperature), should be regarded as illustrative rather than as

specific product information. For more detailed material, we recommend the IIR's excellent FRIDOC database for information from conferences as well as Technical briefs and other books that deal with aspects of chilling, such as refrigeration systems in greater depth.

I would like to sincerely thank all the authors and contributors who have given their time to ensure that the new book is up to date. The information in this book is based on collaboration between experts from around the world. Despite its limited size, it provides the maximum of useful content.

In keeping with tradition, the authors of this book are fully aware of the complexity of chilled foods and would be pleased to receive comments. These should be sent to the Director General of the International Institute of Refrigeration.

Judith Evans
President of IIR Section C

Reference

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Definitions

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The present guidebook uses a number of terms and definitions, the meanings of which are clarified below (IIR, 2025; ASHRAE, 2025).

1.1 COOLING

"Cooling" is a generic term, which denotes:

1 Removal of heat, usually resulting in a lower temperature and/or phase change.

2 Lowering of temperature.

Although "cooling" encompasses both chilling and freezing, when referring to unfrozen products, the term is often used interchangeably with "chilling" (see ► **Section 1.3**), unless freezing is explicitly specified. Accordingly, post-harvest and post-slaughter technologies also use the terms "precooling" and "prechilling" to denote quick chilling carried out immediately prior to further refrigerated processing and/or storage.

1.2 REFRIGERATION

The term "refrigeration" has the following comprehensive definitions:

1 Cooling of a space, substance or system to lower and/or maintain its temperature below the ambient one (removed heat is rejected at a higher temperature).

2 Artificial (human-made) cooling.

In this context, "refrigerated products" refer to perishables that are artificially cooled by a refrigeration system, thereby including both chilled and frozen items. However, in some applications and food standards, the term is occasionally used interchangeably with "chilled products" when freezing is not specifically mentioned.

1.3 CHILLING

Chilling is defined as the cooling of a substance without freezing it. This term denotes a food processing and preservation method designed to lower and maintain the product temperature to a final temperature distribution above the initial freezing point (see ► **Section 1.6**), so that the whole product remains unfrozen. The chilling process is the means by which the food temperature is reduced to the chilled (cool) storage temperature. As already mentioned, for unfrozen items the terms "chilling" and "cooling" are often used as synonyms.

1.4 CHILLED FOOD

The term refers to food commodities maintained at a temperature slightly above their initial freezing point during their production, storage, distribution, and household handling. The effect of lowering the temperature is to reduce the rate of biochemical and microbiological processes leading to quality deterioration and the growth of undesirable microorganisms. The optimum chilled storage temperature for particular products is normally between -1°C and 8°C, whilst for certain fruits and vegetables temperatures around 13°C are best-suited.

Food can be divided into respiring (live) and non-respiring (dead) groups. Respiring food products, mainly fruits and vegetables, are those that remain alive after harvest (or processing) and continue to respire, i.e. consume oxygen and produce heat, carbon dioxide and other gases, such as ethylene, that may increase quality loss. Meat, fishery and most dairy products are examples of non-respiring food products.

1.5 FREEZING

Freezing is defined as the solidification phase change of a liquid or the liquid content of a substance, usually due to cooling. Food freezing is a long-term preservation method designed to cause a phase transition of water molecules in food into ice crystals (when lowering the temperature of food below its initial freezing point), thereby immobilising water, preventing the growth of microorganisms and slowing down enzymatic and oxidative processes that lead to spoilage. The process typically requires freezing to a standardised frozen food temperature of -18°C (corresponding to approximately 0°F) or lower, though the optimal temperature depends on the food type and the desired storage life.

1.6 FREEZING POINT

This is the temperature at which a liquid substance freezes upon removal of heat (usually at atmospheric pressure unless otherwise stated). Since water in food freezes gradually, the initial freezing point is the temperature at which the first ice crystals begin to form. Unless stated otherwise, in this guide freezing point means the initial freezing point.

1.7 COLD (REFRIGERATED FOOD SUPPLY) CHAIN

The term “cold chain” refers to the series of actions and equipment applied to maintain a product within a specified low-temperature range from harvest/production to consumption. The cold chain (also known as refrigerated food supply chain) comprises the consecutive means to ensure continuous and ubiquitous low-temperature control throughout the entire chain for refrigerated processing, storage, transport, distribution, retail and household handling of perishable food commodities. The cold chain concept is used for both the frozen food and chilled food chains. In particular, the chill (or cool) chain refers to the maintenance of chilled conditions from initial cooling to preparation for consumption.

1.8 COOL CHAIN

See the definition for “cold chain” (▶ **Section 1.7**). The cold chain for chilled foods is often referred to as the cool chain.

1.9 PRACTICAL STORAGE LIFE (SHELF LIFE)

The practical storage life (PSL), also referred to as product life, shelf life, keepability, keeping time, etc., can be defined in many different ways. EU legislation stipulates shelf life as the period preceding the “use by” or the minimum durability date (EC, 2005).

The PSL of a food product at a given temperature is "the period of storage at that temperature during which the product retains its characteristic properties and remains both suitable and acceptable for consumption or the intended purpose" (IIR, 2006). In other words, the term "practical storage life" refers to the period between final processing and preparation for consumption during which the food retains its characteristic attributes and remains fit for the intended purpose, taking into consideration the temperatures to which the food is exposed.

1.10 CHILLING TIME

The chilling time (often referred to as "cooling time") is the time taken from the start of the chilling process until the desired final temperature is reached throughout the product. The chilling process should result in a final temperature, normally the equilibrium temperature, close to the intended storage temperature. Sometimes, e.g., in legislation, the chilling process is specified in terms of a centre temperature (the temperature at the thermal centre or the slowest-cooling part of the product) that is reached within a certain time.

1.11 EQUILIBRIUM TEMPERATURE

The equilibrium temperature is the temperature obtained throughout the product after it is allowed to equalise under adiabatic conditions, i.e., when no heat is added to or extracted from the environment. The average product temperature, also known as the "mass average temperature" or "mean temperature", tends to approach the equilibrium temperature at the end of the chilling process.

1.12 SUPERCOOLING

Supercooling of foods is a preservation technique where food is chilled to a temperature below its normal freezing point without actually freezing, which extends shelf life while maintaining freshness. Supercooling is an unstable state achievable through diverse methods, such as slow cooling and precise temperature control to prevent ice crystal formation, which can damage food and reduce quality. Artificial supercooling and stabilising the supercooled state over longer periods may be achieved by different physical means (pressure, electrical and/or magnetic fields, structural modifications, emulsification, demineralisation, etc.), though maintaining a consistent supercooled state remains challenging.

1.13 SUPERCHILLING (PARTIAL FREEZING)

Superchilling is a food preservation technique where products are maintained at temperatures slightly below their normal initial freezing point (i.e. at about -2/-3°C), allowing a small portion of the product's water to freeze. This temperature is maintained during processing, storage, distribution and retail display. As compared with chilling, the advantage is a longer storage life for products which can withstand some ice formation (partial freezing) without noticeable quality loss.

"Deep chilling" is similar to superchilling, but the term is primarily used to indicate storage at temperatures close to, but above the freezing point, e.g. around -1°C for meat, poultry, etc.

1.14 REFRIGERATED (COLD) STORAGE

This term refers to the storage of perishable products in a refrigerated environment, thereby preserving their natural qualities for an extended period of time. Refrigerated storage includes both frozen and chilled food storage, with the latter being the focus of the present guidebook.

1.15 COLD STORE (REFRIGERATED WAREHOUSE)

A cold store, also known as refrigerated warehouse, is an industrial facility designated for the refrigerated storage of food or other perishables in a chilled or frozen state. Cold stores for chilled products are often referred to as cool stores.

1.16 COOL STORE

See the definition for cold store (► **Section 1.15**). A cool store, also known as refrigerated warehouse, is an industrial facility designated for the refrigerated storage of food or other perishables in the chilled state.

1.17 REFRIGERATED (COLD) ROOM

A refrigerated room is a thermally insulated structure (placed separately or as part of a cold store) that provides low internal temperatures maintained by a refrigerating system.

1.18 REFRIGERATING MEDIUM

A refrigerating medium (sometimes called a "coolant") is a substance (usually a fluid) that comes into direct contact with food to chill or freeze it by extracting heat. Secondary refrigerants such as brines or glycols, or even primary refrigerants (the working substances in a refrigeration system), can often serve as refrigerating media. The most commonly used refrigerating medium is air.

1.19 PH

The potential (power) of hydrogen (pH) is a logarithmic measurement of the concentration and activity of hydrogen ions (H^+) in a solution, determining its degree of acidity or alkalinity. The pH scale ranges from 0 to 14, with 7 being neutral (like pure water). Lower numbers (below 7) indicate acidity (more hydrogen ions, H^+), while higher numbers (above 7) indicate basicity (more hydroxyl ions, OH^-). Each whole number on the scale represents a tenfold change in hydrogen ion concentration.

1.20 WATER ACTIVITY

Water activity (a_w) is a measure of the "free" or unbound water available in food to support microbial growth and chemical reactions. It is defined as the ratio of a food's vapour pressure to that of pure water and ranges from 0 (dry) to 1.0 (pure water). Unlike total moisture content, a_w specifically quantifies the water that is energetically available to pathogens and enzymes, making it a critical predictor of a product's shelf life and safety. In their fresh (unfrozen) state, perishables such as meats, fish, vegetables, milk, and eggs typically exhibit a water activity of 0.98–0.99, while cured meats range from 0.90 to 0.95, and various cheeses generally fall within a lower range of 0.85 to 0.95.

1.21 TEMPERATURE LOGGER

A temperature logger (or temperature data logger) is a portable electronic device designed to autonomously measure and record the temperature at predetermined intervals. Unlike a standard thermometer, which only provides a single instantaneous reading, a data logger utilises a microprocessor and internal memory to store thousands of data points. This creates a continuous history for later retrieval and analysis, capturing temperature fluctuations that would otherwise remain imperceptible.

1.22 TIME-TEMPERATURE INTEGRATOR

A time-temperature integrator (TTI) is a "smart" label or device that displays a product's cumulative temperature history. It changes colour or form irreversibly to reflect exposure to both time and temperature, thereby indicating potential quality loss or spoilage. Unlike a static expiration date, TTIs mimic the kinetics of food degradation (such as microbial growth and enzymatic reactions), serving as a useful tool for managing the cold chain of perishable foods and reducing losses from farm to table.

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Chapter 2

Quality of chilled food

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Chilled foods are normally considered high-quality foods, as chilling is the least destructive preservation method in common use. Chilling has the least influence on the eating and nutritional quality of the food by allowing better retention of its "fresh" quality and appearance compared with other processes.

Generally, lowering the storage temperature of the food, preferably below 0°C but not below its initial freezing point, slows down all biological and physiological processes, such as ripening, senescence and microbiological activity. This leads to prolonged practical storage (shelf life) with minimal influence on product quality. However, for some chilled foods, particularly some fruits and vegetables, product temperatures below a certain level may result in chilling injury. Chill injury symptoms include surface pitting, discolouration, internal breakdown, and increased susceptibility to weight loss and decay-causing organisms.

Temperature has a considerable effect on the rate of quality degrading processes, but that effect varies among different processes. ► **Figure 2.1** illustrates the typical change in microbial growth rate with temperature compared to the rate at 0°C (square root rule, along with the rate change for a deterioration reaction or process with a Q_{10} = 2 compared to the rate at 0°C (Ratkowsky *et al.*, 1983).

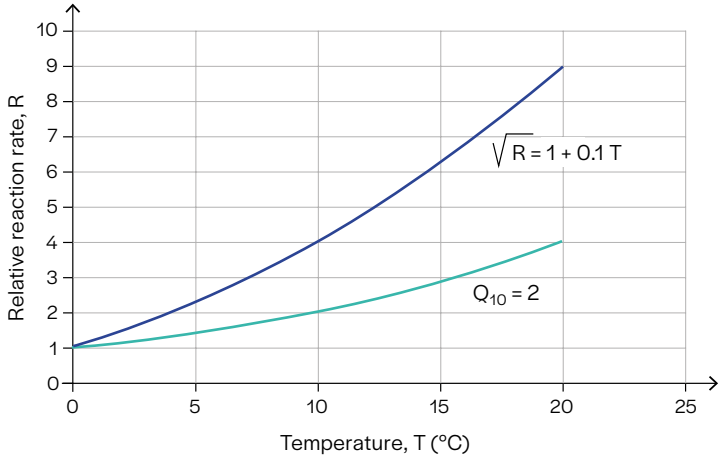


Figure 2.1 Influence of temperature on the microbial growth rate, R ($\sqrt{R} = 1 + 0.1\,T$) and on a reaction with $Q_{10} = 2$[1]

Keys: R = Relative humidity rate T = Temperature

1 Q_{10} = ratio of deterioration rates at two temperatures with an interval of 10°C between them. This quotient indicates how much longer product quality will be retained when the storage temperature is lowered by 10°C.

The optimal chilled storage conditions are provided for a wide range of products in each commodity chapter.

2.1 QUALITY AND SAFETY DEGRADATION PROCESSES

2.1.1 Physico-chemical and enzymatic reactions

Many different physico-chemical and enzymatic processes and reactions are known to affect food quality (e.g. vitamin degradation, production of volatiles, respiration, cell breakdown, colour and texture changes, and rancidity). A wide variety of processes are involved in the development of off-taste, off-colour and other quality defects in different food products. These will be further discussed in each commodity chapter.

2.1.2 Physical changes

2.1.2.1 Unpackaged foods

Evaporative moisture loss is especially important for unpackaged foods. It results in loss of quality due to desiccation and loss of saleable weight. For meat and poultry, evaporative moisture loss is primarily a concern during the chilling process, as these types of foods are often packaged quickly after chilling. For foods which are normally distributed and displayed unwrapped (e.g. many fruits and vegetables), the evaporative moisture loss must be kept low to avoid shrivelling and similar moisture loss-related problems. It should be noted that respiring products, such as fruits and vegetables, can also experience significant weight loss due to respiration in addition to evaporative moisture loss.

In order to minimise the moisture loss of unpackaged products, the following measures are important:

- Fast and immediate chilling (high air velocity, low cooling temperature);
- Low storage temperature;
- High relative humidity (RH) in the storage area;
- Small variations in storage temperature. That is, tight air temperature control and avoiding exposure of the product to conductive (e.g. warm walls) or radiative (e.g. lights, sunlight) heat sources;
- Low air velocity during storage.

2.1.2.2 Packaged products

For packaged products, evaporative moisture loss can still occur inside the packaging (e.g. condensation of water lost from the product on the inside of the packaging). While such moisture loss does not lead to a reduction in saleable weight and often occurs at a much slower rate than in unpackaged products, it can remain significant for some products (e.g. growth of moulds). To minimise moisture loss in packaged products, implement the same methods as for unpackaged products and, if possible, take the following steps:

- Package the product after chilling, once it is close to storage temperature;
- Use close-fitting packaging (e.g. shrink wrap).

For fruits and vegetables, in particular, it is important to minimise physical damage, such as bruising and skin puncture during harvesting or picking, processing, transportation, and distribution. Physical damage can lead to infection by microorganisms and can accelerate chemical changes if cell walls are damaged. Appropriate packaging can reduce the risk of such damage.

2.1.3 Microbiological changes

Microbiological issues are important for all chilled products. Chilling does not stop all microbial growth; in some cases, it only reduces their growth rate. Since chilling normally involves temperatures below 8°C, only cold-tolerant microorganisms (psychrophilic and psychrotrophic) can grow. Psychrophiles have optimum growth temperatures around 12°C–15°C and psychrotrophs around 20°C–30°C. However, organisms in both groups can grow, albeit very slowly, at temperatures as low as -4°C.

Foods may become unfit for consumption due to the presence or growth of pathogenic organisms or spoilage organisms. Pathogenic microorganisms render the food unsafe, while spoilage microorganisms produce unacceptable changes in food's sensory qualities. It should be borne in mind that chilling exerts a limited, if any, effect on the inactivation of microorganisms. Therefore, pathogenic organisms may persist on food if present before chilling, even if growth cannot, or does not, occur at the storage temperature.

2.1.3.1 Hurdle technology

The idea of hurdle technology is that foods safety and quality are determined by a combination of factors, called hurdles. This concept was initially only concerned with

microbiology, especially pathogenic bacteria, but it is equally applicable to quality and other aspects of microbiology. Hurdle technologies in foods may be defined as treatments or substances that are beneficial for the quality and/or microbiological stability of foods.

The microbiological stability of most foods depends on several hurdles, including intrinsic factors such as pH and water activity (a_w), the initial microbiological status, storage temperature, packaging, heat processing, and the presence of additives. For some food products, storage temperature may be the only hurdle. In such cases, the quality of the raw material, including any pre-storage processing, becomes critical for stability and final quality.

Understanding the role of different hurdles is important when applying Hazard Analysis Critical Control Point (HACCP) techniques. The HACCP system is mainly used to establish conditions that control the risk of microbiological chemical, physical and allergenic hazards during food production. In essence, key hurdles, or "critical points", are monitored and controlled.

Predictive microbiology is covered in ► **Section 4.2**.

2.1.3.2 Spoilage organisms

Chilled foods, are often highly perishable and may spoil rapidly at temperatures above 8°C. For respiring foods, the main effect of higher temperatures is an increase in the foods' metabolism and faster onset of senescence. Additionally, the growth of moulds, yeasts and other spoilage organisms on the surface or at injury sites can be significant. Non-respiring foods are often proteinaceous, with a near-neutral pH and a high moisture content (a_w above 0.98), which creates conditions for rapid microorganism growth. Correct chill temperatures prevent or reduce their growth rate.

Water activity (a_w) is the ratio of water vapour pressure of the food to that of pure water at the same temperature, expressed as a ratio between 0 and 1. A high-water activity (greater than 0.95) favours the growth of most microorganisms, while a lower water activity, such as that caused by the presence of solutes like salt and sugar or by physical drying of the food (a_w below 0.85), reduces microorganism growth.

Spoilage microorganisms are different from one product to another. Generally, in foods with near-neutral pH and high-water activity, aerobic Gram-negative bacteria (particularly *Pseudomonas* spp.) are the most common. When vacuum packaging or modified atmosphere packaging is used, or when anaerobic conditions prevail, most aerobic spoilage bacteria are prevented from growing. Instead, lactic acid bacteria (Gram-positive) persist and typically become the principal spoilage organisms in vacuum-packed meat and poultry.

Moulds and yeasts may be the most important spoilage microorganisms in fruits and vegetables, or in chilled foods with low a vailable water. In the case of mould growth, it is not acceptable to remove the part of the food with visible mycelia, as certain moulds can produce toxins (mycotoxins, e.g. aflatoxin) that permeate the entire food, leading to serious human illness. In addition, mould growth may result in enzymatic reactions that cause off-flavours throughout the food.

Snyder *et al.* provide a comprehensive overview of microbial spoilage in foods (Snyder *et al.*, 2024).

2.1.3.3 Pathogenic microorganisms

Foods may become unsafe due to the presence or growth of a wide range of microorganisms, which may either cause infections (e.g. *Salmonella* species and *Listeria monocytogenes*), or produce toxins (e.g. *Staphylococcus aureus*, *Clostridium botulinum*, and some moulds). Toxins may remain in food even after processing has killed viable cells. Foods may appear normal and unspoiled while containing large numbers of pathogenic bacteria. Consequently, the absence of spoilage is not an indicator of safety.

In vacuum-packed foods or in foods with little or no oxygen around the product (anaerobic conditions), *Clostridia*, *Listeria* and *Yersinia* are the main pathogenic species able to grow.

2.1.4 Minimum temperature and conditions for growth

It should be noted that the minimum growth temperature of microorganisms is affected by several factors, including pH, water activity, salt content, food preservatives, and the gaseous atmosphere around the food. ► **Table 2.1** indicates minimum growth temperatures for some common pathogenic bacteria.

Table 2.1 Minimum growth temperatures for pathogenic bacteria

Microorganism	Minimum temperature for growth
Yersinia enterocolitica	-1°C
Listeria monocytogenes	0°C
Aeromonas hydrophila	0°C
Clostridium botulinum, Type E (psychrotrophic/non-proteolytic)	3.3°C
Salmonella	5°C
Bacillus cereus	5°C
Escherichia coli O157:H7 (Shiga toxin-producing Escherichia coli, STEC)	7°C
Staphylococcus aureus	7°C
Clostridium botulinum, Type A (mesophilic/proteolytic)	10°C

Source: (Hudson *et al*., 2011)

In addition, the minimum growth temperature for bacteria is affected by their adaptation to environmental conditions, heat injury (heat treatment) and the presence of competitive microorganisms. As they approach their minimum growth temperature, microorganisms become more demanding with respect to nutrients and more susceptible to other factors. The minimum growth temperatures listed in ► **Table 2.1** assume that all

other factors affecting growth are optimal. Below the minimum temperature for growth, an organism doesn't multiply. However, it often survives and can still pose a health risk or start growing if exposed to warmer temperatures.

Temperature requirements for pathogen growth have significant implications for worldwide chilled food temperature guidance. *L. monocytogenes* and *Y. enterocolitica* can grow at or below 0°C, meaning chilled storage of the foods alone is unlikely to prevent their growth. Thus, only freezing can prevent their growth. Further, other pathogens, such as *Salmonella*, STEC and *Staphylococcus aureus* can grow under conditions of mild temperature abuse. Thus, the primary aim of temperature recommendations for chilled storage is to control the growth rate. Another factor is the capacity for *Staphylococcus aureus* to produce toxins at low temperatures. According to authoritative sources and experimental studies, *S. aureus* can grow at approximately 7°C. However, enterotoxin production has not been demonstrated below 10°C. Properly chilled may allow for limited growth, but it is unlikely that toxins will form, making temperature control a primary tool for preventing toxin risk.

The minimum water activity and/or the minimum pH levels at which these pathogens may grow also varies. *Listeria monocytogenes* and *Staphylococcus aureus* tolerate the lowest water activity (e.g. the highest salt content). For chilled foods that are heat-processed during manufacture, or during the final preparation before consumption, it is important to consider the heat resistance of pathogenic microorganisms and toxins. Generally, vegetative pathogenic bacteria are killed when food is heated so that the centre temperature reaches 70°C to 75°C for a short time (e.g. 2 minutes at 70°C gives a 6 log (6D) reduction for *Listeria monocytogenes*). However, bacterial spores are more heat-resistant. Some strains of Bacillus and Clostridium spores can survive heat processes where the centre temperature reaches or exceeds 100°C. Despite being produced by bacterial cells that have since been killed, microbial toxins can remain heat-resistant and pose food safety risks. Similarly, enzymes produced by microbial growth tend to be heat-resistant and can continue to spoil food, even when the microorganisms have been killed.

2.2 DETERMINATION OF PRACTICAL STORAGE LIFE

The practical storage life (PSL), also commonly referred to as shelf life, indicates how long the food product remains fully acceptable to the consumer. Determining the PSL is a complex task, as many factors influence the consumer's assessment and acceptance of a product.

However, it must be stressed that food safety is the priority requirement when determining the PSL.

2.2.1 Product-Process-Packaging factors

Storage conditions, especially temperature, relative humidity and atmosphere around products, are very important criteria affecting PSL. In addition, Product-Process-Packaging (PPP) factors significantly impact quality and PSL, as further discussed in the commodity chapters. A short outline of the PPP factors follows.

Product Product factors are the nature and quality of the raw material, including parameters such as:

- Different types of meat, different varieties of fruits and vegetables;
- Initial quality, including the number and types of microorganisms and the extent of mechanical damage;
- Degree of ripeness at the time of harvesting for fruits and vegetables;
- Handling of fruits and vegetables during harvesting and transportation;
- Season during which fish are caught;
- Dark Firm Dry (DFD), Pale Soft Exudative (PSE), cold shortening and other conditions for meat (see ► **Chapter 6**).

Generally, the initial microbiological, physical and organoleptic quality must be good to ensure adequate PSL. The PSL figures in the commodity chapters are based on fresh raw materials of good initial quality.

Processing Several processes influence the PSL:

- Chopping, slicing, size reduction, amongst other processes, increase the surface area and damage cells, causing them to release cell contents and initiate enzyme activity. These processes also facilitate the growth of microorganisms. These effects ultimately lead to a decrease in PSL;
- Heat processing (pasteurisation) inactivates most enzymes and kills vegetative microorganisms. Since the normal competitive flora is destroyed during heat processing, the surviving organisms or those present due to recontamination have good growth conditions, so food poisoning risks are greater. Maintaining low temperatures in the chill chain is crucial for such products. If the product undergoes subsequent processing (e.g. slicing) or is vacuum-packed, good hygiene practices are required to ensure good microbial quality;
- Pre-cooling fruits and vegetables with high respiration rates from field temperature to near the storage temperature is essential immediately after harvest;
- The chilling process (chilling rate, final product temperature, evaporative moisture loss) can significantly impact quality and PSL.

Packaging As discussed in ► **Section 2.3** and the commodity chapters, the packaging method and materials can greatly influence PSL, for example by changing the local environment (atmosphere) around the food or reducing moisture loss.

2.2.2 Methods for evaluating quality

2.2.2.1 Microbiological analysis

For many chilled foods, microbial growth is the process that limits PSL. Microbiological analysis is therefore often included in the PSL determination. It can be the only analytical method used, but it demands a good correlation between the number and/or activity of the microorganisms and the sensory quality (smell, taste).

However, for several foods, it is known that the count of microorganisms does not accurately reflect the sensory quality of the product. For example, in vacuum-packed products, the number of lactic acid bacteria count can exceed 50 million per gram, yet the food quality may still be deemed acceptable. In the case of fermented foods, safety may rely heavily on high levels of lactic acid bacteria.

If microbial limits or standards exist for chilled products, microbiological analyses are an essential part of PSL determinations. For some products, guidelines for microbiological quality include approximate limits for spoilage and/or pathogenic microorganisms.

2.2.2.2 Chemical and physical analysis

The result of sensory evaluation depends on the method and the type of taste panel applied. Due to the complexity and expense of using taste panels, it can be more cost-effective and consistent to evaluate foods quality using chemical or physical analyses. Extensive research has been done to objectively determine the quality and/or PSL of various foods in terms of chemical and physical parameters. Several useful methods have been developed, especially with regard to texture, colour, and rancidity.

However, correlation between instrumental methods and consumer acceptance is not always high. The important point in food quality is the consumer's opinion. As yet, no machine or apparatus can completely replace the human nose and mouth. Therefore, the quality and PSL of foods can seldom be determined without the use of sensory evaluation. This indicates the need for continued development of suitable objective methods for measuring food quality, especially for use in on-line quality control during manufacturing.

2.2.2.3 Sensory evaluation

Once microbiological safety is assured, the eating quality of a food product becomes the primary consideration in determining its PSL. Eating quality is usually determined by sensory evaluation, which can be carried out in many different ways. Often, a scoring system is used for general or defined attributes, where a taste panel with trained consumer representatives evaluates the samples and scores for the presence or absence of these attributes.

Different scoring scales are used, and the definition of what constitutes the end of PSL varies among institutes, companies, etc. As previously stated, PPP factors may have considerable influence on PSL, indicating that a single experiment is rarely sufficient.

2.2.2.4 Practical Storage Life data and Practical Storage Life curves

Practical storage life experiments are carried out by placing replicate samples of a product at two or more storage temperatures. While single-temperature storage is a common practice, it is usually inadequate, as chilled foods are exposed to varying temperatures throughout the chill chain. Therefore, it is important to understand the PSL at more than one temperature. Each commodity chapter includes a list of PSLs at different, but constant, storage temperatures.

► **Figure 2.2** shows examples of PSL curves (i.e. diagrams showing the PSL for products over a range of chill temperatures). The distinct shape of the PSL curve for cucumber is indicative of possible chill injury effects at temperatures below about 12°C.

2.2.2.5 Evaluating of quality by estimation of remaining PSL

Chilled foods are exposed to a variety of temperature conditions along the chill chain, and it is necessary to be able to calculate the quality and/or remaining PSL after a certain time.

The rule of additivity states that when foods are exposed to different time-temperature episodes, the effects of the times at each temperature are additive and the cumulative impact on product quality and remaining PSL is unaffected by the sequence of these episodes.

Although the rule of additivity generally holds true for frozen foods, it has been shown to be invalid for many processed chilled foods. A "warm" storage period during the early stages of a chilled product's "life" may influence remaining PSL much more than when such a warm episode occurs in the latter stages. This is thought to be due to whether microorganisms are in the lag or active growth phase when they encounter warm conditions. However, calculation of quality and remaining quality using the rule of additivity can often give an indicative result.

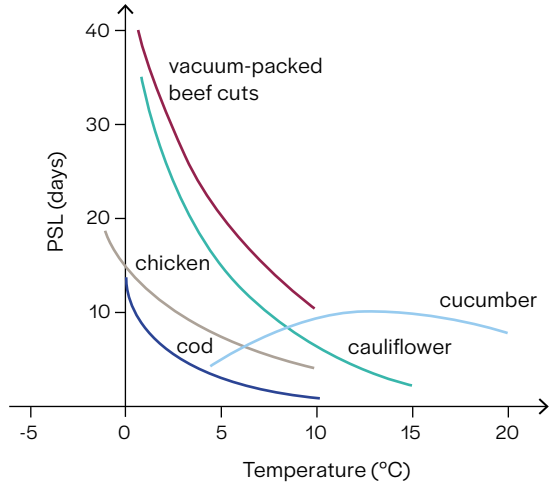


Figure 2.2 Practical storage life of some chilled foods (IIR, 2000)

Example: the PSL curve for chilled chicken (▶ **Figure 2.2**) indicates that the PSL is 14 days at 0°C and 5 days at 8°C. If this product is kept at 0°C for 7 days, 50% of the PSL has elapsed. If the product is kept at 8°C for 2 days, 40% of PSL has elapsed. Consider two processes:

- If the product is kept for 7 days at 0°C, followed by 2 days at 8°C, the total loss is 90% of PSL, indicating that it could be kept for 0.5 day at 8°C or 1.4 days at 0°C and still be of acceptable quality.
- However, if this product is kept for 2 days at 8°C, followed by 7 days at 0°C, the calculated total loss remains 90%, but the quality, as determined by sensory evaluation, may be unacceptable (i.e. the total loss in practice could exceed 100% of the PSL). The reason is that the initial "warm" storage enabled microbial proliferation. The microbiological population at the start of the storage period at 0°C was consequently high, making spoilage more likely than the same product with typical microbial levels.

2.2.3 Food expiry date marking

Generally, the food manufacturer, sometimes in co-operation with the retailer, is responsible for determining the expiry date that is displayed on the label. Other terms used rather than expiry date include best-before date, use-by date and sell-by date. Although they often have similar meanings, these can have slightly different definitions from country to country. In a few countries, a maximum PSL for certain chilled foods is specified by legislation. The legislation of many other countries, while not specifying a set PSL, demands a clear expiry date (or equivalent) except for some unpackaged foods.

The PSL tables in each commodity chapter can be used as a guide. However, these PSL figures are often based on specific experimental data and experience. Bearing in mind that no two types of foods are the same and because of the PPP factors' influence, producers or companies must carry out their own PSL determinations. In addition, most PSL figures are based on a constant storage temperature, while, in practice, most chilled foods will be exposed to a range of temperatures throughout the chill chain. Thus, the expiry date should consider realistic time-temperature conditions that the product is likely to encounter, and preferably, include a safety margin for possible unusual situations. Hence, expiry dates are usually shorter than PSLs.

When deciding on the expiry date marking, the safety date of these foods is determined by the growth kinetics of the most relevant pathogen, often *Listeria* or psychrotrophic *Clostridium botulinum*. The safety date should take priority over spoilage if it is shorter.

2.2.4 Time-Temperature Integrators and temperature logging

It is likely that future legislation will demand increasing control of temperatures in the chill chain, such as the use of temperature recorders in storage rooms, during transportation, and in display cabinets. In some countries, such legislation already exists. For several years, temperature recorders have been standard equipment in refrigerated containers, and are frequently used in cold stores, etc. However, temperature recorders show air temperatures, rather than the product temperatures, and often fail to record the conditions during the loading and unloading processes.

In order to monitor or control the chill chain, including transportation, electronic temperature loggers can be placed close to the food (e.g. between packs in a carton). After storage and transportation, the time-temperature conditions to which the food has been exposed can be read by downloading the logger, and possible temperature control issues can then be identified. Such equipment is widely used for long-distance transportation. Some temperature loggers offer remote on-line interrogation of data or provide near-real-time downloads of data via local WiFi, the internet or similar systems. Such loggers allow for remote monitoring such that temperature deviations can be identified almost immediately, and mitigation actions can be taken to prevent significant quality loss.

For several years, the use of time-temperature integrators (TTI), or indicators, has been considered by food producers and retailers. Indicators can be used to determine if

a predetermined maximum temperature has been reached or exceeded. Integrators integrate (add) the effects of temperature over time, and by means of an irreversible physical change (e.g. colour), indicate the quality and/or remaining PSL of the food. The speed and temperature dependency of the indicator reaction must match the PSL-temperature relationship of the food in question (see ► **Figure 2.2**).

Indicators and integrators can be placed on the retail pack, enabling the consumer to check whether the pack has not been exposed to temperatures above a certain limit, or that the pack has not been exposed to such time-temperature conditions that the product quality (or safety) may be unacceptable. The use of temperature indicators and integrators is currently limited due to factors such as cost and the often poor correlation between the indicators' reaction kinetics and the actual food quality loss kinetics. When using these devices, it is important to ensure that they are placed in locations representative of most of the product. For example, the American Frozen Food Institute and the Global Cold Chain Alliance recently developed a temperature monitoring protocol, which provides a standardised, data driven approach to track temperature profiles from production to final distribution. While developed for frozen foods, the underlying principles can also be applied to chilled foods (American Frozen Food Institute — AFFI — and Global Cold Chain Alliance, 2025).

2.3 PACKAGING

Packaging plays a pivotal role in ensuring the physical protection of food products during storage, transportation and distribution, as well as facilitating their convenient handling. Centralised manufacturing facilities and consolidation of production sites has accentuated the need to use packaging for most chilled food. The packaging can achieve longer PSLs, allowing for longer distribution and display times. In supermarkets, most chilled foods, except for some fresh fruits and vegetables, are displayed packaged in order to avoid contamination by, amongst others, soil, microorganisms, consumers, other produce.

Most countries have introduced legislation on handling waste packaging materials, recycling, etc. Therefore, it is important to use life cycle analysis tools to minimise waste creation when choosing packaging methods and materials.

Packaging for foods is divided into two categories: inner and outer packaging.

- The inner packaging, which directly touches the food, frequently serves as the product's final packaging that is presented for sale to the end user (the consumer). This includes packaging intended for catering and large institutions, such as canteens, as well as packaging for food meant for further processing. Inner packaging can actively alter the immediate environment of food. Other common terms are "consumer packs", "retail packaging", or "primary packaging". Business-to-business (B2B) transfer of bulk products for further processing often does not involve the use of inner packaging.
- Outer packaging typically contains a number of items in inner packaging. Common terms are "outer case", "transportation packaging", "transportation carton", "shipping container", "secondary packaging", etc.

In addition, tertiary packaging is often used to consolidate multiple items with outer packaging into larger items, such as pallets for efficient handling. Tertiary packaging generally comprises pallet bases (usually wooden or plastic), slip sheets and plastic shrink wrapping.

Increasingly, countries are introducing product stewardship schemes or equivalent that require the amounts of packaging to be minimised and/or any packaging to be recycled or disposed of such that its environmental impact is minimised. Producers should consider the potential trade-off between product PSL and packaging types and levels. Poor packaging design or insufficient packaging could lead to excessive product losses, while poor packaging design or excessive packaging can have a large environmental impact.

2.3.1 Inner packaging

The selection of packaging methods and materials for food is determined by various factors, especially the specific requirements of the food itself, as discussed in more detail in the commodity chapters.

2.3.1.1 Packaging methods

While most chilled foods are sold in flexible plastic packages, consumer packs come in various forms that can be grouped into rigid, semi-rigid, and flexible depending upon the type of package. The most common types of inner packaging include:

Wrappers The simplest type of flexible package is the wrap, where a sheet material is used to enclose a quantity of product. Greaseproof paper is often used for butter and margarine. Typically, wrappers are not hermetically sealed.

Overwrapped trays In supermarkets, fresh meat and poultry, fresh fruits and vegetables, etc. are traditionally displayed in trays of wood pulp or semi-rigid plastic, overwrapped with a plastic film with high permeability to oxygen, such as polyethylene (PE) or polyvinyl chloride (PVC). Similarly, such trays are usually not hermetically sealed. The use of such plastic materials will result in aerobic conditions around the food.

Bags, pouches Plastic bags and pouches are widely used. They can be manufactured from a single plastic material or combinations (laminates), depending on the required degree of protection such as permeability to water vapour and gases, etc. Plastic bags and pouches are often heat-sealed, a seal that is sometimes referred to as a hermetic seal.

Vacuum packaging When the package has been filled with food, the air is drawn out, and the package is heat sealed. With a flexible package, the plastic material will be pulled against the food. As mentioned above, a packaging material with low gas permeability must be used. In this way, food is protected from oxygen in the atmosphere, which slows many quality-degrading processes, resulting in an increased PSL. Vacuum packaging also provides added protection, and improved visual appearance, for delicate products such as finely sliced smoked salmon. Vacuum packaging will result in anaerobic conditions around the food product, which can stimulate outgrowth of *Clostridium botulinum* spores (if present) and their toxin production. In addition, anaerobic conditions may not inhibit growth of facultative anaerobes, such as *Listeria monocytogenes*.

Vacuum Skin Packaging (VSP) is a specific type of vacuum packaging. A plastic material with a low melting point is softened by heating before applying a vacuum and sealing the package. During this operation, the soft film moulds itself to the shape of the food to make a skin-tight package. This can give the food product an attractive appearance and better protection, since no gas remains inside the packaging.

Modified Atmosphere Packaging (MAP) For non-respiring products, after removing the air from the package, a modified atmosphere is introduced (gas flushing) before heat sealing. Thus, the packaged food is surrounded by a gas mixture differing from the normal atmosphere. As plastic materials are not impermeable, the composition of the gas mixture will change, albeit very slowly, provided that the packaging material has a very low permeability to O_2 and CO_2 in particular. The modified atmosphere introduced in MAP of non-respiring foods contains, in most cases, at least 20% CO_2, in order to inhibit or reduce microbiological growth.

Modified atmosphere packaging of respiring food products is discussed further in ▶ **Chapter 5**. This packaging is complex, as respiring food consumes oxygen and emits carbon dioxide and other gases and the packaging films are usually semipermeable to respiratory gases, leading to changes in the atmosphere composition once the package is sealed.

Controlled Atmosphere Packaging (CAP) can be achieved when using impermeable plastic packaging, such as laminates with an aluminium foil layer. For example, controlled atmosphere packaging with an oxygen-free atmosphere (100% CO_2) is used for transporting chilled meats. The saturated CO_2 atmosphere extends the lag phase and reduces the growth rate of anaerobic spoilage bacteria, thus extending the PSL by at least 50% in the same conditions of hygiene and temperature as vacuum-packed meat. With good hygiene and strict temperature control (-1°C to -1.5°C), PSLs of 16 weeks can be expected with lamb and beef.

Active packaging Active packaging, as well as acting as a barrier, actively modifies conditions inside the packaging. For instance, oxygen scavengers absorb O_2 and make it possible to maintain a very low oxygen concentration, which can prolong the PSL of food products susceptible to oxidation. This is a form of controlled atmosphere packaging, although the concentration of gases other than oxygen may not be constant. Active packaging can include CO_2 absorbers and emitters, ethylene absorbers, moisture absorbers, ethanol emitters, and the release of preservatives or antioxidants. Smart or intelligent packaging is a type of active packaging where the package modifies the environment in response to information about the product or its surroundings (e.g. from oxygen indicators, and time-temperature indicators or integrators).

2.3.1.2 Materials for inner packaging

In order to choose an appropriate packaging material, several important properties must be considered. The most important properties of packaging materials to be used for foods are:

Water vapour permeability, or Water Vapour Transmission Rate (WVTR) For most foods, the water vapour transmission rate of the packaging material, and of the package

itself, should be low or very low to prevent desiccation and weight loss. However, certain fresh fruits and vegetables should be packed in materials with a higher water vapour transmission rate in order to avoid high relative humidity inside the package, which may lead to condensation and microbiological growth.

Gas permeability Gas permeability refers to the permeability of oxygen (O_2) and carbon dioxide (CO_2) in particular. For some foods, vacuum packaging or modified atmosphere packaging is used to increase PSL by maintaining low O_2 and/or high CO_2 conditions. For such packaging, it is necessary to use a material with low gas permeability (i.e. the oxygen permeability should be below 70–90 ml/(m^2.day.bar)). For foods requiring extra protection against oxygen, plastic laminates, often with a barrier layer and an oxygen permeability of 10 ml/(m^2.day.bar) or lower, should be used. As discussed in the commodity chapters, some foods may require packaging with a higher oxygen permeability (see ► **Section 6.5.1**). In modified atmosphere packaging of respiring products, packaging with higher gas permeability than indicated above is often used (see ► **Chapter 5**).

Physical properties The packaging material used must be able to withstand the conditions it experiences in the chill chain, such as drops, shocks, vibrations and temperature change. For example, when using hot filling, food is put into the package while still hot (often above 90°C), requiring that the packaging material tolerates such temperatures, along with temperatures around 0°C. Packaging for ready meals must often be microwave-suitable and able to withstand high temperatures (e.g. about 200°C or higher during reheating).

Interaction with food (migration) Packaging for food must not, in any way, cause the food to become toxic. Several countries have legislation on packaging, including maximum permissible limits for migration of additives from the packaging material into the food (see ► **Section 2.5**).

2.3.2 Outer packaging

Outer packaging is used for most retail packed chilled foods. Proper packaging for transportation is essential to maintain product quality and to minimise product losses during transportation and marketing. In addition, the outer packaging serves to enclose the product and provides a means of handling.

The transportation packaging must:

- Have sufficient strength to withstand the type of handling likely to occur throughout the chill chain;
- Have sufficient strength to withstand impact and vibrations during transportation, and compression from packages stacked above;
- Withstand high relative humidity, which may occur in several parts of the chill chain, especially during unprotected loading and unloading. The compression strength of cartons made of untreated paperboard (cardboard) can be reduced to less than half, if exposed to a relative humidity of 90% or above.

Outer packaging used in practice is usually reusable and/or recyclable and includes:

- Paperboard (cardboard) cartons or boxes, mainly of corrugated (fibre) board;
- Plastic trays, boxes, film wraps, etc.;
- Foam boxes, trays;
- Wood bins, crates, etc. (especially for fruits and vegetables).

2.3.3 Stacking (tertiary packaging)

In storage rooms and in refrigerated transportation, food products are often placed in outer packaging, which is then stacked into pallets, racks or equivalent. In all cases, it is necessary to ensure that the product quality is not affected by compression from the weight of the stacked products above. In addition, the stacking should not impair general air circulation in the refrigerated facility. An adequate system for even air distribution is useless if poor product stacking obstructs airflow. Air leaving and returning to the air-cooling system will take the path of least resistance (i.e., it will pass through the largest gaps), instead of passing through or over the product. If open spaces designed for air movement (near walls and ceilings, for example) are partially blocked, dead-air zones occur, which could cause local temperatures to increase.

Creating universal principles for stacking is a challenge due to the large variety of packaging used for different commodities and the wide range of pallets, racks, bulk bins, corrugated cartons, and other materials in use. If the product is near storage temperature and not respiring, then stacking should be used to ensure that the minimum surface area of outer packaging is exposed to circulating air, thereby minimising the risk of product temperature fluctuations. Also, no direct contact between packages and walls or floor should be allowed (except in rooms with refrigerated jackets).

For respiring foods or products loaded at above storage temperature, it is necessary to provide airflow through the product stacks to remove excess heat, the heat of respiration and respiratory gases. In most other cases, stacking should be as tight as possible because airflow through the product is not required; however, there must be good airflow around and under the stack (i.e. over the walls, ceiling and floor of the refrigerated structure).

2.4 HANDLING OF CHILLED FOODS IN THE KITCHEN

Chilled foods are not sterile and general good hygienic practices should always be followed. Care should be taken to avoid cross-contamination by pathogenic bacteria between, for example, vegetables and meat, and vice versa, especially if the food is not intended for immediate consumption. Heating and reheating all foods should result in the recommended product temperature being achieved. As a general rule, a temperature of at least 70°C–75°C in the thermal centre or the coldest point should be achieved. To this end, the use of a thermometer is essential.

In a domestic refrigerator, cooling should be carried out as quickly as practicable. However, most domestic refrigerators are not designed for rapid cooling. The refrigerator

thermostat should be set so that the coldest zone within the refrigerator maintains a maximum of 4°C (e.g. EU Regulations (EC) No. 852/2004 and No. 853/2004). However, it should be noted that there are usually significant temperature differences inside the refrigerator cabinet, and the mean temperature is often above 4°C.

Transportation of chilled foods from the retail store to a home should be done as quickly as possible, with the chilled foods carried in an insulated box or similar device. If the journey time is long, the chilled food is unprotected (not in an insulated box), and the ambient temperature is warm, significant increases in product temperatures may occur. Subsequent cooling to the correct chill temperature in a domestic refrigerator may take several hours. When determining the PSL (see ► **Section 2.2.3**), these conditions should be taken into account.

2.5 LEGISLATION

Most countries have established mandatory temperature limits for the storage, transportation and distribution of chilled foods, especially non-respiring products. In addition to the regulations mentioned below, further information on legislation can be found in the commodity chapters.

For example, the European Union (EU) introduced Council Directive 93/43/EEC in the 1990s, making HACCP a legal requirement for EU member states, including the United Kingdom (UK). The Directive was repealed by EU Regulation (EC) 852/2004 on the hygiene of foodstuffs, which came into force on January 1, 2006. Other relevant EU Regulations include No. 853/2004 and No. 2073/2005. However, the HACCP system remains highly relevant for ensuring the safety of all types of chilled foods, particularly in relation to microbiological hazards.

In the United States, the Food Safety Modernization Act (FSMA) similarly emphasises a preventive, risk-based approach to temperature control for chilled foods. Under the FDA's Preventive Controls for Human Food regulation (21 CFR Part 117), food facilities are required to identify biological hazards associated with time-temperature exposure and implement, monitor, and document preventive controls, such as refrigeration and temperature monitoring, where necessary to significantly minimise or prevent those hazards. Together with FDA Food Code and the Sanitary Transportation Rule, the FSMA reinforces the importance of continuous temperature control across storage, transportation, and distribution as a core element of chilled food safety management.

Raw materials In most countries legislation does not prescribe detailed specifications for raw materials. Typically, a statement like, "raw materials used in the manufacture of... must be of sound and merchantable quality and have the required degree of freshness", is used. For meat, poultry and dairy products, regulations are usually more detailed in this respect, typically dealing with issues such as veterinary health inspection, veterinary control, transportation of live animals, approval of slaughterhouses and hygiene.

Processing Some countries have legislation on processing, for example, requiring certain meat products to be heated to a minimum centre temperature (e.g. 72°C or 75°C). For

dairy products, internationally accepted temperature requirements for pasteurisation of the raw milk have been in force for many years. In many cases, compositional standards also apply (e.g. for some meat and dairy products).

Cooling The cooling process is usually dealt with in general terms (such as initiating the chilling process without unnecessary delay and completing it as rapidly as practicable). However, there are some specific cases, for example, in the European Union countries where the cooling of carcasses, half carcasses, etc. after slaughter must result in an internal temperature of 7°C or colder. In many countries, there are special requirements for water chilling poultry.

For prepared meals and other heat-processed products, several countries have regulations on the cooling process in order to ensure that the dangerous temperature range (50°C to 10°C) is passed through rapidly to prevent microbiological problems. In one instance, the product temperature must drop from 65°C to 10°C within 3 hours. In another, it needs to decrease from 70°C to 10°C within 2 hours (see ► **Table 10.2** in ► **Chapter 10**).

Storage In many countries, a maximum storage (or product) temperature for non-respiring foods is specified. The maximum temperature for a specific food may vary across different countries. While 5°C is typically the specified chill storage temperature, in some cases it can be as low as 2°C or 3°C, or even as high as 8°C. In some countries, a maximum storage or product temperature of 3°C is used for heat-processed and vacuum-packed (or modified atmosphere packaging with very low oxygen) products without additional "hurdles". The reason is to prevent growth or toxin production from non-proteolytic *Clostridium botulinum* types B and E (see ► **Table 2.1**). Generally, these maximum temperatures also apply to transportation, distribution and retail display.

Transportation Besides the above temperature requirements for storage, the ATP[2] agreement (see ► **Section 3.3**) has specified temperature requirements for transportation of non-respiring chilled foods. During loading, transportation and unloading, food temperature must not, at any point in the load, exceed the temperatures specified in ► **Table 2.2**. Furthermore, it is a requirement that the temperature control avoids any risk of freezing any part of the load.

Local distribution and retail display In principle, the same temperature requirements apply as for storage. However, some countries have introduced specific tolerances, particularly for local distribution.

Refrigerants Regulations concerning ozone-depleting substances have led to the progressive phase out of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) via the Montreal Protocol.

Hydrofluorocarbons (HFCs) and natural refrigerants, including ammonia, carbon dioxide and hydrocarbons (e.g. butane, isobutane and propane), are used as replacement refrigerants.

2 ATP: Agreement on the international carriage of perishable foodstuffs and on the special equipment to be used for such carriage.

Table 2.2 Maximum temperatures during transportation between countries, according to ATP

Foodstuff	Maximum temperature
Red offal	+3°C (1)
Butter	+6°C
Game	+4°C
Milk (raw or pasteurised) in tanks, for immediate consumption	+4°C (1)
Industrial milk	+6°C (1)
Dairy products (yoghurts, cream and fresh cheese)	+4°C (1)
Shellfish	of melting ice
Meat products (2)	+6°C
Meat (other than red offal)	+7°C
Poultry and rabbit	+4°C

(1): In principle, the duration of carriage should not exceed 48 h.
(2): Except for products stabilised by salting, smoking, drying or sterilisation.

Source: (United Nations Economic Commission for Europe (UNECE), 2024)

However, due to the high global warming potential (GWP) of most HFC refrigerants, the Montreal Protocol was recently extended to include the phase-out of HFCs. The phase-out schedule is slower for developing than for developed countries. All sectors of the food industry need to be prepared to replace CFC, HCFC and HFC refrigerants if they have not done so already.

Hydrofluoroolefin (HFO) refrigerants are possible low GWP alternatives to HFC refrigerants but are usually mildly flammable and there are also further environmental concerns because many are Per- and PolyFluoroAlkyl Substances (PFAS). Therefore, HFOs may not be long term refrigerant options.

Natural refrigerants are unlikely to be regulated for environmental reasons but often have other constraints (e.g. toxicity, flammability). Therefore, the food industry needs to be careful when choosing refrigerants to both minimise environmental impact and ensure refrigeration system longevity.

Labelling Many countries require that the labelling of chilled foods must include some or all of the following information:

- Name of the product;
- Producer, importer or agent in the country of sale;
- Expiry date (the date of minimum durability or a “use by” date);

- Storage conditions (temperature);
- Net quantity;
- List of ingredients (if applicable);
- Instructions for storage and use.

Microbiological criteria Some countries, including the EU, have microbiological regulation for certain chilled products. This is mainly the case for highly perishable products (e.g. minced meat). Many countries have microbiological guidelines for non-respiring chilled foods. For microbiological standards or guidelines to be meaningful, they need to include sampling plans and to specify the microbiological analyses to be used.

Packaging In many countries, the composition of packaging materials, particularly plastics, is regulated by means of lists of permitted materials. The definition of suitability often includes limits for total and/or specific migration of components from the packaging material to the food. An area that has attracted considerable interest in recent years is the handling of waste packaging materials, including reuse, recycling, incineration and Life Cycle Assessment (LCA). Legislation on product stewardship is being prepared, or is already in force, in some countries (see ► **Section 2.3**).

Thawed products In some situations, frozen products, especially fish, meat and poultry, are thawed and sold as chilled products. Some countries have introduced legislation requiring that consumers be informed that such products have been previously frozen.

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Chapter 3

Chilling technology

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In this chapter, the different types of chilling technology are discussed. The various systems used in the chilling process are outlined in ▶ **Section 3.1** and the different parts of the chill chain are considered in more detail in ▶ **Sections 3.2** and ▶ **3.4**.

For chilling processes in which the food temperature must be reduced quickly, the required refrigeration capacity is very large. In chilled storage, transportation and distribution, there must be sufficient refrigeration capacity to maintain the temperature, but it is typically not enough to lower food products' temperature within a reasonable period.

Calculating the required refrigeration capacity can be complicated but should be performed before selecting the equipment. The ASHRAE Refrigeration Handbook Chapter 24 provides heat load estimation methods (ASHRAE, 2022).

3.1 CHILLING PROCESS: PRINCIPLES, FACTORS AND IMPACTS

The chilling or cooling process results in a substantial reduction of the food temperature. The initial and final temperatures as well as the desirable chilling rate vary based on the product. Generally, the process should be initiated without delay to rapidly chill the products.

However, it should be noted that very rapid chilling, using extremely cold air or chilling to very low product temperatures may lead to quality deterioration for some products.

After the chilling process, the average product temperature should be at or near the intended storage temperature. Products significantly warmer than the intended storage temperature are sometimes transferred to the storage room due to several poor practices:

- Insufficient chilling time is allowed;
- Insufficient refrigeration capacity in the chilling system;
- Overloading the chilling system;
- Variability in size of products (e.g. larger product items incompletely cooled);
- Temperature of the cooling medium may be limited to prevent surface freezing of the product.

In such cases, the reduction of product temperature in the storage room will usually be slow, which may result in:

- Reduced storage life;
- Increased microbial growth;
- Increased weight loss;
- Formation of condensation on products already present in the storage room;
- Degradation of quality.

Most perishable food have a high moisture content, so their specific heat capacity is within the range of 3.5 to 4.1 kJ/(kg.K). Therefore, lowering the mean temperature of such a product from 30°C to 5°C would demand a heat removal of about 95 kJ/kg. Low-moisture foods with high fat content that also require chilling, such as cheese or butter, have much lower heat capacity values. For respiring products, such as fruits and vegetables, it may also be necessary to consider the respiration heat. Respiration heat is typically lower than the heat removed for temperature reduction, see ► **Chapter 5**.

The choice of a chilling system for a particular food must consider many factors, including the required throughput of product, the limitations due to thermodynamic or quality issues and economic considerations (e.g. capital and operational costs).

Heat can be removed from a product's surface by four basic mechanisms: radiation, conduction, convection or evaporation. Most food chilling systems rely on convection as their primary heat removal method (vacuum chilling is a notable exception; see ► **Section 3.1.3**). Even if there is significant radiation and evaporative heat transfer, it is often most convenient to approximate these mechanisms as pseudo-convection (additional to the base convective heat transfer). Heat is transferred from the product's surface to a cooling medium, which passes over the product. The most common media are air (air blast), water (hydrocooling) or combined air/water systems (evaporative cooling). The rate of heat removal from the product depends on the surface area available for heat flow, the temperature difference between the surface and the medium, and the surface heat transfer coefficient. Typical values of the coefficient range from 5 W/(m^2.°C) for slow-moving air to 500 W/(m^2.°C) or higher for agitated water.

However, the rate at which heat can be removed from the surface is not the sole criterion that governs the time needed to cool a product. Product size has a marked influence, as heat must be conducted from within the product to its surface before it can be removed. Foods are relatively poor conductors of heat, and this imposes severe limitations on attainable chilling times for large individual items, such as animal carcasses, or small items cooled in bulk where there is limited air penetration through the bulk items such as fruits and vegetables in large bins with solid sides.

Packaging is also of great importance. Some food, such as fruits, are wrapped and placed in cartons before chilling. The combined effect of the wrap and the static air enclosed in the carton considerably slows the chilling process due to the low thermal conductivity of most wrapping materials and the trapped air. Fully or partially sealed plastic liners can serve as effective moisture barriers, maintaining a higher relative humidity near the product than in the surrounding air. Such liners can reduce desiccation due to evaporative cooling but must be carefully selected for respiring products in order to avoid generating anaerobic conditions because they also act as barriers to oxygen and carbon dioxide transfer. Cartons for respiring products such as fruits and vegetables usually have vents that allow air to pass through the carton. This reduces the effective size of the item being cooled and increases the cooling rate and allows for better respiration heat removal. Vented cartons should be arranged in stacks with the vents aligned and facing the direction of airflow during air-blast chilling. During subsequent storage, vent alignment may become less crucial or even actively avoided due to lower respiration rates at lower temperatures. This is because airflow requirements to remove respiration heat are significantly lower compared to rapid chilling.

Several mathematical models have been developed to calculate and predict the chilling time for different products (see ► **Section 4.1**, and ► **Section 10.4**).

Rapid chilling While attempts to increase chilling rates are complicated by a number of factors there are several advantages if faster chilling can be achieved. Most foods are of high value and any increase in product throughput will improve cash flow and utilize expensive equipment more efficiently. Rapid reduction in temperature retards microbial growth and consequently extends storage life and slows rate of quality loss. Different foods exhibit particular quality advantages as a result of rapid chilling (these points are discussed in the commodity chapters). One important advantage of rapid chilling of unwrapped products is a reduction in moisture loss.

3.1.1 Air-blast chilling

Air-blast chilling, chilling by means of forced air convection, is the most widely used method, as it is flexible, economical and hygienic. Systems range from the simplest, where a fan draws air through an air-cooling system and blows the cooled air around an insulated room, to blast chilling tunnels or spiral tunnels where products move continuously through the system on a belt or conveyor. Relatively low rates of heat transfer from product surfaces are attained in such air-chilling systems, but the rate-controlling factor, especially for large items, is usually the conduction of heat from the product's core to its

surface. A major disadvantage of air chilling is the loss of water from the surface of unwrapped product due to evaporation.

To prevent the surface from freezing, certain foods have a minimum allowable air temperature. See ► **Section 10.4**). An increase in air velocity will reduce chilling time (higher chilling rate), but this has to be set against the energy consumption (the power required by fans to circulate the air), which increases proportional to air velocity to the power of three (cubed). An air velocity between 1 m/s and 3 m/s is often the most suitable, but for smaller and/or unpackaged products, higher velocities may be more cost-effective because surface heat transfer is more constraining than conduction.

Air distribution is a major issue in real-world applications. Despite designing systems to distribute air evenly throughout the product, poor chilling system management and a lack of understanding of air distribution often lead to uneven cooling. Irregular stacking, as discussed in ► **Section 2.3.3**, can prevent the air from efficiently flowing over or through the products.

During both chilling and storage, water vapour is transferred from unwrapped products to the air and then to the evaporator coil. If the temperature of the evaporator coil is below 0°C, frost forms, thus reducing air circulation rate and cooling efficiency. This effect can occur in chilled storage rooms (and in transport equipment and display cabinets), where the air temperature is below about 3°C. In these cases, regular defrosting of the evaporator coil is necessary to restore the refrigeration system's performance. The evaporator coil's size should be increased to compensate for frosting deterioration.

For some vegetables, such as potatoes, cauliflower, broccoli, chicory or tomatoes, which benefit from high humidity, an "air-wash" system that uses evaporative cooling of water similar to a cooling tower is sometimes applied. In this system, warm return air in the cold room comes into contact with a refrigerated water spray or water is sprayed over the air-cooling evaporator. A demisting mesh or equivalent is usually used to prevent water droplets from carrying over into the supply air. The air exiting such systems typically have a temperature range of 1 to 1.5°C and a relative humidity of 97% to 98%, due to the evaporative cooling of the air by the water spray. Humidification at higher air temperature is also possible with such air-wash systems or similar equipment.

3.1.2 Water chilling (hydrocooling)

Water chilling, which is also often referred to as hydrocooling or immersion cooling, is often a cost-effective method of achieving rapid chilling in small products. The product is immersed in, or sprayed with, cold clean water, usually at a temperature close to 0°C. Depending on legislation in the country, this water is often treated with a mild disinfectant (e.g. chlorine or ozone).

Practical systems vary from simple stirred or unstirred tanks to plants where the product is conveyed through agitated tanks or under sprays. During the hydrocooling process, small weight gains are often recorded in products that do not require drying, such as poultry. Hydrocooling is typically used for some fruits and vegetables, where contact with water does not affect their quality.

For products that cannot come into direct contact with water, some are hydrocooled after being packaged in tight-fitting sealed plastic wraps or bags (e.g. vacuum-packed).

Hydrocooling does not offer significantly faster rates of chilling than air-blast chilling for very large product items.

An alternative system to either air-blast or immersion cooling is spray chilling. Spray chilling systems use a combination of air and water sprays during the initial chilling phase, then often switch to air alone for the final phase. The sprays are not always applied continuously, but in short intermittent bursts (such as 90-second applications every 15 minutes for the first 8 hours of beef chilling).

Spray chilling and immersion chilling are commonly used for poultry, see ▶ **Section 6.3.2**).

Refrigerated seawater (RSW) for chilling of fish at sea is a common variation on hydrocooling used in the fishing industry. Fish are put into tanks through which refrigerated seawater is recirculated.

Other common hydrocooling variations include the use of ice slurries or flake ice. Ice slurries are a mixture of slush ice and water that can be pumped (usually up to about 40% ice by mass). Ice slurry is often generated in a scraped-surface heat exchanger using water with a small amount of solute, such as salt, added to generate "soft ice" rather than pure ice which can be too brittle. The advantages of ice slurry are that it can be used like water in a hydrocooler but has a much higher cooling capacity for the same mass and stays close to 0°C due to the latent heat of the ice as it melts.

Flake ice is usually generated by a stand-alone icemaker, often found in fishing ports. Typically, the ice is stored in a refrigerated bunker, then packed around the product to be cooled in an insulated container or tank. Heat transfer occurs by conduction from the ice and by convection from the melt water. The ice-to-product ratio should be adjusted to the required cooling and any heat gains from the environment surrounding the container or tank. For fish being cooled from 20°C to 0°C, the minimum requirement is about 0.25 kg of ice per kg of fish.

For most products, many countries have regulations stipulating that the product weight after hydrocooling or spray chilling cannot exceed the initial weight of the product when it first enters the chiller (e.g. for meat carcasses being spray chilled). It's also worth keeping in mind that surface drying can be a crucial factor in limiting microbial growth. If the surface remains wet, microbiological problems could reduce storage life.

3.1.3 Vacuum chilling

Products having a large surface area relative to their volume and the ability to readily release internal water are well suited for vacuum cooling. This is particularly the case for products with a high and open internal porosity, such as many baked goods, as well as leafy vegetables, whose structure facilitates rapid moisture evaporation. The products are placed in a vacuum chamber, typically operating at 530 to 670 Pa, and the resulting evaporative cooling removes heat from the product. Suitable products, such as lettuce, are typically cooled in 20–30 minutes per load. In general terms, a 5°C

reduction in product temperature is achieved for every 1% water that evaporates, as the latent heat of evaporation is high relative to the specific heat capacity. Pre-wetting is commonly applied to facilitate cooling without net loss of product weight. Vacuum chilling is a rapid cooling method, but it is inherently a batch process rather than a continuous one. The requirement for large vacuum chambers results in very high capital investment costs.

3.1.4 Other chilling processes

Cryogenic chilling The typical process involves placing the food in a cabinet or move it through an insulated tunnel while spraying it with liquid nitrogen or CO_2 which then boils or sublimes. Surface freezing of the product is the primary challenge when using "total loss" refrigerants such as liquid nitrogen or solid CO_2 for chilling. This method is only acceptable for products that can tolerate surface freezing. Systems that use cryogens to produce cold gas, which is passed over the food, are less efficient, but reduce freezing risk. While the initial investment for cryogenic chilling systems tends to be low, operating costs are high.

Chilling of liquids Chilling of liquid products, such as milk, beverages and fruit juices, may be carried out in several ways. One method is batch chilling. The food is chilled in a vessel, typically made of stainless steel, with a cooling medium circulating through the jacket of the vessel or through a coil immersed in the liquid. For closed vessels, a variation is where a vacuum is applied to reduce chilling time due to the additional evaporative cooling effect. In continuous systems, devices like multi-plate chillers or scraped surface heat exchangers are employed as heat exchangers to cool the flowing liquid product. Liquid products can also be chilled using air-last or hydrocooling after packaging into containers such as tetrapaks.

Chilling of liquids with particles A high proportion of ready meals are liquids with particles or mixtures of solids and liquids, such as meat or vegetables in a sauce or gravy. Most chilling systems used for solids or liquids (as described above) can be used, but the chilling rate is usually significantly lower because the chilling of the solids within the liquid is conduction controlled.

3.2 CHILLED STORAGE

3.2.1 Storage temperature

The chilled storage of perishable products is normally carried out at air temperatures between -1°C and +8°C. Higher temperatures are recommended for some fruits and vegetables, including those that are susceptible to chilling injury, while colder temperatures, about -3°C, are used for superchilling (see definition in ► **Chapter 1**). The aim is to maintain a constant temperature in chilled storage rooms, with minimal fluctuations. In some air-based systems, chilling and chilled storage occur in the same room. In these cases, it is important to prevent the chilling process for new products from affecting the storage conditions of previously chilled products.

For most food, the product should be cooled to a maximum of 1 to 2°C above the desired storage temperature before entering the chilled storage room. This requires little

or no heat to be removed from the product during storage. However, for certain fruits and vegetables, the heat of respiration requires continuous heat removal throughout storage to maintain product temperature and quality.

Once the food has reached its desired temperature, it is crucial to maintain a consistent temperature throughout the storage period. For some chilled foods, a variation of 1°C to 2°C, especially at temperatures around 0°C, may greatly influence their storage life. In some cases, lowering the storage temperature from +1°C to -1°C can double the storage life. Many chilled foods have an optimal storage temperature of about 0°C (slightly above the initial freezing temperature). For fruits and vegetables, it is particularly important to avoid freezing the food or storing at a temperature that is too low if the product variety is susceptible to chill injury.

Temperature variations can most easily be minimised when: the storage room has adequate insulation and refrigeration capacity, the temperature difference between the air-cooling system surface and the room temperature is kept low, the airflow rates are high enough to limit the air temperature change as it passes over the air-cooling evaporator, and the air distribution is sufficiently even. Irregular stacking, and/or products directly placed against walls, ceilings or floors will hinder the airflow. Most storage facilities have a space between the walls, the ceiling, and the stacked products, such as bollards on the floor to prevent pallets from being too close to the walls. Such air gaps facilitate air circulation around the exterior of the facility, intercepting heat entering through surfaces, lights and doors before it can reach product stacks.

Heat and moisture infiltration through doors can have significant impact by creating variations in storage conditions. Door protection systems (e.g. vestibules, air curtains or plastic strip curtains), and good door management and rapid acting doors (e.g. rapid-roll doors, can minimise the duration of the door's opening, which prevents large variations in temperature and relative humidity.

For long-term storage, the target is a maximum temperature increase of 1°C in the circulating air as it moves through the room, together with short-term fluctuations of less than 0.5°C.

Both time-related temperature changes at a given place and spatial temperature differences at a given time within the storage facility should be considered. Air temperature fluctuations over time tend to be larger in magnitude than the resulting time-related change in the product's temperature. Time-related temperature variations result from sources of heat, such as door openings, air entering via ventilation, the loading of hot products, and the type and precision of the air temperature control system. Temperature variations based on location are related to the proximity of large heat sources (e.g. doors and hot products), but also to air distribution uniformity and air-circulation rates.

For effective temperature control, the sensing element of the thermostat should be placed in a carefully chosen location: not close to or in a direct line with the supply air so that the temperature is representative of the average temperature in the room. In larger rooms, multiple sensors can be used with a control system considering both the average

and the variability of readings. For instance, it can increase air circulation in response to high variability and increase refrigeration if the average is too high.

3.2.2 Relative humidity

Most food held in chilled storage rooms that is unwrapped or in non-sealed packages lose water through evaporative mass transfer. This is controlled by several factors, including the surface-to-volume ratio, the vapour pressure difference between the food surface and the room's surrounding air as well as the air velocity above the product. However, an increasing number of chilled foods are protected against such desiccation by means of appropriate packaging solutions like plastic liners.

A high relative humidity in the storage room generally prevents excessive evaporative moisture loss and secondary effects such as shrivelling or wilting of fruits and vegetables. On the other hand, high relative humidity can also promote the growth of microorganisms and lead to condensation issues. Recommended relative humidities in the practical storage life tables are the ones that have been found to be safe for preventing microbial growth, despite some moisture loss being expected.

A relative humidity of at least 90% is desirable for most fruits and vegetables. Some vegetables, such as broccoli, lettuce, parsley, and spinach, are especially prone to wilting, and relative humidity levels well above 90% are recommended, unless protective packaging or other measures to restrict water loss are used.

During chilled storage of unwrapped meat, a relative humidity of approximately 90–95% is often recommended.

A few dry products are kept in chilled storage so caution must be taken to prevent water uptake. Specifically, onions, nuts, dried fruit, and dried fish are in equilibrium at 70% relative humidity (a_w = 0.70). If these are stored in chilled rooms with other products that readily evaporate water due to their high water content, they might get damaged by water absorption.

Paperboard packaging can significantly influence relative humidity, as it tends to absorb moisture if exposed to high relative humidity air and desorb moisture if exposed to low relative humidity air. Most products are packaged in paperboard that has previously equilibrated in low relative humidity air. As a result, paperboard tends to absorb moisture, thereby reducing the relative humidity of refrigerated facilities.

High relative humidity A high relative humidity is important for unwrapped food placed in chilled storage. It can be achieved through a combination of the following:

- Minimise air temperature as much as possible;
- Keep the temperature difference between the product and the air-cooling system's surface to a minimum;
- Use an air-cooling system with a large surface area and an appropriate control system to maintain a small difference between the air and refrigerant temperatures;
- Avoid using paperboard packaging for stored products, as they tend to be hygroscopic;

- As a last resort, increase the relative humidity of the room by evaporating water or introducing steam. Misters that emit a fine mist of water can be very effective humidifiers. They have the advantage of not introducing extra sensible heat at the same time, as is the case for steam humidifiers. Typical misting mechanisms include conventional high-pressure spray nozzles and ultrasonic transducers.

Low relative humidity In situations where it is necessary to lower the humidity in a chill store, it is best to control humidity and temperature independently (i.e. humidity control secondary to temperature control). In the case of humidity being too high, using a dehumidifier can help solve the problem. This issue may arise seasonally, such as in winter when the compressor only operates for short periods or in summer when door openings allow for the entry of highly humid air. The humidity can be lowered by introducing warm, dry air into the return air stream of the cooling system, thus forcing the cooling system to work for a longer period or at a lower temperature. This dries the air circulating inside the store, a process known as reheat dehumidification. Methods include using electric heating elements near the return side of the air-cooling system or operating some of the air-cooling coils semi-permanently in defrost mode, if they use the hot gas defrost method. These methods should be used as infrequently as possible, since they generate extra sensible heating loads in the refrigeration system. Other dehumidification methods include operating the air-cooling system at a lower refrigerant temperature, which will result in less frequent cooling but more effective moisture removal during operation. Another alternative is using a desiccant dehumidifier. Both methods have the disadvantage of increased energy use due to the lower refrigerant temperature, lowering the system's coefficient of performance (COP), while regenerating the desiccant requires more energy. The best method to reduce relative humidity is to minimise all sources of humidity entering the storage facility, particularly ambient air interchange through doors and moisture evaporation from products.

3.2.3 Air velocity

When storing unwrapped products, it is essential that there is enough air movement around and through the products to maintain a constant temperature. High air velocities increase moisture loss and appearance changes due to desiccation. Most of the airflow should be directed toward the exterior of the storage facility to capture heat entering through insulated surfaces, doors, and lighting.

For wrapped products, low air velocities are desirable to minimise energy consumption. It is recommended to evenly distribute air through ducting, air socks, or other methods, as well as through proper stacking and adequate package design.

For respiring produce and certain fermented products, it is essential to allow air to circulate throughout and around all parts of the produce in order to remove respiration or fermentation heat and emitted gases. However, the typical airflow rate used to remove respiration and fermentation heat and gases during storage is much lower than the flow-rate required to rapidly chill the product down to storage temperature.

For some chilling and chilled storage facilities, it can be challenging to get the airflow, air distribution systems and product stacking systems arranged such that all of the following conditions are simultaneously satisfied, where relevant:

- High air velocity above and through the product to enable its rapid chilling down to the storage temperature;
- Low air velocity above and through the unwrapped product at storage temperature to minimise desiccation;
- Intermediate air velocity over and through any respiring product at storage temperature to remove respiration heat and gases;
- Sufficiently high airflow rate to prevent significant temperature change in the air-cooling system and to ensure its efficient operation;
- Sufficiently high airflow rate and uniform air distribution to avoid local hot spots near heat sources.

3.2.4 Ventilation

Some foods develop strong odours, making it advisable to ventilate the room. When several types of chilled food are stored in the same room, ventilation may be necessary to prevent sensitive foods (e.g. dairy products, eggs) from picking up odours from other foods. Similarly, storing different varieties of fruits and vegetables in the same room may cause problems, as ethylene from some commodities can accelerate ripening in others, thereby adversely affecting their quality and shortening their storage life. In the case of respiring products with high respiration rate, as discussed in ► **Chapter 5**, active ventilation may also be necessary to prevent oxygen levels getting too low and/or carbon dioxide levels getting too high for worker safety in the storage facility. For ethylene sensitive products, such as climacteric fruits and vegetables, then ventilation and/or ethylene scrubbing may be necessary to keep ethylene concentrations low.

In many situations, sufficient air turnover is supplied by infiltration and door openings, but dedicated ventilation systems may be required for certain fruits and vegetables. When introducing fresh air, care should be taken to avoid condensation on the cold products by directing the air away from them. Note that directly blowing fresh ambient air over cooling coils can rapidly block them with frost, making it imperative to first blend fresh air with the bulk internal air before the cooling coils. The fresh air should be clean, uncontaminated and free of odour. The air replacement rate, commonly referred to as the rate of air changes per hour (ACH), represents the number of times per hour that a volume of fresh air equivalent to the volume of the empty room is introduced into the room.

In regions where the ambient temperatures are lower than the required storage temperature, ambient air can be used for cooling, a process known as “free cooling”. For example, in many temperate climates, it is usual to cool potatoes with ambient air at night. However, it is important to ensure proper temperature control to avoid chilling injury to sensitive products.

3.2.5 Insulation

Proper insulation of chilled storage rooms, and other facilities for storage and distribution is essential. The effectiveness of insulation is evaluated by the overall heat transfer coefficient of the walls. The K-coefficient is the heat transferred through a surface area in a given time frame, under steady-state conditions, for a particular temperature difference. In chilled storage rooms, a typical K-value of 0.3 W/(m^2.°C) or less is often used.

For heavily insulated transportation vehicles, K must be less than 0.4 W/(m^2.°C), see ▶ **Section 3.3**. A low K-coefficient reduces the transmission of heat into the room, leading to reduced temperature fluctuations and lower power consumption of the refrigeration system.

Various insulation systems are widely employed. The insulation should not contain any thermal bridges, and the internal cladding must be hygienic and easy to clean. Sandwich panels, in which the insulation material, typically polyurethane (PU), polyisocyanurate (PIR) or polystyrene foam, held between two layers of cladding, are often used. Special attention must be given to the fire risk such as installation of ultra-low oxygen systems if the store is fully automated or automatic sprinklers, and the foam should be self-extinguishing and/or contain a flame retardant. Furthermore, the insulation must have a complete vapour barrier on the outer surface to prevent it from becoming water logged over time.

3.2.6 Condensation

Condensation occurs when air comes into contact with surfaces at temperatures below the dew point of the air. Therefore, exposure of chilled foods to surrounding warm air must be minimised. For example, this is a problem during transport in hot or humid climates or in cases where chilled products have a surface temperature of 0°C or lower and are transferred to a storage room at 5°C with a relative humidity above 75%. In chilled storage rooms, considerable condensation may occur when warm or humid air enters the room via doors left open for longer than necessary. If air circulation is poor, the warm, humid air will mix into the bulk internal air more slowly, so it is more likely that the moisture will condense on the stored products and surfaces near the door, rather than on the evaporator coil.

Condensation on the product surface stimulates the growth of microorganisms. For food in tightly sealed packages with a low water vapour transmission rate (WVTR), condensation will be on the package, not on the food. Condensation may cause damage to some packaging (e.g. a loss of rigidity of untreated paperboard cartons).

3.2.7 Controlled atmosphere storage

Controlled atmosphere (CA) storage requires airtight chilled storage rooms where the atmosphere gas composition is actively adjusted and continuously controlled and regulated. By changing the proportions of gases present in the air, the shelf life of many products can be extended.

This type of storage is practical only for the chilled storage of fruits and vegetables, especially apples and pears (i.e. products that need to be stored for long periods). Controlled atmosphere storage is further discussed in ► **Chapter 5**.

3.3 CHILLED TRANSPORT

This is only briefly discussed in this book. For more complete information, the reader should refer to IIR publications on refrigerated transport (Heap, 2010; IIR and UNEP, 2025a).

Generally, the same principles as for chilled storage apply. However, it is usually more difficult to maintain proper temperature and relative humidity conditions due to loading, unloading, time spent in unrefrigerated places, etc. Also, it is more difficult to maintain adequate air circulation and distribution, as transportation vehicles are often loaded with as much product as possible for economic and load-stability reasons. In addition, it may be difficult, even for skilled personnel, to load and stack the cargo in transport or distribution vehicles in a manner that will always allow free circulation of air throughout the load.

As mentioned in the "Guide to Refrigerated Transport" (Heap, 2010), the ATP Agreement specifies that transport between two contracting countries shall be undertaken only in equipment certified under the ATP. The ATP requirements include tests on the overall K-coefficient of the insulated body and on the performance of the refrigeration system. According to these requirements, usually insulated containers or vehicles have a K-coefficient below 0.70 W/(m^2.K), and heavily insulated vehicles (e.g. for transport of frozen as well as chilled products) have a K-coefficient below 0.40 W/(m^2.K). The ATP agreement includes requirements for control of product temperatures during transport, see ► **Table 2.2**.

In long-distance transport, temperature recording is common and frequently mandatory. In local distribution, a delivery truck may stop at several points during a single trip; the frequent door openings may cause increases, or at least fluctuations, in air and product temperatures in the truck. In such cases, temperature recording is made more difficult, partly because it is hard to determine the temperature sensor's position most representative of the product in the vehicle. However, it is still recommended, as some monitoring is better than none.

3.4 RETAIL DISPLAY CABINETS

Retail display cabinets are essentially small-scale storage facilities, so the challenges associated with storage are accentuated. Retail display is often considered the weakest link in the professional chill chain, as it represents a compromise between what is needed to maintain proper temperature control and ease of access for potential purchasers.

In retail stores, chilled food, especially non-respiring food, are often presented in horizontal open cabinets, or vertical multi-deck display cabinets with either single or twin air curtain systems to minimise air spill. Both designs use forced air circulation. As the air entering the display case from the cooling system may be as cold as -2°C to -4°C, care

must be taken to prevent any potential freezing of the product. The return air to the cooling system will be warmer, often around 4°C or 5°C or higher. In addition, considerable spatial or time-related temperature differences may occur in open-display cabinets.

The products in the front of open cabinets may be several degrees warmer than the air circulating around them due to ambient air ingress and heat radiation from the surroundings.

Open cabinets need frequent defrosting, resulting in increased product temperatures, especially in packages exposed to radiant heat and ambient air ingress. Passive or off-cycle defrosting is recommended, as it requires less energy. After defrosting, it takes some time for the product temperature to decrease. The net result, supported by several temperature surveys, is that many chilled foods are displayed at temperatures that markedly increase the rate of quality deterioration and the growth of spoilage and/or pathogenic microorganisms.

Vertical glass-door cabinets are becoming increasingly popular for display of chilled foods, such as dairy products. These cabinets provide better temperature conditions than typical open cabinets. Glass-door units usually exhibit less temperature fluctuation and consume less energy than their open-fronted counterparts. Many countries are introducing regulations restricting the use of vertical-display open cabinets. As a result, vertical glass-door cabinets are now being used for a wider range of products than they were in the past. In many countries, display cabinets must meet Minimum Energy Performance Standards (MEPS) and/or energy labelling requirements (IIR and UNEP, 2025b).

Unwrapped meat, fish and delicatessen products, e.g. sliced meats, pâté, and prepared salads can be displayed in glass-fronted cabinets (service counters or "serve-over" cabinets) with natural or forced-air circulation. For unwrapped products, appearance is often the factor limiting the display life and deterioration in appearance is often due to dehydration/desiccation. Thus, evaporative moisture loss is a very important factor, necessitating a high relative humidity, low air velocity and low air temperatures in the cabinets. Natural air circulation minimises dehydration but offers insufficient control of the product temperature. Forced-air circulation enables efficient temperature but can increase moisture evaporation from unwrapped products. Some cabinets are equipped with, or retrofitted with, active humidification systems to increase air relative humidity in order to reduce dehydration. The choice of display system depends on the type of product to be displayed, its sensitivity to temperature and dehydration, whether it is wrapped or not, and the duration of its exposure in the equipment.

3.5 MONITORING

The cost and size of monitoring sensors have steadily reduced due to advancements in electronics and battery technology. Combined with the near-ubiquitous nature of Internet access via WiFi and other communication protocols (the Internet of Things, IoT), has made real-time monitoring of products, storage conditions, and refrigeration system performance commonplace. Many products are monitored as they move through the chill chain, allowing for traceability of both the storage conditions and the products themselves.

The most commonly measured variable is temperature, since it is the key parameter affecting product quality. Other variables often measured are relative humidity,

refrigerant pressure and refrigeration system energy use. Sensors that directly measure product quality aspects are also emerging for some products (e.g. hyperspectral sensors).

These monitoring systems allow better control of storage conditions and refrigeration systems. They can also identify "breaks" in the cold chain earlier, so that they can be rectified before the impact on product quality is large. They can also manage or separate affected product so that product quality and market value losses are minimised. The use of temperature-time indicators and temperature logging is covered further in ▶ **Section 2.2.4**.

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Chapter 4

Modelling

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The increasing power and availability of computers have led to a surge in the use of mathematical modelling and simulation to optimise the design of chill chain processes. User-friendly computer programmes have been developed that enable the calculation or prediction of important parameters such as chilling time, weight loss, temperature distribution, refrigeration system performance, changes in quality attributes, and microbiological growth. Computers are also integrated into the control and monitoring programmes of many food processing and storage plants, and in the design and optimisation of refrigeration machinery, cold stores, air distribution systems, etc.

In spite of the large number of models proposed in research literature, no single methodology has been widely accepted as a standard. Further, development of models is continually evolving, and this is reflected in the frequent publication of new approaches or suggested improvements to existing models. Therefore, those seeking to use predictions to aid in the design or operation of a chill chain must use their own judgment in choosing an appropriate prediction method for their particular circumstances.

It is expected that models will continue to be developed and will be increasingly accurate and reliable. The growing adoption of machine learning (for example, AI-supported models) is likely to have a significant impact on predictive modelling. However, it is important to acknowledge the limitations of such techniques regarding the quality of the learning data sets. As machine-learning/AI model development evolves, it is likely that they will become more widely used by industrial organisations undertaking chill-chain activities.

Modelling requires high knowledge across a wide range of competencies, including mathematics, physics, chemistry, biology, food science, computer science, and data science. As a result, a collaborative approach is required in model development and implementation. Along with helping the chill chain process design, modelling can also be used to reduce the cost of research and operational experiments (for example by allowing interpolation or extrapolation of existing data). Further, it can anticipate operational problems (for example, preventative maintenance if onset of abnormal conditions are detected), or optimise operating systems (for example, virtual trials of different control strategies or alternative product loading "what-if" scenarios). Nowadays, mathematical models of complete systems are often referred to as "Digital Twins".

The validation of any mathematical model is a critical step. It should include comparisons of model predictions with measured data. Important elements of validation include:

- **Using as broad a range of measured data as possible** for a wide range of operating conditions.
- **Estimating model input data independently from the model** using scientific rather than empirical approaches, wherever possible. Any parameters that are "fitted" to improve model prediction accuracy should be clearly identified.
- **Undertaking an analysis to show the sensitivity of model predictions to uncertainty in model input data**. Such a sensitivity analysis helps identify which input data need to be estimated more precisely and provides a better understanding of the important mechanisms for the system of interest.
- **Eliminating measured data points that appear to be "flyers" only if there are valid reasons**, as they may be valid points that show significant weakness in the model.
- **Using appropriate comparison metrics**. For instance, percentage differences are often a useful way to express deviations between predicted and measured value, with the exception of temperatures, where absolute differences must be used. Other useful statistics include root mean squared error and normal mean error.
- **Clearly stating the situations and conditions for using the model**. Beyond these constraints, model accuracy may be significantly lower.

The required accuracy of any model depends on its intended use. A reduced-order model may be adequate to explore control strategies to save energy, or for scenarios where time variability of temperature is more important than spatial variability. If spatial variability in temperature is important, a more complex modelling approach such as Computational Fluid Dynamics (CFD) may be needed to achieve the required precision.

4.1 CHILLING PROCESSES

There is a range of mathematical models available for simulating heat and mass transfer during cooling. These vary from simple formulae requiring straightforward calculation, limited to products of a simple shape under constant convection cooling conditions, to complex methods (e.g., finite-element methods) that can manage complex shapes with varying thermal properties, being chilled under time-variable conditions, taking into account evaporative moisture loss and radiation as well as convection and conduction. CFD approaches are increasingly being used, as they allow for predictions of the airflow around the product and the chilling facility, as well as conduction/convection within the product. The models require data on the thermal properties of the product and packaging (i.e., thermal conductivity, specific heat, and density), and the possible influence of the relevant temperature range on these properties. The models may also require information about the arrangement of the products within a package, the location of air vents (if any), pallet stacking arrangement, and the configuration of the forced air circulation system used in the cooling process.

Typically, computer programmes are used to solve models that predict temperatures in different parts of the product to be chilled, moisture loss and any other factors of interest. Predictions are usually made for different values of air temperature, air velocity around the product, heat transfer coefficients, taking into account how these variables are affected by packaging, air distribution, and product stacking systems designs and/or patterns.

In many situations, the accuracy of the heat transfer predictions is not constrained by the predictive method's accuracy as much as it is by the uncertainty associated with product variability (e.g., size variation, composition heterogeneity), or non-uniform initial temperature, and ill-defined cooling conditions (e.g., air velocity and air temperature variations). Careful estimation and validation of model input data is critical for the creation and deployment of models.

Many of the models developed in this area are intended for the air chilling of meat, especially carcasses or half carcasses, and for forced air cooling of fruits and vegetables in boxes or cartons. The purpose is to aid in the design and optimisation of the air chilling system and packaging design (i.e., throughput, product temperatures, moisture loss, energy consumption, capital costs, etc.). The models have usually been tested by comparing calculated results with experimental results.

Despite the availability of models, selecting the optimum chilling system can be challenging, as it is difficult to cope with the unforeseeable situations that occur in practice (e.g., irregular stacking, product variability, or the overloading of the cooling system).

Models are being continuously improved and extended to support the development and optimisation of emerging chilling technologies.

4.2 CHILLED STORAGE

More recently, models have been developed to estimate the air and product temperature variability in relation to position and time in chilled storage facilities. Such models must consider the airflow and distribution patterns within the facility in order to predict the air and product temperatures at every point inside. Product temperature modelling in such facilities is further complicated because product stacks in storage have complex geometry (e.g., palletised product items with a mixture of product, packaging, and trapped air).

Usually, such models use CFD approaches to predict the airflow, which often involves a combination of forced and natural convection. While CFD is rapidly improving, CFD models of airflow in storage facilities are often, at best, indicative of the real flow patterns rather than being highly accurate. The highly complex and ever-evolving product geometry, as the product is loaded and unloaded in a storage facility, makes such modelling even more challenging. Validating such CFD models is difficult and attempts are often only superficial. Therefore, the results of CFD models should be treated with caution. However, they can help understand general trends and patterns. This allows air distribution system designs and product stacking arrangements to be improved. In particular, air distribution models are valuable to identify airflow "dead" zones that could result in some products experiencing significantly higher temperatures than the rest of the storage facility.

Similarly to CFD models, many reduced-order models using lumped parameter or data-driven (including AI) approaches have also been used to model chilled storage. The purpose of such models is often to improve energy efficiency or logistical management of the complete system rather than getting detailed predictions of air and product temperature histories. An important advantage of reduced-order models is that they can often be run on relatively standard personal computers, whereas full CFD models usually require high-performance computers to achieve practical processing times. Other advantages of reduced-order models include fewer input data requirements and that model users do not need to have as much expertise as for CFD simulations (e.g., defining appropriate boundary conditions and managing domain discretisation – meshing – algorithms).

4.3 MICROBIOLOGICAL GROWTH

Predictive microbiological models allow computer-based quantitative predictions of microbial survival and growth in food. This process demands data on the survival, lag time, and growth rate of the target microorganism. These data are influenced by several factors (hurdles), especially storage temperature, the properties of the food product (i.e., water activity, salt content, pH, acid), the presence of preservatives (e.g., nitrite), and aerobic/anaerobic storage. Results from very large numbers of experiments, carried out by different research groups, have been collected in open access databases, such as Combase ("ComBase" 2024).

The relationship between temperature and growth rate (or generation time) can be evaluated in different ways, such as by means of the Ratkowsky (square root) formula shown in ► **Figure 2.1**. The computer-based models may be used to calculate the maximum growth rate or the time needed to reach a certain level of contamination.

Predictive modelling is applicable to all types of microorganisms, and several computer programmes are commercially available for this purpose. Most models have concentrated on microorganisms of major public health significance: *Salmonella typhimurium*, *Salmonella enteritidis*, other *Salmonella* species, *Listeria monocytogenes*, *Clostridium* species, *Bacillus* species, and Shiga toxin-producing *Escherichia coli* (STEC).

The models can usually handle multiple factors (hurdles) simultaneously. Thus, predictive microbiology can be used in the design of food and chill chain processes. Ross *et al*., 2014 provides an introduction to predictive microbiology and food safety.

4.4 QUALITY ATTRIBUTES

Modelling of quality attributes has also developed rapidly in recent years. Originally, such modelling generally used relatively simple kinetic approaches based on first-order rate equations and temperature-dependent rate changes, such as the Arrhenius equation or a constant Q_{10} (see ► **Chapter 2**). While well proven for many chemical reactions, such approaches can have significant limitations when applied to complex quality attributes such as texture or taste.

Many quality attributes are the complex outcome of many reactions and processes, of which some are chemical (such as rancidity), some biological (like respiration), and some are physical phenomena (such as moisture loss). Often, a single factor is rate-limiting (e.g., oxygen levels affecting respiration rates of some fruit and vegetables), allowing a simple model to approximate a very complex process. However, multiple factors may be significant (e.g., carbon dioxide and ethylene levels as well as oxygen for respiration), making the model more complex and involving various parameters and requiring additional model equations.

As understanding of these factors affecting quality attributes continuously improves, kinetic parameters for these factors are often included in these processes, rendering the model more mechanistic and less empirical. An example currently available is a model for the softening of kiwifruit, which includes models of respiration and ethylene biosynthesis. Even such sophisticated models still struggle to accurately account for the seasonal variability of biological products (e.g. that depend on growing conditions, including climate and soil type). The causal relationships for these effects are non-trivial. Robust parameter estimation requires large amounts of detailed data that is often unavailable. Alternatively, stochastic approaches have been introduced, resolving unknown and uncertain information of the process by estimating statistical confidence levels of the model's outcomes.

Despite their current limitations, kinetic models of quality attributes are useful tools to improve the understanding, design, and operation of chilled chain processes. Kinetic models can run in parallel to models that predict temperature-time profiles along the chill chain. Once properly calibrated, they can be used as virtual "sensors" to monitor quality changes in the supply chain. Such approaches are currently being proposed in so-called "digital twin" frameworks.

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Chapter **5**

Fruit and vegetables

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5.1 RAW MATERIALS

Fruit and vegetables differ from other foods in that they remain metabolically active after harvest. Biological processes such as fruit ripening, dormancy break and senescence will continue, contributing to changes in quality during storage. Senescence in fruits and vegetables is a genetically programmed process that continues after harvest. It is associated with increased respiration, transpiration, ethylene production or sensitivity, degradation of cell walls and membranes, pigment loss, and reduced resistance to pathogens. The rate of senescence is strongly influenced by temperature, atmospheric composition, and handling practices, making postharvest management strategies such as refrigeration and controlled atmosphere storage essential for extending shelf life.

Pest and disease activity will also continue after harvest, potentially compromising produce quality and food safety. Underlying biological activity, together with other effects such as transpiration, can result in physical, textural, flavour and visual changes in produce which can impact its marketability. Through chilling, produce respiration can be minimised to reduce both the depletion of energy reserves and the activity of wider metabolic processes that can contribute to quality and safety losses. Suitable management of storage temperature and humidity can also contribute to minimising postharvest stress stimuli which can also further reduce quality. While respiration drives metabolic ageing through energy consumption, transpiration primarily affects produce quality through water loss and associated physical deterioration.

Optimum storage conditions will vary significantly between product type and cultivar. Other factors — particularly pre-harvest environmental conditions and maturity at harvest — will also contribute to variation in optimum conditions. Different production conditions, e.g. climate, growing areas, irrigation, the use of fertilisers and pesticides in the field or in the orchard, may have a pronounced influence on the quality and storage life of fruit and vegetables. Also, inappropriate storage conditions may result in chilling injury through over-cooling, changes in flavour due to low oxygen stress or increased spoilage through accelerated rates of senescence.

5.1.1 Maturity stage at harvest

In addition to pre-harvest influences, the state of a product at harvest will influence expected behaviour and storage requirements. Fresh products will travel through a natural trajectory of development, maturity and senescence, such as the progression of unripe fruit to ripe to overripe. Produce may be harvested at any point along this progression depending on type and intended supply chain, although ongoing biological activity may mean developmental progression will continue after harvest and can be influenced by postharvest treatment.

The biological and commercial maturity may vary significantly between products and supply chains, and understanding the appropriate maturity indices is crucial for optimising harvest timing to ensure optimum quality and shelf-life for fruit and vegetables. Biological or physiological maturity is where developmental cycles reach their zenith (e.g. fruit ripening), or horticultural maturity where produce is ready for marketing/consumption. For example, broccoli represents immature flower buds, which are consumed before reaching biological maturity (flowering/fruiting).

While some products may be harvested biologically mature (e.g. strawberry), others may be harvested when unripe in anticipation of ripening before consumption whilst enhancing robustness for an extended supply chain. Alternatively, products may be harvested for consumption in an immature state (e.g. broccoli), for which continued development would be undesirable.

Maturity state is specific to each product and intended supply chains, and this should be accommodated in the design of postharvest management strategies. Typical optimum will slow or prevent undesirable biological development to forestall adverse quality

changes. However, postharvest management should also be carefully managed to avoid adverse effects. Excessively cold storage temperatures will result in damage from chilling stress in vulnerable products (e.g. banana) or result in reducing sugar development in potato which reduces suitability for processing. Where modifications to storage atmospheres or ethylene management are utilised, off-flavours or impaired ripening after storage may occur under certain conditions.

Some commodities, such as non-climacteric fruits, which do not exhibit a postharvest rise in respiration or ethylene production and therefore do not continue to ripen after harvest (e.g. citrus, grapes, strawberries), are harvested mature and the purpose of chilling is to reduce respiration and to retard further ripening. In contrast, many climacteric fruits, characterised by a pronounced increase in respiration and ethylene production during ripening (e.g. banana, apple, tomato), are harvested or picked unripe, and chilling must suppress the ripening process. Cultivar choice can significantly impact storage life, either through reducing senescence or minimising dormancy break.

The correct harvesting time depends on the physiological stage of cultivar of the product type, of the production region and on the expected time until consumption or processing. Fruit and vegetables can be harvested at optimal maturity if they are intended for local sale/processing with consumption within a few days after harvesting, noting that the optimal ripeness also depends on the specific product being made from the fruit or vegetables. Produce intended for long-term storage should, in most cases, be harvested at a stage of not too advanced maturity. Unless a very high degree of protection (packaging) is used, produce cannot withstand long-distance transport if fully ripe at the time of harvest.

Determination of optimum maturity for harvest can be judged against a range of maturity indices, including chemical or physical quantities such as soluble solid content (°Brix), starch/sugar content, titratable acidity, texture and specific gravity in addition to subjective measures such as colour or shape.

5.1.2 Treatment before chilling or chilled storage

Most fruit and vegetables are very sensitive to mechanical stress and must be handled with care during harvest, external and internal transport, sorting, etc. to maintain the natural protection of the skin against microorganisms and prevent bruising/mechanical damage. This applies to the field or orchard, but also after the chilling process, i.e. throughout the chill chain. It is important to remove damaged produce, especially any exhibiting mould which can affect healthy fruit and create off-flavour. Where produce is stored for extended periods, grading should be repeated to support this.

Washing is recommended for several types of fruit and vegetables. Washing may be performed using chlorinated water, or water with fungicides, but the use of such compounds is limited by regulations, which vary widely from one country to another. Superficial scald of apples may be prevented by pretreatment with diphenylamine (DPA) or ethoxyquin (stop-scald). Where washing is used, effective drying must be maintained to minimise disease development through increased humidity.

Dormancy break leading to the sprouting of potatoes or onions may be reduced by low-dose irradiation, provided that local regulations permit this treatment. Chemical treatment may be allowed in some countries; however, although chlorpropham was widely used, it has now been largely deregistered and organic alternatives (e.g. caraway seed oil and mint oil) have shown beneficial effects in reducing sprouting.

A wax covering has been recommended for some special cases (citrus fruit, apples). Many citrus fruits are washed, disinfected and waxed (and sometimes fungicides are incorporated) before packing and storage.

Treatment, especially surface treatment, with diphenyl, ortho-phenyl-phenol, thiabendazole (TBZ), benomyl and other fungicides is allowed in several countries for citrus fruit, bananas, and some other tropical fruits. Sulphur dioxide (SO_2) is commonly used to inhibit the growth of *Botrytis cinerea* on grapes and Phostoxin (PH_3) fumigation used as well for date disinfestation.

5.1.3 Minimally processed fruits and vegetables

Since 1990, the production of fresh cut, packaged vegetables and/or fruit products, requiring minimal or no further processing prior to consumption, has shown remarkable growth in several countries. Consumers and institutions recognise the convenience of minimal preparation, minimal waste and the maintenance of a fresh-like quality, often associated with the use of natural ingredients; however, these products may still include permitted additives (e.g., calcium salts or acidulants) to preserve texture and quality, rather than being free of additives. This type of product has several different names, including minimally processed, ready-to-use, ready-to-eat, fresh-cut, prepared cut, salads, or “grade 4” fruit and vegetables.

Washing, cutting, slicing and mixing of fresh fruit and vegetables are the main steps in preparing such products, but peeling, grating, chopping, or shredding may be included. In some countries washing is performed using chlorinated water or ozonised water to reduce microbial load, whilst treatment with antioxidant washes, particularly antioxidant soaking in the case of fruit (e.g. ascorbic acid), can retard browning.

The product is packaged in plastic trays or containers, sometimes overwrapped with high-permeability plastic films, but more frequently in less permeable plastic packaging, thus allowing modified atmosphere packaging to be used (see ► **Section 5.6**). For juices, airtight food grade containers with minimal headspace are preferred and they may require pasteurisation unless labelled and handled as fresh.

Tissue disruption or wounds produced by processing (peeling, cutting, slicing, etc.) cause exudation of cellular juices, favouring microbial development. Several pathogenic bacteria may grow in minimally processed products, and processors should ensure that microflora present on whole vegetables or fruit do not present a hazard when used in a prepared, packaged food. Generally, prepared cut produce spoils faster than whole produce. The factors, besides microbial spoilage, that shorten the practical storage life are enzymatic browning, surface discolouration and senescence caused by continuous

respiration and the production of ethylene. A practical storage life of more than 2 weeks demands storage at 5°C or colder, good microbial quality of the product when packaged, and the use of modified atmosphere packaging (enriched CO_2 and/or reduced O_2 concentrations), vacuum packaging, or similar packaging techniques. Some of the newer non-thermal methods, e.g. the use of bacteriocins or competitive bacteria (lactic acid bacteria), or high-pressure processing (HPP) treatment, could help improve microbial quality and safety.

For fresh fruit and vegetables, deviations from recommended chill-chain temperatures (most commonly storage at warmer-than-prescribed conditions) are frequent and inevitably lead to quality defects. In the case of minimally processed produce, temperature abuse additionally increases the risk of microbial growth and foodborne disease.

It is evident that extended storage, e.g. that achieved by means of modified atmosphere packaging, adds to this risk.

5.2 CHILLING PROCESS

Chilling is an essential tool to preserve product quality and safety through control of postharvest biological activity of both the harvest produce and accompanying microbial/pest load. However, careful control of temperature must be maintained across the supply chain in order to maximise quality retention.

Precooling As long as the product temperature remains high, respiration, transpiration and various other metabolic processes will be accelerated, generally leading to very rapid changes resulting in quality and safety decline. It is necessary to reduce the temperature of produce after harvest to maximise its storage life. Delay in cooling shortens the storage life of most commodities, especially climacteric fruits, which both produce and respond to ethylene; a plant growth regulator that increases the rate of ripening and senescence. High postharvest temperatures are also detrimental for non-climacteric fruits, as they accelerate metabolic activity and quality deterioration even in the absence of ethylene-driven ripening. The rate and final target storage temperature of the cooling process depend on the produce in question, the physiological maturity conditions of that item at the time of cooling, any potential chilling injury risk for that product, and the potential for freezing damage of the product. Stepwise cooling (cooling to an initial temperature, followed by later cooling to a lower temperature) can be employed to reduce the incidence or expression of chilling injury. Chilling injury is further covered in ► **Section 5.5**.

Precooling may be used in the field, i.e. before transport to a sorting-washing-packaging plant where the final chilling process takes place. Rapid precooling is more important in warm regions than in colder regions and is most important for products with high heat production (see ► **Table 5.1**). Precooling reduces the loss of water and slows down or inhibits the development of microorganisms.

The main chilling methods used in precooling and in the final chilling process are: hydrocooling by immersion or spraying with cold water, air blast cooling, a combination of hydrocooling and blast cooling (hydrair cooling), using a current of air containing a fine mist

of water, cooling by contact with ice, and vacuum chilling. More information on chilling methods can be found in ► **Section 3.1**.

Hydrocooling is very efficient and is suitable for most unpackaged fruit and vegetables. Air blast cooling is used for many products, e.g. strawberries, grapes, cauliflower, etc. It demands appropriate stacking.

Cooling by broken ice, in contact with the produce, or on top of the containers (top icing) is used mainly for lettuce, spinach, radishes, celery and cantaloup melons. Vacuum chilling is mainly used for vegetables with a large surface/volume ratio such as spinach, lettuce, cauliflower and celery. Often the product is pre-wetted to counteract dehydration loss. Care should be taken to avoid surface freezing.

Refrigerating capacity The required refrigerating capacity for the chilling process and for storing fruit and vegetables is influenced by specific heat capacity and by respiration heat:

- Specific heat capacity: most fruit and vegetables have a high-water content (about 90%) and a specific heat capacity of 3.5 to 4.0 kJ/(kg.°C) [0.85 to 0.95 kcal/(kg.°C)].
- Respiration heat (see ► **Table 5.1**). Heat production and CO_2 production are linked, as 1 kJ equals about 0.05 l of CO_2, when the respiration quotient is around 1. The values of respiration heat may vary quite considerably according to the cultivar, area of production, physiological state (i.e. ripeness), growing conditions and growing season of produce; moreover, data reported in literature vary considerably. In ► **Table 5.1**, the highest and the lowest values for measured respiration heat are given[1].

In the first cooling phase right after harvest, the specific heat capacity will be the dominant factor determining refrigerating capacity as field heat needs to be removed to reach the storage temperature in a sufficiently short time. Once the storage temperature is reached, the respiration heat remains the most important heat load directly related to the product. Because respiration heat production is strongly temperature dependent — lower temperature results in lower heat of respiration — it is important to store at the lowest temperature possible, especially for produce that will be stored for a long time.

1 Respiration heats often shown as a value based on maximum and minimum values. To compute heat evolution at harvest time, use either the highest figure or median one but not the low value.
Some data included for low temperatures which cause injury to certain cultivars.

Table 5.1 Respiration heat of some fruit and vegetables at various temperatures

Fruits	Respiration heat in kJ/(t.24h)			
	0°C	5°C	10°C	20°C
Apple				
early ripening	840–1,590	1,340–2,720	3,520–5,230	5,070–10,680
late ripening	460–920	1,170–1,420	1,760–2,680	3,770–6,200
Apricot	1,340–1,470	2,850–4,820	5,360–8,790	11,720–17,170
Banana				
green	–	1,880–4,440	3,430–8,460	7,540–13,400
ripening	–	3,430–5,070	5,610–10,130	8,165–20,940
Berries				
Blackberry	4,020–5,860	7,327–11,720	13,400–24,290	33,500–50,240
Blackcurrant	1,760–2,847	3,770–6,990	5,610–15,700	19,260–48,150
Blueberry	510–2,560	2,310–3,080	5,890–8,970	13,330–22,290
Gooseberry	1,210–1,760	2,050–3,890	3,050–7,540	10,470–27,630
Raspberry	4,061–7,955	7,120–14,240	12,560–24,290	29,310–62,810
Redcurrant	1,170–1,720	2,050–3,980	3,020–8,170	10,470–26,800
Strawberry	2,630–4,020	3,768–7,960	7,750–15,160	15,070–25,960
Cherry				
sweet	1,340–1,840	2,390–3,890	3,310–8,580	13,400–19,050
sour	1,340–1,880	2,640–4,690	3,690–9,380	14,860–20,940
Citrus				
Grapefruit	420–920	920–1,300	1,590–2,180	4,400–4,820
Lemon	500–840	920–1,680	1,470–2,810	2,680–5,020
Orange (several cultivars)	420–920	920–1,630	1,800–3,020	5,820–5,950
Fig (fresh)	–	2,820–3,330	5,640–5,890	14,610–24,340
Grape				
American	770	1,280	2,050	8,460
Vinifera	260–510	770–1,540	2,050	–

Fruits	Respiration heat in kJ/(t.24h)			
	0°C	5°C	10°C	20°C
Kiwifruit	650–770	1,540–1,690	3,080–3,360	4,100–5,940
Mango	–	2,560–5,640	–	19,220–38,690
Melon	1,170–1,680	1,880–2,300	3,560–3,980	8,170–8,790
Papaya	–	1,030–1,540	2,890	–
Peach (several cultivars)	1,090–1,630	2,180–3,520	5,570–7,910	12,140–15,700
Pear				
early ripening	670–1,260	1,880–3,980	2,510–5,440	10,050–23,030
late ripening	670–920	1,510–3,560	2,010–4,770	8,170–18,840
Pineapple				
mature-green	–	510	1,030–1,790	4,870–7,430
ripening	–	3,430–3,890	5,650–6,070	7,120–7,540
Plum	1,170–1,840	2,510–5,650	5,020–10,890	10,470–20,100
Rhubarb	2,930–3,350	3,980–4,600	5,440–6,700	15,910–16,750
Walnut	210	420	840	1,260
Watermelon	–	770–1,030	1,540–2,306	4,360–6,410

Vegetables	Respiration heat in kJ/(t.24h)			
	0°C	5°C	10°C	20°C
Artichoke (globe)	3,840–11,530	6,660–15,380	14,100–25,110	34,590–59,710
Asparagus	5,020–5,650	6,700–7,330	12,560–13,820	25,120–31,400
Avocado	–	5,130–7,690	–	18,960–88,920
Bean				
Broad bean	1,680–2,510	4,820–6,490	9,210–12,560	27,840–33,920
Green bean	4,900–6,070	9,000–10,470	14,030–17,800	34,120–49,830
Beetroot	1,010–1,680	2,720–2,930	4,400–5,230	12,770–18,420
Broccoli	4,870–5,380	8,200–9,480	19,220–22,300	71,240–81,200
Brussels sprout	4,190–5,860	9,210–1,720	14,450–19,680	42,290–44,800
Cabbage				
White cabbage (spring)	2,430–3,480	4,530–5,490	7,460–8,500	9,220–10,470
White cabbage (winter)	1,260–2,090	1,880–3,560	3,140–4,610	9,210–10,470
Red cabbage (early)	1,970–2,510	3,980–4,400	6,070–7,120	14,240–16,330
Red cabbage (winter)	1,260–1,590	1,880–2,090	2,510–3,350	8,790–10,050
Savoy	3,980–5,440	6,490–7,540	13,400–15,700	33,500–37,680
Carrot (topped)	840–2,430	2,430–3,350	2,720–3,770	7,746–11,720
Cauliflower	2,090–5,440	4,610–6,700	10,680 – 11,930	26,380–34,750
Celeriac	1,260–2,090	2,720–3,980	4,610–7,330	10,680–12,560
Celery	1,150–1,790	2,090–2,820	5,030–7,000	16,400
Corn (sweet with husk)	7,690–13,070	11,020–21,270	26,650–30,750	68,670–79,690
Cucumber	1,630–1,760	2,090–2,930	4,400–5,230	13,190–15,070
Endive	9,210–11,510	15,910–17,590	21,560–24,080	44,380–47,730
Garlic	1,880	3,980	6,070	13,190
Green pea (in pod)	7,540–9,000	13,400–16,330	17,170–23,030	49,407–55,687

Vegetables	Respiration heat in kJ/(t.24h)			
	0°C	5°C	10°C	20°C
Kale	2,180–2,850	3,560–4,400	5440–6,700	13,610–16,480
Kohlrabi	1,970–2,300	2,930–4,400	5,020–5,650	8,790–9,840
Leek	3,060–4,610	11,100–13,190	23,660–24,700	46,890–51,080
Lettuce (leaves)	4,870–6,920	6,150–8,970	8,200–11,790	21,010–30,490
Mushroom	9,840–10,470	12,770–13,820	20,940–21,770	51,920–54,850
Onion	1,010–1,680	1,340–2,180	1,970–2,930	3,980–5,020
Parsley	7,690–10,250	13,580–19,480	21,780–42,020	50,220–57,660
Pepper, sweet	–	2,560	3,590	11,280
Potato	920–2,260	1,050–1,680	1,420–1,880	2,090–3,770
Radish, red	4,820–5,230	6,910–7,540	8,580–9,630	25,960–27,634
Rutabaga	1,260–1,470	1,680–2,720	2,390–4,610	8,790–10,260
Spinach	5,230–7,120	11,100–17,170	18,000–27,010	54,430–77,460
Tomato				
mature-green	–	1,280–2,050	3,080–4,610	7,180–10,510
ripening	1,170–1,510	1,680–2,300	2,720–3,560	6,910–8,790
Turnip (root)	1,540–2,310	2,430–2,560	3,330–4,870	6,150–6,410
Watercress	3,840–6,660	11,280–12,560	23,320–31,010	77,390–89,170

Source: IIR (2000)

5.3 STORAGE, TRANSPORT AND DISPLAY

After the chilling process, the produce must be continuously held at a low temperature.

The principal parameters in the cold store are the temperature, humidity and speed of the air, the composition of the atmosphere, and the amount of ventilation (air replacement). Generally, fruit and vegetables should not be exposed to temperatures below their initial freezing point, which for most products is around -1°C.

Fresh cut fruits and vegetables and juices should be kept at 0–4°C to minimise microbiological growth, as temperatures above 5°C can increase the risk of pathogen proliferation such as *Listeria monocytogenes*. Increased microbial load can be indicative of non-compliant temperatures or prolonged storage. These products should be consumed within 3–7 days depending on the packaging utilised.

For most commodities, a reduction in product temperature of 8°C will reduce the rate of respiration by a factor of 2. After the chilling process, the temperature of the produce should be kept constant, as fluctuations may cause an increase in the rate of moisture loss.

The containers of produce should be stacked in such a way that a suitable circulation of air takes place between, or even through, the packages or containers throughout the stack. This is particularly important if the produce generates a lot of heat, e.g. asparagus, strawberries or peas. Adequate ventilation during cooling will avoid localised chilling damage due to cold pockets as well as quality degradation because of hot spots.

Produce may be stored either in normal storage rooms, or in rooms with a controlled atmosphere, see ► **Section 5.4**.

Storage of different kinds of produce (mixed loads) in the same room is possible if they all tolerate the same temperature, and if they do not influence each other, either by tainting or by accelerating ripening by giving off ethylene.

Citrus fruit, potatoes, onions, celery and certain other produce give off strong odours and may give off-flavour to commodities such as apples, pears and melons, and to other foods, e.g. butter, milk and nuts. Ethylene, a gaseous hormone released mostly during climacteric fruit ripening, can accelerate ripening in unripe fruit or promote senescence in ethylene sensitive produce. Products which produce high volumes of ethylene (e.g. apple, tomato, banana) should not be stored with produce sensitive to ethylene such as Brassica crops and unripe produce. Systems capable of accurately monitoring ethylene concentrations are now available and can be used to optimise ventilation and ethylene removal strategies, including chemical and photocatalytic scrubbers (e.g. FAO, 2003; Caprioli and Quercia, 2014). Such control is particularly relevant in closed or poorly ventilated storage environments, where ethylene can accumulate to levels that adversely affect product quality.

As mentioned in ► **Section 3.2.2**, the relative humidity of the atmosphere around the produce is important for produce that is normally unwrapped. Where relative humidity is too low, this leads to weight loss, rapid shrivelling, wilting, etc.; a high relative humidity

will reduce or prevent the loss of turgidity and reduce water loss, but will, especially if condensation on the produce occurs, favour growth and spread of microorganisms, particularly moulds.

For some fruit, fungicides may be used if permitted. A relative humidity above 90% is recommended for most fruits and vegetables.

For dry fruit, onions, etc. the relative humidity should not exceed 70%. In some cases, 50% is the recommended maximum relative humidity and lower thresholds for freeze-dried produce.

In closed rooms, the atmospheric composition may be modified by the respiration of the produce, and by the release of ethylene and other volatile substances. This may lead to quality defects, physiological injuries, see ► **Section 5.7.2**. Thus, a certain supply of fresh air (ventilation) is needed, measured by the ratio of volume of fresh air compared with the volume of the room. The ratio highly depends on the produce and its respiratory activity; it can be less than one air change per day, or 2 to 3 air changes per hour.

5.4 CONTROLLED ATMOSPHERE STORAGE

5.4.1 Principle

Controlled atmosphere (CA) storage involves a reduced concentration of oxygen and/or an increased concentration of CO_2 around the produce. CA storage may have a favourable effect on practical storage life, provided that an appropriate temperature, relative humidity, and air circulation are maintained in the storage room.

5.4.2 Atmospheric effects

Reduction of the oxygen concentration slows down all oxidative metabolic processes (respiration), including ripening, softening, senescence and ethylene production. A low oxygen concentration can be very effective in improving the storage life and quality. At an oxygen concentration that is too low, fermentation may occur, leading to unacceptable quality, due to the formation of ethanol, acetaldehyde, etc. The optimal oxygen concentration selected is generally around 2% and depends on storage temperature, product type and condition.

An increase in CO_2 levels slows respiration and may, at the correct storage temperature, reinforce the effect of decreased oxygen concentration. At CO_2 concentrations above 4–5%, microbial activity will be slowed. The effect of a high CO_2 concentration varies for different products, but the sensitivity is generally higher at lower oxygen concentrations.

5.4.3 Implementation

In controlled atmosphere storage, desirable atmospheric composition can be achieved through the introduction of nitrogen and/or CO_2, or through accumulation from background respiration. The rate of implementation, and the need for pre-conditioning, can vary between product types. Optimum controlled atmosphere storage will minimise

aerobic respiration but without stimulating anaerobic metabolic processes such as fermentation, which will occur under excessively low oxygen conditions. Inappropriate controlled atmosphere conditions can result in flavour changes due to the accumulation of fermentation products, and other quality changes, such as internal/external discolouration or physiological disorders such as bitter pit in apple. Generally, the oxygen concentration is low, and the CO_2 concentration is moderate, e.g. 2% O_2 and 4% CO_2, see ► **Tables 5.3** to **5.9**. However, optimum gas composition can show significant variation. Furthermore, a fixed ("flat-line") approach to atmospheric composition may be suboptimal. Adjusting atmospheric conditions in response to produce respiration activity (e.g. dynamic controlled atmosphere) allows controlled atmosphere treatments to be aligned with produce condition, thereby maintaining optimal control over respiratory behaviour.

In modified air storage, the atmosphere is left to be naturally modified by the respiration activity of the product. The sum of the concentrations of CO_2 and O_2 is around 21%, as in air. The composition is maintained by means of controlled ventilation and air replacement. A "naturally" modified atmosphere is also created in many plastic packages, see ► **Section 5.6**.

When modified atmospheres are implemented, stores must remain sealed between harvest and use, as the need for pre-opening ventilation prevents sequential access. Sealed stores can also represent a safety concern, as low-oxygen environments are dangerous and must be secured (locked) and occupational health and safety rules must be observed.

5.4.4 Applications

Controlled atmosphere storage is used mainly for apples and pears but can also be used for cabbages, kiwi fruit, etc. The tendency is to increase the number of products in controlled atmosphere storage rooms and to use controlled atmosphere in transport, e.g. in refrigerated containers.

5.4.4.1 Types of controlled atmosphere used

The different types of controlled atmosphere can be classified into three types depending on the level of control they achieve.

A first type can be denoted as ventilated CA. This was one of the first CA methods and is rarely used today. The atmosphere is naturally modified by the respiration activity of the produce, resulting in a mixture of O_2 and CO_2 concentrations totalling 21%. When O_2 concentrations become too low, fresh air is introduced into the room, hence the name ventilated CA. This type doesn't need much equipment – only an airtight room – and was, in many cases, operated manually.

A second type can be denoted as real controlled atmosphere, as it involves a real control system, both controlling the O_2 concentration level and CO_2 concentration level independently. Accurate O_2 and CO_2 sensors monitor the atmospheric concentration inside the room. Deviations from setpoint values are corrected using CO_2 scrubbers to take out excess CO_2. Fresh air is introduced into the room if O_2 becomes too low. Typically, nitrogen separators are installed to introduce nitrogen into a room at the start of CA

storage, rapidly establishing the desired low oxygen concentration. As CA equipment has become more efficient over the years, improved room tightness allows lower O_2 concentrations to become feasible. This resulted in many acronyms denoting this evolution. CA types you can find nowadays are denoted as LLO (Low-Level Oxygen), ULO (Ultra Low Oxygen) and HLO (Hyper-Low Oxygen). These are always accompanied by efficient CO_2 scrubber systems that keep CO_2 under 3% and, in many cases, as low as 0.5%. However, they all control the O_2 and CO_2 levels to some constant value that is mostly set once and stays the same during the whole storage period.

A third type is called Dynamic Controlled Atmosphere storage (DCA). Contrary to the former systems, the O_2 and CO_2 level setpoints can vary depending on the physiological state of the produce. Most of the time, only O_2 levels are varied, and CO_2 is kept constant. Different systems exist; they vary in the way the produce's physiological state is measured. The first developed systems lowered the O_2 concentration gradually and tried to measure ethanol produced due to fermentation. When ethanol was detected, oxygen levels were increased again. Another system measures the low oxygen stress using chlorophyl fluorescence. When stress is detected, the O_2 level is increased slightly to remove the stress. These two systems need extra dedicated sensors compared to the non-dynamic CA. A third type of DCA, called RQ-DCA, does not need any additional sensors and estimates the RQ or respiration quotient of the whole room using the existing O_2 and CO_2 sensors already in place. Once more, O_2 levels are gradually lowered until the respiration quotient (RQ) increases above 1. This indicates the onset of fermentation, at which point oxygen levels are raised. When RQ values evolve close to 1 again, the O_2 concentration is decreased again, resulting in a dynamic O_2 profile during the storage period. When rooms are airtight enough, O_2 levels below 1% towards 0.5% are reached.

5.4.4.2 Controlled atmosphere storage rooms

The rooms used for controlled atmosphere storage must be as gas-tight as possible, with impermeable wall finishes. The normal requirements for refrigerated storage rooms must be met, i.e. suitable insulation, water vapour barrier, etc. There are specific requirements and special methods for measuring the air-tightness of controlled atmosphere storage rooms (IIR, 2006).

In controlled atmosphere storage, the regulation and maintenance of the desired atmosphere require special equipment. It is common practice to provide the desired atmosphere rapidly after the produce is placed in the storage room and the doors are closed (rapid CA). Special techniques or equipment are used to rapidly reduce oxygen concentration. In the early days of CA, catalytic burners (often using propane) were used to lower the O_2 concentration rapidly. However nowadays more modern technology using selective adsorption or selective diffusion of gases through membranes is used either on the atmosphere of the room itself or to make nitrogen from fresh air to flush into the rooms. The concentrations are rigorously controlled and kept as close to setpoint levels as possible. Nowadays all CA systems have accurate O_2 and CO_2 sensor units. One measurement unit serves several rooms. At set intervals (one to several hours), the room is measured and needed actions are taken automatically. If CO_2 levels are above setpoint, the

atmosphere in the room is fed through external equipment where CO_2 is absorbed by chemical or physical means, e.g. scrubbers or active carbon. If the oxygen concentration is too low, fresh air may be introduced. Leaky rooms might suffer from too-high O_2 levels because more O_2 leaks into the room compared to the O_2 consumed by the produce respiration. Trying to solve this by injecting nitrogen is not efficient. Nitrogen injection to lower oxygen concentrations can only be used efficiently when O_2 levels are still high at the start of CA. The pull-down process is most of the time stopped between 10% and 5% of oxygen. Lower O_2 levels can only be achieved efficiently by the natural respiration of the produce.

The ethylene concentration must be low, especially for sensitive produce such as bananas and kiwifruit. Ethylene may be removed in several ways; in most cases, the method used is oxidation of ethylene. In addition to removing ethylene from the storage atmosphere, ethylene effects can also be reduced by treatment with ethylene action inhibitors such as 1-methylcyclopropene (1-MCP). This compound binds to ethylene receptors in the produce and can delay ripening and senescence, helping maintain firmness and quality for longer storage periods (Blankenship and Dole, 2003; Watkins, 2006). 1-MCP is commonly applied as a gas treatment prior to or at the start of storage, and its effectiveness depends on factors such as cultivar, maturity stage at harvest, temperature, and storage atmosphere composition. While 1-MCP can be highly beneficial for some commodities (e.g. apples, pears, and kiwifruit), it may be less appropriate where uniform ripening is required after storage.

Other synthetic plant growth regulators are also used in postharvest systems to manage ripening and senescence processes. For example, aminoethoxyvinylglycine (AVG) and aminooxyacetic acid (AOA) inhibit ethylene biosynthesis, while gibberellins (e.g. GA_3) can delay senescence and maintain firmness in certain fruits. Cytokinins may be applied to retard leaf yellowing in leafy vegetables, and auxin-based treatments are sometimes used to reduce pre- and postharvest fruit drops (Kader, 2002; Wills *et al.*, 2007). In addition, postharvest treatments, such as fungicides, edible coatings, and calcium applications, are widely used to control decay, reduce moisture loss, and maintain structural integrity (Wills *et al.*, 2007). The suitability and effectiveness of these treatments depend on commodity type, intended storage duration, market requirements, and regulatory approval in the target region.

Controlled atmosphere storage necessitates controlled temperature and gas composition. Sometimes different gas compositions are proposed by different experts for the same cultivar, and it is difficult to choose between them. Optimal storage conditions for the same cultivar might also differ when grown in different regions or climates. Some examples of controlled atmosphere are shown in the practical storage life tables in ▶ **Tables 5.3** to **5.9**.

5.4.4.3 Hypobaric storage

In hypobaric storage, a pressure of around 0.1 bar is provided. This reduces the oxygen content around the produce, with the same beneficial effects as in controlled, or modified, atmosphere storage. A certain degree of air replacement is used to remove volatile

substances such as ethylene. A high relative humidity should be used but is technically difficult to accomplish. The principle is also used in transport, mainly for expensive products such as flowers.

Controlled atmosphere storage is only effective when applied in the long-term. Stores will require ventilation when opened for marketing, after which the produce should be stored and marketed under normal air conditions and will be subject to normal biological behaviour.

5.5 CHILLING INJURY

For several types of fruit and vegetables, exposure to temperatures below a critical limit, but above the initial freezing temperature, may result in chilling injury. Typical symptoms of chilling injury are internal or external browning, superficial spots, failure to ripen, development of off-flavour and off-taste, etc. Fruit and vegetables from tropical and subtropical zones are the most susceptible to chilling injury, as are several Mediterranean products.

The extent of damage depends on the temperature, duration of exposure and the sensitivity of the fruit or vegetable. Some commodities have high sensitivity, while others have moderate or low sensitivity.

► **Table 5.2** indicates the critical temperature for some commodities. More information may be found in the practical storage life tables at the end of this chapter. It must be noted that for each commodity the critical temperature depends on species and/or variety. In some cases, unripe fruit is more sensitive than ripe fruit.

Chilling injury can commonly arise under conditions where control facilities are limited or subject to failure (e.g. during transport or interfaces between supply chain stages).

5.6 PACKAGING REQUIREMENTS

Transport packaging Secondary packaging (boxes, crates, cartons, etc.) plays a protective role against mechanical handling, dust, insects, infection by fungi, etc. The packaging can also diminish the rate of loss of water or hinder gaseous exchange and thus modify the composition of the atmosphere around the produce. The increasing use of plastic films of various sorts is an important development in packaging (box liners, gastight or perforated bags, pallet covers), giving a partially modified atmosphere.

Retail packaging (prepacking, primary packaging) maintained up to the point of consumption has the advantage of maintaining high relative humidity around the produce, preserving its appearance and freshness, reducing weight loss, and increasing storage life.

In plastic packaging, the atmosphere inside the pack (microclimate) will change due to respiration. The composition of the created atmosphere depends on the permeability of the plastic material to gases, on the variety (respiration rate), on the storage temperature, on the ratio of product weight to packaging area, etc. This type of packaging may be called modified atmosphere packaging. Flushing the package with the desired gas mixture before sealing is often used in modified atmosphere packaging. Packaging inserts are also available, which can locally modify gas composition through ethylene or oxygen removal.

Table 5.2 Critical temperatures under which chilling injury may develop

Commodity	Critical temperature (°C)
Aubergine	8
Avocado*	4–10
Banana	12–14
Bean (green)	6–7
Bell pepper	7–9
Cucumber	7–12
Grapefruit	10–12
Kiwifruit	2–3
Lemon	10–14
Mandarine	4
Mango	7–10
Melon*	3–10
Nectarine	2–10
Orange	2–10
Peach	2–10
Pineapple*	7–12
Plum	2–10
Sweet potato	12–15
Tomato (green)*	10–12

* Unripe fruit is more sensitive than ripe fruit.

Source: IIR (2000)

The problem with modified atmosphere packaging for respiring produce is to choose the right plastic material. If the permeability is too low, the oxygen will be consumed, leading to fermentation, and the CO_2 concentration may become too high, harmful to several products; or a very high relative humidity may develop in the pack, leading to microbial growth. The permeability of the plastic material and the respiration rate both depend on temperature, making it complicated to decide on the most appropriate plastic material. Packaging permeability can vary significantly depending on material choice, and the use of alternative materials (e.g. sustainable/recyclable alternatives) can impact the ability

to achieve optimal control. The ability of modified atmosphere packaging to control produce behaviour will also cease once the packaging is opened (e.g. during consumer use) and accelerated declines in senescence may be seen on return to air storage.

Perforated packages are often used for apples, pears, oranges and carrots. This allows a certain amount of ventilation, limiting the risk of too-low oxygen and too-high CO_2, ethylene and relative humidity. On the other hand, the composition of the microclimate may not produce a pronounced improvement in the shelf life.

Temperature fluctuations in the chill chain may lead to condensation of water inside the package or on the plastic cover. Microbial growth may be limited by the use of a fungicide (if permitted in the country), or the presence of calcium chloride as an absorbent of water.

Edible coatings may also be used to modify shelf life. Application of coatings made of polysaccharides (alginate, chitosan, cellulose), waxes or lipids can provide a semi-permeable membrane to modify gas exchange with the environment. These may also include active components such as essential oils, metallic ion complexes and other antimicrobials to reduce spoilage. While common in some products (e.g. wax application to citrus), wider implementation has been limited by practical effects (e.g. application challenges), incomplete evidence surrounding efficacy, regulatory challenges and concerns regarding consumer acceptance. Edible coatings interact with chilling needs by modifying water loss and gas exchange parameters — these may exacerbate low oxygen stress and increase chilling injury risk in susceptible products. Therefore, optimisation is likely to be required on a case-by-case basis (Dhall, 2013; Valencia-Chamorro *et al.*, 2011).

For minimally processed produce, modified atmosphere packaging is often used. By means of relatively high CO_2, microbial growth is slowed or completely inhibited.

Opacity of packaging may also influence shelf life, particularly in potato, which can be subject to greening when stored in transparent packaging under high light intensities.

5.7 QUALITY-INFLUENCING FACTORS

Many fruits and vegetables have a high rate of respiration and exhibit rapid moisture loss. A high rate of respiration and consequently a high rate of heat production are, in general, an indication of short storage life. The preferred temperature for maximum storage time should be as low as possible, depending on the freezing point of the product and on its susceptibility to chilling injury.

As mentioned above, a delay in cooling may shorten the storage life; therefore, chilling (or precooling) should be initiated quickly.

If the moisture loss is high, the vegetable can become unacceptable in quality. A high relative humidity (95 to 100%) can be achieved by packaging in (perforated) plastic bags or by icing. Some vegetables are susceptible to chilling injury if the storage period is too long — some, e.g. cucumbers, are sensitive to ethylene given off by other produce (fruit).

5.7.1 Ripening and shelf life after storage

Shelf life after chilled storage, especially after controlled atmosphere storage for several months, is clearly very important. This is seldom mentioned in practical storage life tables because of its extreme variability, depending on the state at harvest, storage conditions, and state on removal from storage, but also on packaging, storage conditions, etc. after removal from the chill storage room.

Ripening of fruits involves several biochemical processes, e.g. colour changes in the skin and flesh, accumulation of sugars, changes in organic acids, breakdown of cell wall components, production of characteristic aroma compounds, and ethylene production. The relationship between respiration and ripening is different for climacteric and non-climacteric fruits. Climacteric fruits, e.g. bananas, apple and pear, show a very rapid rise in respiration rate (CO_2 production) and ethylene evolution when they ripen. For non-climacteric fruits, e.g. citrus fruit, and strawberry, there is very little change in respiration rate and ethylene production during ripening. In climacteric fruit, changes in respiration and corresponding metabolic activity will occur during ripening. Reduced storage temperatures will delay the onset of respiratory maxima, with the corresponding reduction in metabolic activity reducing the rate at which ripening-related changes occur (e.g. softening, colour change).

At low temperature storage, e.g. at 0°C, pears, plums and peaches do not ripen, but they will ripen if the temperature is sufficiently high. The optimal temperature and the duration of the ripening process depend on the length of storage at low temperature. Generally, ripening at a higher temperature, 15–18°C, is necessary for pears. Post-storage ripening is generally not useful for apples.

If fruit has been harvested too early, or stored too long, other means to promote ripening may be necessary. Golden Delicious apples may need to be exposed to 50% O_2 plus at least 100 ppm ethylene, at ordinary temperatures, to develop the right quality and colour. Bananas are ripened in ripening centres after transport, usually 3–5 days in sealed chambers at 16–18°C, 90% relative humidity, and 100–150 ppm ethylene.

5.7.2 Storage disorders

The most important disorders, apart from shrivelling (insufficient relative humidity), freezing (a temperature that is too low), and tainting by incompatible produce, are microbial damage and physiological damage.

Microbial damage may be caused by bacteria, e.g. in vegetables such as carrots and lettuce, but more often by fungi (yeasts and filamentous fungi, such as *Penicillium*, *Botrytis*, *Mucor*, etc.). Infection may spread easily from a damaged product to neighbouring products, due to an abundance of spores, especially if conditions are warm and humid, and if the produce is senescent, mechanically damaged, rich in sugar, etc. Pre-harvest exposure (e.g. *Botrytis*) is most likely to influence postharvest disease development, and therefore pre-harvest crop hygiene should be maximised. Effective fungicides exist but their use is limited by national regulations, with few on-label registrations being available for postharvest use.

Physiological injury is very common, usually caused by an unfavourable storage temperature (chilling injury) or storage for too long at the recommended temperature. For long time storage of fruit, e.g. apple and pear, it is also important to pick at the right maturity stage. Fruit picked too early will be more susceptible to scald and fruit picked too late will be more susceptible to senescence-related injury. The injury may consist of superficial dark blemishes (scald), that may be sunken (pitting of citrus fruit), internal browning (a common low temperature injury to apples), off-flavours, inability of fruit to ripen, and undesirable growth in celery, cauliflower, potatoes or onions. Other factors may lead to injury: oxygen concentration that is too low (fermentation), excess CO_2 (brown heart of apples), presence of ethylene (undesirable growth or accelerated ripening), presence of certain aromatic substances, humidity, etc. The different cultivars of one species may have quite different susceptibilities to injury, such as internal browning of apples.

There has been considerable interest in variable storage conditions, which could be useful to avoid physiological injury. Examples are apples warmed to 15°C for 5 days during storage at 0°C; progressive cooling of bananas, etc.

Certain oranges from some growing areas may have a marked green colour even though the fruit is fully ripe from an eating point of view. Holding such fruit at about 20°C in 95% relative humidity for a week may result in the fruit turning yellow to orange. The temperature is then lowered to that required for the optimal storage conditions.

These injuries are closely linked to metabolic disturbances but how they arise is not yet clearly understood, despite considerable research work (Lurie and Watkins, 2012; Watkins, 2003; Whitaker, 2004) e.g. α-farnesene and scald; alteration of membrane lipids by cold. In some cases, useful prophylactic measures may be taken, such as storage of certain cultivars rather than others, treatment of the plant or post-harvest (scald), storage in favourable temperatures and ventilation conditions, or in controlled atmosphere.

In the case of very long storage, e.g. controlled atmosphere storage, it is prudent to remove small samples of fruit or vegetables from the store at intervals and to see how they behave at ordinary temperatures. In this way one may avoid prolonging storage of foods that are already of a questionable or even unacceptable quality.

5.8 RECOMMENDED STORAGE CONDITIONS

The practical storage life is limited by loss of quality (appearance, flavour, firmness, scent, physiological injury, microbial attack). Storage life depends on temperature, but it varies widely according to the initial stage of maturity of the produce, its freshness, the extent of microbial infection, etc. The appropriate storage temperature depends on the production area, variety and stage of maturity, and the practical storage life tables only give potential values.

Generally, temperature and storage life are linked exponentially, practical storage life decreasing rapidly as the temperature rises above the optimal storage temperature. The maximum practical storage life is obtained when the storage temperature is as low as possible, but care should be exercised in order to avoid freezing and chilling injury.

A high rate of respiration and consequently a high rate of heat production generally are an indication of short storage life, see ► **Table 5.1**.

The initial freezing point for fruits and vegetables is around -1°C, ranging from -0.2°C for lettuce to about -2°C for some grapes.

Different types of produce have different optimal storage temperatures. If it is necessary to keep a wide range of fruit and vegetables in a few chambers, they must be separated into suitable groups, e.g.

- At 0°C: apples, pears, stone fruits, grapes, berries, green beans, roots;
- At 7°C: oranges, mandarins, ripe pineapples, coloured tomatoes, potatoes, cucumbers, green beans, papayas (papaws), avocados;
- At 12°C: more sensitive produce, such as lemons, grapefruit, bananas, green pineapples, green tomatoes, mangoes, etc.

If only one room, such as at 5°C, is available, the time-temperature relationship becomes important. Some produce can only tolerate such a temperature for only very brief periods (see also ► **Section 5.3**).

The order of attention given to different aspects of storage conditions is also important. Storage temperature is of primary importance and should be controlled first, before other conditions that may be controlled. Next will be relative humidity should be controlled, followed by oxygen and carbon dioxide concentrations, for instance, with a modified atmosphere package or long-term CA storage. Additional beneficial effects will decrease in this sequence, ceasing to operate if the former levels of control fail.

5.9 PRACTICAL STORAGE LIFE TABLES

Since the objective is to keep the produce in a satisfactory commercial condition, too optimistic values for practical storage life have been avoided in the tables.

Due to the large variations among species, cultivars, and individual examples of the same cultivar, the information in ► **Appendix**, **Tables 5.3** to **5.9** does not apply to every case. Therefore, each user should adapt it to their specific product and region. Practical storage life depends on temperature but also varies widely according to the initial maturity stage of the produce, their freshness, the extent of microbial infection, and the development or maturity stage at harvest or at the beginning of storage (use of indicators of degree of maturity of fruit).

Before the practical storage life tables, a list of abbreviations, as well as an index of English and French (and Latin) names of the fruit and vegetables are given.

The practical storage life tables give information on the practical storage life, sometimes at different storage conditions. If the desired or expected storage period is short, the storage temperature can be slightly higher or lower, without causing significant undesirable effects. Recommended conditions for controlled atmosphere storage are provided for some commodities.

Table 5.3: recommended storage conditions and practical storage life of temperate fruits.

Table 5.4: recommended storage conditions and practical storage life of apples. Many varieties are liable to develop scald or other chilling injuries in chill storage; some examples are mentioned.

Table 5.5: recommended storage conditions and practical storage life of pears.

Table 5.6: recommended storage conditions and practical storage life of tropical and Mediterranean fruit.

Table 5.7: recommended storage conditions and practical storage life of citrus fruit. Lemons and grapefruit are more sensitive to low temperature (below 10°C) than oranges and mandarins. The two main causes of loss during storage are rot and physiological peel disorders, usually aggravated by low temperatures (chilling injury). Generally, citrus fruit peel is sensitive to the loss of water at low RH. Citrus fruit with growth of moulds, especially green moulds, that emit large quantities of ethylene, may accelerate senescence of sound fruit and create off-flavours.

Table 5.8: recommended practical storage life of grapes. The danger of development of the fungus Botrytis cinerea has led to the practice of sulphur dioxide (SO_2) injection into the air around the grapes, either continuously at 8 ppm or intermittently, such as once a week at 0.25% to 1% concentration over 20 minutes. Inhibition can also be achieved by using a generator pad, typically with a metabisulphite, which releases SO_2.

Table 5.9: recommended practical storage life of vegetables.

Practical storage life data for nuts are not included. However, refrigerated storage of nuts (fruit or seeds) retards deterioration (mould, rancidity, insect infestation).

Relative humidity should be 70% or less. Practical storage life may be some months at 10°C, increasing by 50%–100% if stored at 0°C.

Generally, practical storage life is much longer for nuts in shells than for shelled nuts. Wrapping them in plastic film, sometimes perforated, may extend their practical storage life. Vacuum packing can also increase the practical storage life.

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Chapter **5**

Fruit and vegetables

Appendix: additional information for guidance

ADDITIONAL INFORMATION FOR GUIDANCE

INFORMATIONS COMPLEMENTAIRES

This table gives a list of abbreviations, an English and a French index of names quoted, completed by their Latin name.

On trouvera, ci-dessous, la liste des abréviations, un index en anglais et en français des noms cités, complétés de leur nom latin.

ABBREVIATIONS USED IN TABLES CONCERNING FRUIT AND VEGETABLES

ABRÉVIATIONS UTILISÉES DANS LES TABLEAUX CONCERNANT LES FRUITS ET LÉGUMES

t	temperature (°C)	*température (°C)*
RH	relative humidity (%)	*humidité relative (%)*
PSL	practical storage life, in days (d), weeks (w), months (m)	*durée pratique de conservation, en jours (d), semaines (w) ou mois (m)*
BC	"brown core"	*brunissement des régions carpellaires*
BD	breakdown	*blettissement, dégradation générale*
BH	brown heart	*cœur brun*
C_2H_4	ethylene	*éthylène*
CA	controlled atmosphere	*atmosphère contrôlée*
CF	“core flush”	*“core flush” (rosissement intercarpellaire)*
CI	chilling injury	*maladie due au froid*
CO_2	carbon dioxide	*dioxyde de carbone*
IB	internal browning	*brunissement interne*
LO	low oxygen	*basse teneur en oxygène*
LTB	low temperature breakdown	*décomposition due aux basses températures*
MAP	modified atmosphere packaging	*emballage sous atmosphère modifiée*
O_2	oxygen	*oxygène*
SO_2	sulphur dioxide	*dioxyde de soufre ou anhydride sulfureux*

ULO	ultra low oxygen	*très basse teneur en oxygène*
Recom.	recommendations are noted without punctuation signs	*les recommandations sont notées sans signes de ponctuation*
Cult.	cultivar: the optimal temperature for long term storage varies considerably for different cultivars	*cultivar : la température optimale pour un entreposage prolongé varie beaucoup d'un cultivar à l'autre*
!	sensitive or take care, pay attention to	*sensible à*
!!	very sensitive, or take great care, pay much attention to	*très sensible à*
Scald ! etc.	fruit sensitive to scald, etc.	*fruit sensible à l'échaudure, etc.*
polybag	polyethylene bag	*sac ou sachet en polyéthylène*

COUNTRIES
PAYS

AR	Argentina – *Argentine*	**IL**	Israel
AU	Australia – *Australie*	**IN**	India – *Inde*
BE	Belgium – *Belgique*	**IT**	Italy – *Italie*
BR	Brazil – *Brésil*	**JP**	Japan – *Japon*
CA	Canada	**NL**	The Netherlands – *Pays-Bas*
CH	Switzerland – *Suisse*	**NZ**	New Zealand – *Nouvelle-Zélande*
CN	China – *Chine*	**PH**	Philippines
DE	Germany – *Allemagne*	**PT**	Portugal
DK	Denmark – *Danemark*	**SI**	Slovenia – *Slovénie*
ES	Spain – *Espagne*	**RU**	Russia – *Russie*
FR	France	**US**	United States – *Etats-Unis*
GB	United Kingdom – *Royaume-Uni*	**ZA**	South Africa – *Afrique du Sud*
GR	Greece – *Grèce*		

INDEX OF FRUIT AND VEGETABLES NAMES
INDEX DES NOMS DE FRUITS ET LEGUMES

English	Français	*Latin*
Apricot	Abricot	*Prunus armeniaca L.*
Almond	Amande	*Amygdalus communis L.*
Apple	Pomme	*Malus pumila Mill.*
Artichoke (globe)	Artichaut	*Cynara scolymus L.*
Artichoke (Jerusalem)	Topinambour	*Helianthus tuberosus L.*
Asparagus	Asperge	*Asparagus officinalis L.*
Avocado	Avocat	*Persea americana Mill.*
Banana	Banane	*Musa L. (paradisiaca)*
Bean (broad)	Fève	*Vicia faba L.*
Bean (French)	Haricot	*Phaseolus vulgaris L.*
Bean (Lima)	Haricot de Lima	*Phaseolus lunatus L.*
Beet	Betterave	*Beta vulgaris L.*
Bilberry	Myrtille	*Vaccinium myrtillus L.*
Black currant	Cassis	*Ribes nigrum L.*
Black walnut	Noix (de noyer noir)	*Juglans regia L. (v. nigra)*
Blackberry	Mûre	*Rubus fruticosus L.*
Blueberries	Bleuets (Canada)	*Vaccinium corymbosum and V. angustifolium*
Broccoli	Brocoli	*Brassica oleracea L. var, botrytis L. sub-var. cymosa Lam.*
Brussels sprout	Chou de Bruxelles	*Brassica oleracea L. var. gemmifera D.C.*
Cabbage	Chou	*Brassica oleracea L. var. capitata L.*
Carrot	Carotte	*Daucus carota L.*
Cashew apple	Pomme cajou	*Anacardium occidentale*
Cauliflower	Chou fleur	*Brassica oleracea L. var, botrytis L. sub-var. cauliflora D.C.*
Celeriac	Céleri rave	*Apium graveolens L. var, rapaceum D.C.*
Celery	Céleri (feuilles)	*Apium graveolens L. var. dulce*

Cherimoya	Chérimolia	*Anona cherimolia Mill.*
Cherry	Cerise	*Prunus cerasus L.*
Chestnut	Châtaigne	*Castanea sativa Mill.*
Chicory (witloof)	Endive	*Chicorium intybus L. var. Foliosum Hegi.*
Chinese cabbage	Chou de Chine	*Brassica chinensis L.*
Chinese gooseberry	Kiwi	*Actinidia chinensis*
Chive	Ciboulette	*Allium schoenoprasum L.*
Coconut	Noix de coco	*Cocos nucifera L.*
Corn (sweet)	Maïs doux	*Zea mays L.*
Cranberry	Canneberge	*Vaccinium macrocarpon L. and Vaccinium oxycoccos L.*
Cucumber	Concombre	*Cucumis sativus L.*
Custard apple	Pomme cannelle	*Anona squamosa*
Date	Datte	*Phoenix dactylifera L.*
Dill	Aneth	*Anethum graveolens L.*
Eggplant	Aubergine	*Solanum melongena L.*
Endive	Endive (frisée)	*Cichorium endivia L.var. crispum*
Endive (Escarole)	Scarole	*Cochorium endivia L. var. latifolium*
Fennel	Fenouil	*Foeniculum vulgare Mill.*
Fig	Figue	*Ficus carica L.*
Filbert (hazelnut)	Noisette (aveline)	*Corylus avellana L.*
Garlic	Ail	*Allium sativum L.*
Gherkin	Cornichon	*Cucumis sativus L.*
Ginger	Gingembre	*Zingiber officinale Roscoe*
Gooseberry	Groseille à maquereau	*Ribes grossularia L.*
Grape	Raisin	*Vitis vinifera L.*
Grapefruit	Pamplemousse (pomelo)	*Citrus paradisi Macf.*
Guava	Goyave	*Psidium guajava L.*
Horse radish	Raifort	*Cochlearia armoracia L. rusticana*

Kale	Chou frisé	*Brassica oleracea L. var. acephala D.C.*
Kiwifruit	Kiwi	*Actinidia deliciosa (Hayward variety) and Actinidia chinensis (golden variety)*
Kohl-rabi	Chou rave	*Brassica oleracea L. var. caulorapa D.C.*
Leek	Poireau	*Allium porrum L.*
Lemon	Citron	*Citrus limon L.*
Lettuce	Laitue	*Lactuca sativa L.*
Lime	Lime	*Citrus aurantifolia Swing.*
Loquat (medlar)	Nèfle	*Mespilus germanica L.*
Lychee	Litchi	*Litchi chinensis Sonner.*
Mandarin	Mandarine	*Citrus reticulata Blanco*
Mango	Mangue	*Mangifera indica L.*
Mangosteen	Mangoustan	*Garcinia mangostana L.*
Melon	Melon	*Cucumis melo L.*
Mushroom	Champignon	*Psalliota campestris Fr.*
Nectarine	Nectarine (brugnon)	*Prunus persica Sieb. et Zucc.*
Okra	Gombo	*Hibiscus esculentus L.*
Olive	Olive	*Olea europaea L.*
Onion	Oignon	*Allium cepa L.*
Orange	Orange	*Citrus sinensis Osbeck*
Papaw/Papaya	Papaye	*Carica papaya L.*
Parsley	Persil	*Petroselinum crispum Mill.*
Parsnip	Panais	*Pastinaca sativa L.*
Passion fruit	Grenadille (fruit de la passion)	*Passiflora edulis*
Pea	Pois	*Pisum sativum L.*
Peach	Pêche	*Prunus persica Sieb. et Zucc.*
Peanut	Arachide	*Arachis hypogaea L.*
Pear	Poire	*Pyrus communis L.*
Pecan nut	Noix de Pécan	*Carya illinoensis Koch.*
Pepper (hot)	Piment	*Capsicum sp. L.*

Pepper (sweet)	Poivron	*Capsicum annuum L.*
Persimmon (US)	Plaquemine	*Diospyros virginiana L.*
Persimmon (Japanese)	Kaki	*Diospyros Kaki L.*
Pineapple	Ananas	*Ananas comosus L.*
Pistachio	Pistache	*Pistacia vera L.*
Plum	Prune	*Prunus domestica L.*
Pomegranate	Grenade	*Punica granatum L.*
Potato	Pomme de terre	*Solanum tuberosum L.*
Pumpkin (winter squash)	Potiron (courge d'hiver)	*Cucurbita maxima Dcne.*
Quince	Coing	*Cydonia oblonga Mill.*
Radish	Radis	*Raphanus sativus L.*
Raspberry	Framboise	*Rubus idaeus L.*
Red currant	Groseille rouge	*Ribes rubrum L.*
Rhubarb	Rhubarbe	*Rheum rhaponcitum L.*
Rutabaga	Chou navet	*Brassica napus L.*
Salsify	Salsifis	*Tragopogon porrifolius L.*
Shallot	Echalote	*Allium ascalonicum L.*
Spinach	Epinard	*Spinacia oleracea L.*
Strawberry	Fraise	*Fragaria L.*
Summer squash	Courge d'été	*Cucurbita pepo L.*
Sweet potato	Patate douce	*Ipomoea batatas L.*
Swiss chard	Bette	*Beta vulgaris L. var. cicla*
Tapioca	Manioc	*Manihot esculenta*
Tomato	Tomate	*Lycopersicum esculentum Mill.*
Turnip	Navet	*Brassica rapa L.*
Walnut	Noix commune	*Juglas regia L.*
Watercress	Cresson de fontaine	*Nasturtium officinale Brown*
Yams	Ignames	*Dioscorea alata*

TABLE 5.3 TEMPERATE FRUIT
TABLEAU 5.3 FRUITS DES RÉGIONS TEMPÉRÉES

COMMODITY CULTIVAR	FRUITS CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
APRICOT	ABRICOT	-0.5 to 0	90–95	0	21	1–3 w	AU, ZA, US, CA, IT	CO_2 pretreatment (20%)	Prétraitement au CO_2 (20 %)
		-1 to 0	90	3	3	3–4 w	GR	Rapid cooling No evidence for CA storage 5 weeks in MAP (Greece)	Refroidissement rapide Entreposage CA sans effet apparent 5 semaines en MAP (Grèce)
		-1 to 0		0	21	2–3 w	GR		
		0		7	3	4–5 w	DE, US, ZA		
BILBERRY	MYRTILLE	-1 to 0	85–90	0	21	2–3 w	DE, US, ZA		
BLACKBERRY	MÛRE	-0.5 to 0	90–95	0	21	2–4 d	ZA, US, CA, AU	Decay ! Rapid cooling; Beneficial effect of 20 to 40% CO_2 (US)	Pourritures ! Refroidissement rapide ; Effet bénéfique de 20 à 40 % de CO_2 (US)
		-1	90	0	21	4–6 d	NL		
BLACK CURRANT	CASSIS	-1 to 0	90–95	0	21	1–3 w	US, NL, DE, GB	Rapid cooling with CO_2 (40%) → 4 weeks	Refroidissement rapide avec CO_2 (40 %) → 4 semaines
BLUEBERRY	BLEUETS (Canada)	0	90–95	0	21	2 w		Rapid cooling; Beneficial effect of CO_2 on decay	Refroidissement rapide ; Effet bénéfique du CO_2 sur les pourritures
		-0.5 to 0		12–20	17–19	2 w			
		0		12–20	2–5	≤ 6 w	NZ		
CHERRY	CERISE								
– Sweet	– Douce	-1 to 0	90–95	0	21	2–3 w	US, NZ, ZA, IT, AR	Rapid cooling Use of polyethylene film CO_2 improvement (≤ 20%) MAP (Greece)	Refroidissement rapide Utilisation de film polyéthylène Amélioration par le CO_2 (≤ 20 %) MAP (Grèce)
		-1 to 0		10	3	4 w	FR, NZ, IT		
		-1 to 0		10–15	18–19	4 w	US, CA		
		0		17	3	1 m	GR		
– Sour	– Amère	0 to 1	90–95	0	21	1 w	NL, US, ES		
		0		5	3	5 w	DE		
CRANBERRY	CANNEBERGE	2 to 5	90–95	0	21	2–4 m	US, ZA, CA	CA storage of little interest	Peu d'intérêt de l'entreposage CA
FIG (fresh)	FIGUE (fraîche)	-1 to 0	90	0	21	1–2 w	US, ZA, AU	Beneficial effect of CO_2 (15–20%) won decay & firmness	Effet bénéfique du CO_2 (15–20 %) sur les pourritures et la fermeté
GOOSEBERRY	GROSEILLE À MAQUEREAU	-0.5	90	0	21	4 w	DE, US, NL		

COMMODITY CULTIVAR	FRUITS CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
KIWI FRUIT	KIWI								
– Hayward	– Hayward	0	> 95	5	2	6 m	NZ	C_2H_4 management required CA associated with C_2H_4 scrubbing	C_2H_4 !! gestion requise CA associée à la fixation de C_2H_4
– Gold	– Gold	0.5	> 95	2	2	4 m	NZ		
– Red	– Red	1	> 95	2	2	2 m	NZ		
MELON	MELON								
– Musk melon	– Melon								
– Cantaloup	– Cantaloup	2 to 5	95	0	21	2 w	US	Precooling CI (pitting) susceptible if t < 13°C	Prérefrigération Possibilité de CI (pitting) si t < 13°C
		5 to 7	90	0	21	2–3 w	AU, IL		
– Honey dew	– Honey dew	7 to 10	90	0	21	2–4 w	CA, US, AU		
– Water melon	– Pastèques	12 to 17	85	0	21	2–3 w	IL		
		15	95–99	5	5	2 m	ES		
NECTARINE	NECTARINE	-1 to 0	90	0	21	1 m	US, ZA, AU, AR	CI ! (IB) Hydrocooling; Fungistat; CA	CI ! (IB) Hydrocooling; Traitement fongista-tique; CA
		-0.5 to 0	95	5	2	50 d	IT		
OLIVE	OLIVE								
– fresh	– fraîche	7 to 10	85–90	0	21	1.5 m	US	CI if t < 7°C Potential effect of LO	CI si t < 7°C Effet bénéfique possible du LO
– for process	– pour transformation	4.5	85–90	0	21	3 m	US		
PEACH	PÊCHE	-0.5 to 0	90	0	21	2–3 w	US, ZA, ES, IT	CI (woolliness) !! Cult ! Most sensitive when unripe ! 2 to 5°C temp. range to be avoided ! Fungistat; CA storage before process (US)	CI (cotonneux) !! Cult ! Fruits immatures très sensibles Eviter les températures comprises entre 2 et 5°C ! Traitement fongistatique ; Entreposage CA avant transformation (US)
		0	95	0	21	2 w	NL, IL		
		-1 to 0	95	0	21	2–6 w	AU, DE		
		0	95	4-5	2	45 d	IT, US		
– Clingstone	– Clingstone	-0.5	90	0	21	1 m			
– Freestone	– Freestone	-1 to 0	90	0	21	1 m	IT		
PERSIMMON									
– KAKI (JP)	– KAKI (JP)	-1	90	0	21	2–5 m	US, IL	60% CO_2 for 24h (firmness, astringency decreasing)	60 % CO_2 pendant 24h (fermeté améliorée, astringence diminuée)
– PLAQUEMINE (US)		-1	90	0	21	3 m	US, AU		
PLUM	PRUNE	-1 to 0	90–95	0	21	1–7 w	IL, AU, AR	Cult (CI) ! Rapid cooling	Cult (CI) ! Refroidissement rapide
		-0.5	90–95	0–5	1–2	> 1 m	IL, US, IT		

COMMODITY CULTIVAR	FRUITS CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
QUINCE	COING	-0.5 to 0	90	0	21	2–3 m	US	Fungistat	Traitement fongistatique
RASPBERRY	FRAMBOISE	0	95	0	21	4 d	CH, US, ZA	Rapid cooling	Refroidissement rapide
		-0.5	95	0	21	4 d	AU	Add 20% CO_2 for transport	Ajouter 20 % de CO_2 pour le transport
RED CURRANT	GROSEILLE ROUGE	0 to 2	85–95	0	21	5 d	GB, DE, US, GR	Precooling; Avoid sweating	Préréfrigération ; Eviter le voile de condensation (embuage)
STRAWBERRY	FRAISE	-0.5	95	0	21	8 d	AU	Precooling	Préréfrigération
								Beneficial effect of CO_2 (20%)	Effet bénéfique du CO_2 (20 %)
						10–14 d	AR	CO_2 pretreatment (60%) for 6h (Argentina)	Prétraitement au CO_2 (60 %) pendant 6h (Argentine)

TABLE 5.4 APPLES
TABLEAU 5.4 POMMES

COMMODITY CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
ANTONOVKA	3 to 4	90	0	21	3.5 m	RU		
ABBONDANZA	2 to 3	90	0	21	5–7 m	IT	IB !	IB !
	3	95	2	3	6–7 m	IT		
BALDWIN	3 to 4	90	0	21	3–6 m	NL, DE		
BELLE DE BOSKOOP	3 to 4	95	0.2–2	< 1	5–7 m	FR, NL, DE, BE, CH	Scald ! LTB ! CO_2 sensitive !	Echaudure ! LTB ! Sensible au CO_2 !
BERLESCH PIPPIN	0 to 2	95	3	3	6 m	DE	Scald !	Echaudure !
BRAEBURN	0 to 1	95	1–2	1–2	> 6 m	US, NZ, FR	CO_2 (BH or CF) !	CO_2 (BH ou CF) !
BRAMLEY'S SEEDLING	4	95	5	1	6–8 m		LO controls scald	LO maîtrise l'échaudure
CALVILLE BLANC	4	95	3–5	2–3	6 m	FR		
CANADA	3 to 4	90	0	21	3–5 m	FR, CH, DE	Bitter pit !! LTB !	Bitter pit (tache amère) !! LTB !
– REINETTE	4	95	3	3	6–7 m	FR		
CORTLAND	0	95	3–5	3	5–6 m	US	LO → IB; LTB Use CO_2 < 2.5% (1st month)	LO → IB; LTB Régler CO_2 < 2.5 % (1er mois)
COX's ORANGE P.	3.5	95	< 1	2	4–5 m	BE, DE	CO_2 ! (CF) CI ! if t < 3°C	CO_2 ! (CF) CI ! si t < 3°C
	4	95	< 1	1.25	6 m	FR, GB, NL	LO → less CF LO → risk of fermentation	LO → moins de CF LO → risque de fermentation
CRISPIN MUTSU	1		5	3	7 m	DE		
	0		3	3	7 m	AU, DK	CO_2 injury if > 5% and O_2< 2.5%	Altération due au CO_2 si > 5% et O_2< 2.5%
	0		0–3	1.5	7 m	US	BD if O_2 < 1.5%	BD si O_2 < 1.5 %
	1		1	2	7 m	JP		
ELSTAR	1	95	1–2	1.5–2	7 m	BE, FR, CA, DE, GB	CO_2 sensitive (CO_2 > 2%) !	Sensible au CO_2 (CO_2 > 2%) !
	2 to 3	95	3	2–3	6 m	DE, DK, FR	O_2 < 2% → CF	O_2 < 2% → CF
EMPIRE	0	95	2	1.5	6 m	US, CA		
FUJI	0	95	1–2	2	8 m	AU, US, BR, JP, FR, NZ	Water core ! CO_2 sensitive (BC) LO sensitive (fermentation)	Cœur vitreux ! Sensible au CO_2 (BC) Sensible au LO (fermentation)

COMMODITY CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
GALA	0	95	1–2	1–2	4 m	CA, AU, ES, US, ZA	Rapid CA LO → less flavour ! High CO_2 → less BD	CA rapide LO → moins de saveur ! Taux élevé de CO_2 → moins de BD
	1 to 2	95	3	2	4 m	BR, DE, FR		
	1 to 2	95	2	1.5	5 m	FR		
GLOCKENAPFEL	1	95	3	3	7–8 m	DE		
GLOSTER	1	95	2	2	6 m	BE	Water core ! O_2 < 1% → injury ! High CO_2 → CF !	Cœur vitreux ! O_2 < 1 % → altération ! Taux élevé de CO_2 → CF !
	2 to 4	95	3–4	2-3	5–6 m	CH		
	0 to 2	95	< 2	1.3–1.5	6–7 m	DE, FR		
GOLDEN DELICIOUS	1 to 2	95	0	21	5–6 m	US, FR	Rapid CA LO (less scald) CO_2 tolerant	CA rapide LO (moins d'échaudure) Tolérant au CO_2
	0	95	2–3	1.5–2	8 m	US		
	0	95	2.5	2.5	7–8 m	CA, FR		
	0 to 2	95	2–4	1–1.5	7–9 m	IT, FR, DE, IL		
	2	95	4–5	2-3	7–9 m	CH		
GRANNY SMITH	0 to 2	95	0	21	5 m	FR, US	Scald ! ULO → less scald or CF LO → alcoholic taint !	Echaudure ! ULO → moins d'échaudure ou de CF LO → altération fermentaire !
	0 to 2	95	< 1	0.8–1.2	8–9 m	FR, US		
	0 to 2	95	1–3	2–3	8–9 m	IL		
	-0.5 to 0.5	95	0–1	1.5	8-9 m	US, ZA		
	-1 to 2	95	3	1–2	8-9 m	DE		
	-1 to 0.5	90	1	1.5	9 m	AR		
IDARED	3 to 4	95	1–3	1–2	8 m	GB, FR, DE, CH	LTB ! High CO_2 → CF !	LTB ! Taux élevé de CO_2 → CF !
	0 to 1	95	2–3	2	7 m	US, BE, CA		
	2		3	3	7 m	ES, FR		

COMMODITY CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
JONAGOLD	0 to 1		0	21	3 m	FR	CO_2 >5% or O_2 <1.5% → injury	CO_2 >5 % ou O_2 <1.5 % → altération
	0		3–5	1–1.5	≤ 7 m	US, IL, FR		
	0		1.5	1.2–1.5	≤ 7 m	CA		
	1		4	1.2	9 m	NL		
	2		< 1	2	9 m	GB, DK		
	2		4	2	9 m	CH		
	2		< 2	1.5	9 m	DE		
	2		3–4	3	9 m	ES		
JONATHAN	3		3	1–2	6 m	DE, SI	LTB ! Jonathan spot ! High CO_2 → CF ! LO → fermentation	LTB ! Tache Jonathan ! Taux élevé de CO_2 → CF ! LO → fermentation
	4		3	3	6 m	CH		
	0		3	3	6 m	AU		
LAXTON'S SUPERB	3		1.7–5	1.3–2	6 m	US		
MAC INTOSH	3	95–97	1–1.5	1.5	≥ 6 m	CA	High CO_2 or LO → injury! CI (after 6 m) ! Rapid CA Use CO_2 < 2.5% (1st month)	Taux élevé de CO_2 ou de LO → altération CI (après 6 m) ! CA rapide Régler CO_2 < 2.5 % (1er mois)
	3		3–5	2.5	≥ 6 m	CA, US, DE		
	2		3–5	4	≥ 6 m	US		
MELROSE	1	95–97	3	1.2	6 m	SI	Scald !	Echaudure !
	3		3	3	< 5 m	FR		
	2 to 3		2–3	1–2	< 5 m	BE, DE		
NORTHERN ROSE	0	95	3	3	8 m	US, CA		
RED DELICIOUS	0	85–90	0	21	5–7 m	GR	LO → less scald, less mealiness	LO → moins d'échaudure, moins farineuse
	-0.5 to 0.5	95	1.5–2	1.5	6–8 m	ZA, IL, FR		
	0	90–95	0–0.3	1.3–2.3	6–8 m	US, AU, AR	High CO_2 and LO → alcoholic taint !	Taux élevé de CO_2 ou de LO → altération fermentaire !
	0		2–5	2	8–9 m	ES, US, AR		
REINE DES REINETTES	4	90	0	21	3 m	FR	Water core ! LTB ! No benefit in CA storage	Cœur vitreux ! LTB ! Pas de bénéfice de l'entreposage en CA
ROME BEAUTY	-1 to 0	95	1–3	2–3	6–8 m	AU, US, CA, IT	LTB ! Scald !	LTB ! Echaudure !

COMMODITY CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
SPARTAN	2	95–97	1–3	2–3	6 m	DK, GB, CH	LO injury ! CO_2 > 2.5% → CF !	Altération due à LO ! CO_2 > 2.5% → CF !
	0		2.5	2–2.5	6 m	CA, US		
	0		1.5	1.2–1.5	4–5 m	CA		
STARKING	0	95	3	3	7 m	ZA, IT		
STURMER PIPPIN	2	95	0	21	> 5 m	NZ		
STAYMAN	0	95	0–2.5	1.3–3.5	6–8 m	US, AU, CA, IT		
WINESAP	-0.5	95	1–2	2–3	6–8 m	US	CO_2 sensitive !	Sensible au CO_2 !
YELLOW NEWTON	2.5 to 3.5	95	5–7	2–3	6–8 m	US		
YORK IMPERIAL	-0.5 to 0.5	95	0–3	1.5–2.5	7–9 m	US		

TABLE 5.5 PEARS
TABLEAU 5.5 POIRES

COMMODITY CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
ALEXANDER LUCAS	-1 to 0	95	0	21	3–5 m	DE, NL	CO_2 !! (very sensitive)	CO_2 !! (très sensible)
	-1 to 0	95	1	3	6 m	DE		
ANJOU (D')	-1 to 0	95	1–2	2–3	7 m	DE, IT	$CO_2 \leq O_2 - 1\%$	$CO_2 \leq O_2 - 1\,\%$
	-1 to 0.5	95	< 0.5	1–2	7 m	US		
BARTLETT (Williams Bon Chrétien)	-1	95	1	2	4 m	AU, CA	Hydrocooling High CO_2 → BH BD if O_2 < 1% ! Scald (in air) !	Hydrocooling Taux élevé de CO_2 → BH BD si O_2 < 1 % ! Echaudure (dans l'air) !
	-1 to 0	95	0.5–3	1–3	3 m	FR		
	-1	95	3–4	2–3	6 m	ES		
	2	95	3	2		DE		
BEURRÉ HARDY	-1 to 0	95	3–5	2–3	2–3 m	FR	CO_2 sensitive (Italy)	Sensible au CO_2 (Italie)
BLANCA DE ARANJUEZ	-1	90	0	21	5 m	ES	BH !	BH !
	-1	95–99	3	3	6 m	ES		
BOSC	-1	90–95	0	21	3.5 m	US, CH, AU, NZ	O_2 < 1.5% ; CO_2 > 1.5% (injury + poor ripening)	O_2 < 1.5 % ; CO_2 > 1.5 % (altération + maturation ralentie)
	-1		1	2–2.5	6 m	AU, CA		
	0		2	2	6 m	CH		
	-1		1.5	4	5–6 m	IT		
COMICE	0	95	5	3–5	5–6 m	IT, FR, CH	High CO_2 → IB Late harvests promote to BC !	Taux élevé de CO_2 → IB Récolte tardive favorise BC !
	-0.5 to 0	95	< 0.8	2	5–6 m	BE		
	-0.5	95	3	3	5–6 m	ES		
	-0.5	95	0	21	3 m	NZ		
CONFERENCE	-1.5 to -0.5	95	0	21	4–6 m	DE, NL, GB, CH	CO_2 injury ! (BH if CO_2 > 1%)	Altération due au CO2 ! (BH si CO_2 > 1 %)
						NZ		
	-1 to -0.5	95	<1	2–3	7-8 m	GB, BE, DK, NL		
	-0.5	95	2–4	2–4	6 m	FR		
GENERAL LECLERC	0	95	5	3	5–7 m	ES, CH, FR	High CO_2 reduces rot	Taux élevé de CO_2 diminue les pourritures
	-0.5	90	2–4	2–3	5–6 m	IT		

COMMODITY CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
GUYOT	-1 to -0.5	95	5–6	0–15	5 m	ES, FR	Scald !!	Echaudure !!
KRYSTALLI	-1 to 0	85–90	0	21	6–7 m	GR		
	-1 to 0	85–90	5	3	7–8 m	GR		
LOUISE BONNE	-1	95	0	21	< 4 m	DE		
	-1 to -0.5	95	3	3	6–7 m	FR, GR, IT	CO_2 sensitive	Sensible au CO_2
	-1	95	2	2	6–7 m	CH		
PACKHAM'S	-1 to -0.5	95	0	21	5 m	ZA, US, AU, IT, NZ		
	-1	95	3	2	7 m	AU, DE	Scald !!	Echaudure !!
	-1	95	1–2	2-3	7–8 m	FR	CO_2 tolerant	Tolérance au CO_2
	0	95	2	2	7–8 m	CH	LO → poor ripening	LO → maturation incomplète
PASSE CRASSANE								
– green	0	95	5	3	≤ 8 m	ES, IT	IB !	IB !
– yellow	5	95	5	5	6 m	FR		
ROCHA PEAR	0	90–95	0	21	4 m	PT	Scald !! CO_2 injury (BH) if CO_2 > 1%	Echaudure !! Maladie due au CO_2 (BH) si CO_2 > 1 %
WINTER NELIS	-1 to -0.5	95	2–3	2–3	8 m	NZ, AU		
	-1 to 0.5	95	0	21	4–6 m	ZA, US, CH, DE		
YA LI PEAR	0	90–95	0	21	6 m	CN	CI ! (slow temp. lowering after harvest)	CI ! (abaissement lent de la température après récolte)
							Scald !! CO_2 !! (BH)	Echaudure !! CO_2 !! (BH)

TABLE 5.6 TROPICAL AND MEDITERRANEAN FRUIT
TABLEAU 5.6 FRUITS TROPICAUX ET MÉDITERRANÉENS

COMMODITY CULTIVAR	FRUITS CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
AVOCADO	AVOCAT	5 to 12	85–90	0	21	2–6 w	IL, AU		
		7 to 12		3–10	2–3	2 m	IT		
– Taylor	– Taylor	4.5	85–90	0	21	2 w	US		
– Fuerte	– Fuerte	7 to 8	85–90	0	21	3–4 w	US, ES	Cult. !	Cult. !
– Fuchs	– Fuchs	10 to 13	85–90	10	2	2 w	US	Maturity !	Maturité !
– Lula	– Lula	4.5	85–90	0	21	4 w	US	CI ! (internal and superficial browning)	CI ! (brunissement interne et superficiel)
		4.7		5	3	4 w	FR	In polybags + C_2H_4 scrubbing	En polybags + fixation de C_2H_4
		4.7		10	2	8 w	FR	Individual wrapping	Emballage individuel
– Hass	– Hass	5.5 to 7	85–90	0	21	40 d	AR		
		8 to 12		3–10	2–5	2–4 w	AR		
BANANA	BANANE								
– Green	– Verte	13	90–95	0	21	10–20 d	US, AU		
		12	85–90	0	21	10–20 d	ES	Maturity !	Maturité !
		13	98	2–7	2–7	1 m	AU	Cult. !	Cult. !
		12	98	5–6	2–5	3 w	FR	PSL improved if C_2H_4 scrubbing in polybags	Amélioration du PSL si élimination du C_2H_4 en polybags
– Lacatan	– Lacatan	14		2–5	2–5	1 m	US	Sanitary treatment	Traitement sanitaire
– Plantain	– Plantain	13 to 15.5	85–90	0	21	28 d	ES, PH	Ripening: 16–20°C with C_2H_4	Maturation complémentaire : 16–20°C avec C_2H_4
		10	85–90	0	21	5 w	PH		
CHERIMOYA (Anona)	CHÉRIMOLIA (Anone)	8 to 9	90	0	21	2 w	ES, PH	Maturity ! Size !	Maturité ! Taille !
		13	90–95	0	21	2–4 w	AR	CI !	CI !
CUSTARD APPLE	POMME CANNELLE	5 to 7	90	0	21	4–6 w	AU, PH		
DATE (fresh)	DATE (fraîche)	0	85	0	21	1–2 m	DE		
GUAVA	GOYAVE	8 to 10	90	0	21	2w	US, AU, BR	Cult. !	Cult. !
LOQUAT	Nèfle	-0.5	95	0	21	2–3 w	AU, IL		

COMMODITY CULTIVAR	FRUITS CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
LYCHEE	LITCHI	1.5 to 2	90–95	0	21	3–5 w	US, AU	Use of polybags	Utilisation de polybags
		0 to 1.5	90	0	21	3–5 w	IN, PH		
MANGO	MANGUE	7 to 14	90	0	21	4–7 w	IN, AU, BR, PH, US		
		13	90	5–10	3–5	4–7 w	US	Cult. !	Cult. !
– Amélie	– Amélie	12	95	5	5	4 w	FR, BR	Maturity !	Maturité !
– Haden	– Haden	8	90	10	6	4 w	BR	CI ! if t < 10°C (Argentine)	CI ! si t < 10°C (Argentine)
– Julie	– Julie	12		5	5	4 w	FR		
MANGOSTEEN	MANGOUSTAN	5	85–90	0	21	6–7 w	IN, PH		
PAPAW (PAPAYA)	PAPAYE	12	85–90	0	21	1–3 w	US	Hot water treatment (20 min) at 45°C; Waxing	Traitement à l'eau chaude (20 min) à 45°C ; Enduction cireuse
PASSION FRUIT	FRUIT DE LA PASSION	7 to 10	85–90	0	21	3–5 w	IN, PH, DE, AU		
PINEAPPLE	ANANAS	8 to 13	85–90	0	21	4–6 w	IN, US, PH, AU	CI ! if t < 10°C	CI ! si t < 10°C
POMEGRANATE	GRENADE	0 to 2	85–90	0	21	3 m	IN, PH, US, AU		
SAPOTA (SAPOTILLA)	SAPOTILLE								
– turning	– tournante	20	85–90	0	21	2.5 w	PH		
– ripe	– mûre	0 to 2	85–90	0	21	2 w	PH		

TABLE 5.7 CITRUS FRUIT
TABLEAU 5.7 AGRUMES

COMMODITY CULTIVAR	AGRUMES CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
GRAPEFRUIT	PAMPLEMOUSSE	10 to 15	90	10	19	6–16 w	IL, US, AU, IT, ES	Cult !: CI (pitting) !! t between 7°C to 12°C prohibited 10% CO_2 reduces sensitivity Film individual packaging Waxing	Cult !: CI (pitting) !! t entre 7°C et 12°C proscrite 10 % CO_2 réduit sensibilité Emballage en film individuel Enduction cireuse
		12 to 14	85–90	0	21	4–6 w	AR		
– Marsh	– Marsh	13	95–99	0	10	70 d	ES		
LEMON	CITRON	13 to 14	85–90	0	21	4–6 m	IL, US, AU	CI (pitting) ! Removal of C_2H_4 recommended	CI (pitting) ! Extraction de C_2H_4 recommandée
– green	– vert	12	85–90	0	21	1–4 m	GR		
– colored	– coloré	5 to 6	90	0	21	3–6 w	AR		
LIME	LIME	13	85–90	0	21	4–6 w	ES, US, AU	Removal of C_2H4 ; Waxing	Extraction de C_2H_4 ; Enduction cireuse
MANDARIN	MANDARINE	4	85–90	0	21	5–6 w	GR	Cult. !	Cult. !
		5	85–90	0	21	4–6 w	ES, IL, AR		
		5	95–99	0	10	35 d	ES		
CLEMENTINA	CLEMENTINE	4	95	5	5	6–8 w	FR		
ORANGE	ORANGE								
– Jaffa	– Jaffa	10 to 12	85–90	0	21	8 w	IL	CI ! (pitting below 7°C for many cult); Importance of maturity stage ! Precooling Sanitary treatment Waxing Film individual packaging	CI ! (pitting en dessous de 7°C pour beaucoup de cultivars) ; Importance du stade de maturité ! Prérefrigération Traitement sanitaire Enduction cireuse Emballage en film individuel
– Navel	– Navel	2 to 7	90	0	21	6–10 w	ES, ZA, AU, US, GR		
– Salustiana	– Salustiana	2	90	0	21	12 w	IL		
– Valencia Late	– Valencia Late	8 to 10	90	0	21	12 w	IL		
		2	90	0	21	16–20 w	IL, ES		
– Verna	– Verna	1 to 2	90	0	21	14–16 w	ES		

TABLE 5.8 GRAPES
TABLEAU 5.8 RAISINS

COMMODITY CULTIVAR	T (°C)	RH (%)	PSL	SOURCES	NOTES	OBSERVATIONS
Vinifera						
– Almeria	-1 to -0.5	90-95	3–6 m	ZA, US	SO_2	SO_2
– Alphonse Lavallée	-1 to -0.5	95	3 m	ZA	SO_2	SO_2
– Barlinka	-1 to -0.5	95	4–6 m	ZA	SO_2	SO_2
– Blue Alicante	-0.5	92-95	3–4 m	NL	SO_2	SO_2
– Chasselas	-1 to -0.5	95	4 w	ZA	SO_2	SO_2
– Flame Tokay	-1 to -0.5	95	6–10 w	US	SO_2	SO_2
– Italia	-1 to -0	95	2–3 m	IT	SO_2	SO_2
– Muscat de Hambourg	-1	95	4 w	ZA	SO_2	SO_2
– Ohanez	-1	95	1–3 m	ZA	SO_2	SO_2
– Red Emperor	-1	95	4–6 m	US, ZA	SO_2	SO_2
– Regina	-1 to -0	95	2 m	IT	SO_2	SO_2
– Thompson Seedless	-1 to -0	95	3–4 m	US, GR	SO_2	SO_2
– Waltham Cross	-1	95	3 m	ZA	SO_2	SO_2
American						
– Catawba	-0.5	90	2 m	US	No SO_2 treatment	Pas de traitement au SO_2
– Concord	-0.5	90	1–1.5 m	US	No SO_2 treatment	Pas de traitement au SO_2
– Muscadine	-0.5	90	2–3 w	US	No SO_2 treatment	Pas de traitement au SO_2

TABLE 5.9 VEGETABLES
TABLEAU 5.9 LÉGUMES

COMMODITY CULTIVAR	LEGUMES CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
ARTICHOKE									
– Globe	ARTICHAUT	0	95–98	0	21	4–7 w	AU, DE	Precooling Perforated polybags Shrivelling !	Prérefrigération Polybags perforés Flétrissure !
		0 to 1	98	4–6	2–4	≤ 8 w	FR, ES		
– Jerusalem	TOPINAMBOUR	-0.5	95	0	21	8–16 w	AU, US		
ASPARAGUS	ASPERGE	0 to 2	95–98	0	21	2–3 w	AU, US, CA, DE, IT	Cult. ! Hydrocooling Off flavour if CO_2 > 7% or O_2 < 2% Rapid CO_2 pretreatment (20%)	Cult. ! Hydrocooling Saveur étrangère si CO_2 > 7 % ou O_2 < 2 % Prétraitement précoce au CO_2 (20 %)
		1 to 4		10–41	10–16	2 w	IT		
		0	98	4–5	3–5	2–4 w	DE, NZ		
		0	98	3	2–3	5 w	FR		
BEAN, dry (broad)	HARICOT, sec	4 to 10	40–50	0	21	6–10 w	US		
BEAN		7 to 8	92–95	0	21	1–2 w	US, AU, CA	Chilling (pitting, russeting) !! Rapid cooling	Réfrigération (pitting, brunissement) !! Refroidissement rapide
– snap or french	HARICOT VERT	7 to 8	98	3–5	2	10 d	DE, IT		
BEAN Lima	HARICOT DE LIMA	0 to 4.5	95	0	21	5–7 d	US, CA		
BEET	BETTERAVE								
– bunched	– en botte	0	92–95	0	21	< 2 w	DE, AU, US	Polybags	Polybags
– topped	– sans fanes	0	92–95	0	21	4–6 w	DE, AU, US		
BROCCOLI	BROCOLI	0	95–98	0	21	< 2 w	US, CA, AU, DE, IT	C_2H_4 ! (toughening + yellowing)	C_2H_4 ! (durcissement + jaunissement)
		0	98	5	3	4 w	DE	Icing; Aeration	Glaçage ; Aération
		5	98	10	1	3 w	US	Polybags	Polybags
BRUSSELS SPROUTS	CHOUX DE BRUXELLES	-1 to 0	95–100	0	21	3–5 w	AU, DE, US, CA, CH	C_2H_4 !! Aeration Perforated polybags	C_2H_4 !! Aération Polybags perforés
		-1		5	1	3 m	NL		
		0	95–100	4–5	2–3	2–4 m	DE		
		5	95–100	5–7.5	2.5–5	6 w	US		

COMMODITY CULTIVAR	LEGUMES CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
CABBAGE	CHOU								
– early	– précoce	0	98–100	0	21	3–6 w	US, AU, NL		
– late	– tardif	0	98–100	0	21	2–4 m	AU, CH		
		0	98–100	2.5–5	2.5–5	> 6 m	US	Cult.! Better results with very high RH	Cult.! Meilleurs résultats avec HR élevée
– white	– blanc	0	98–100	0	21	6–7 m	DE, NL		
		0	98–100	4–5	2-3	7–8 m	DE		
– green	– vert	-2	98–100	0	21	3 m	DE		
– chinese	– chinois	0	95–100	0	21	2 m	NL, US, AU		
		0	98–100	3	3	3 m	DE		
CARROT	CAROTTE								
– young	– jeune	0 to 1	98–100	0	21	10 d	NL	CO_2 ! LO ! C_2H_4 !! (bitterness) Precooling Aeration Perforated polybags	CO_2 ! LO ! C_2H_4 !! (amertume) Préréfrigération Aération Polybags perforés
– topped	– sans fanes	0	98–100	0	21	5–8 m	US, CH, CA, IL, NL		
							GR		
CAULIFLOWER	CHOU FLEUR	0	95	0	21	3–4 w	US	Wilting ! Vacuum cooling Pre-packaging CO_2 > 5% ® off-flavour when cooked	Flétrissure Vacuum cooling Préemballage CO_2 > 5% ® saveur étrangère après cuisson
		0	98–100	0	21	3–4 w	CA		
		0	98–100	3	3	1–2 m	CH		
		0	98–100	5–7	3–4	2–3 m	IT		
CELERIAC (tuber)	CÉLERI RAVE (tubercule)	0	95	0	21	3–5 m	DE, US, CH	CO_2 ! High RH recommended	CO_2 ! RH élevée recommandée
		0	98–100	0	21	6–8 m	US		
CELERY (leafs)	CÉLERI (feuilles)	0	98–100	0	21	2–3 m	US, AU, CA	Vacuum cooling Aeration High RH (polybags)	Vacuum cooling Aération RH élevée (polybags)
		0	98–100	5	3	2–3 m	AU		
		0	98–100	0	2–4	2–3 m	US		
CHICORY									
– witloof	– ENDIVE	0	98–100	0	21	2–4 w	US, BE	Light !! (greening) High RH Perforated films Interest of 5% CO_2	Lumière !! (verdissement) RH élevée Films perforés Intérêt de 5 % de CO_2
– red	– CHICORÉE ROUGE (de trévise)	-0.5		5	3	3 m	IT		

COMMODITY CULTIVAR	LEGUMES CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
CORN (sweet)	MAÏS DOUX	0	95	0	21	1 w	US, AU, CA, DE	Hydrocooling + icing Perforated films	Hydrocooling + glaçage Films perforés
CUCUMBER	CONCOMBRE	10 to 13	95	0	21	1–2 w	DE, US, CH, NL	C_2H_4 (yellowing) ! CI (pitting) ! Rapid cooling; Wrapping; Waxing	C_2H_4 (jaunissement) ! CI (pitting) ! Refroidissement rapide ; Filmage ; Enduction cireuse
		7 to 9	95	0	21	1.5–2 w	CA, IT, AU		
		12	98	0	1-4	3 w	IT		
EGGPLANT	AUBERGINE	8 to 12	90–95	0	21	1 w	US, AU, IT, IL	Cult. and maturity-stage ! CI (if t <10°C) ! C_2H_4 (pitting & browning) !	Cult. et maturité ! CI (si t <10°C) ! C_2H_4 (pitting & brunissement) !
ENDIVE (Escarole)	SCAROLE (endive vraie)	0	95–100	0	21	2–3 w	US, CA, NL	Vacuum or hydrocooling; Icing	Vacuum ou hydrocooling; Glaçage
GARLIC (dry)	AIL (sec)	0	65–70	0	21	6–7 m	US, AR	Curing Aeration	“Curing” Aération
		-1		5	3	7 m	IT		
GHERKIN	CORNICHON	13	90–95	0	21	4–6 d	NL		
GINGER	GINGEMBRE	13	65	0	21	6 m	US	CI !	CI !
HORSE RADISH	RAIFORT	-1 to 0	90–95	0	21	10–12 m	US	Light ! Perforated films	Lumière ! Films perforés
KALE	CHOU FRISÉ	0	95	0	21	3–4 w	US		
KOHL-RABI	CHOU RAVE								
– with leaves	– avec feuilles	0	92–95	0	21	2 w	US, DE	Aeration Perforated films	Aération Films perforés
				5	3	3 w	DE		
– without leaves	– sans feuilles	0	92–95	0	21	3 m	DE		
				5	3		DE		
LEEK	POIREAU	0	≥ 95	0	21	3 m	CA, US	Vacuum or hydrocooling Yellowing ! Sealed packaging	Vacuum ou hydrocooling Jaunissement ! Emballage scellé
		0		5-10	1-3	4–5 m	US, IT		
LETTUCE	LAITUE	0 to 1	98	0	21	2–3 w	AU, IL, US	CO_2 ! C_2H_4 !! Vacuum cooling Perforated wrapping	CO_2 ! C_2H_4 !! Vacuum cooling Emballage perforé
– Iceberg	– Iceberg					3–4 w			
– Romaine	– Romaine	0	98	2	3	1 m	US		

COMMODITY CULTIVAR	LEGUMES CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
MUSHROOM	CHAMPIGNON	0	95	0	21	5–7 d	US, AU, CA, NL		
		0		15–20	18	> 7 d	US	Micro perforated films	Films micro-perforés
		0		8–10	10–15	10–20 d	IT		
OKRA	GOMBO	7 to 10	90–95	0	21	7–10 d	US, ES, AU		
ONION	OIGNON								
– green	– vert	0	92–95	0	21	1.5–3 w	DE, US		
– dry	– sec	0	65–70	0	21	6–8 m	US, CA, IT, DE,	Polyethylene liners Curing Aeration	Emballage de polyéthylène “Curing” Aération
							CH, AR		
		-2	80	0	21	10 m	NL		
PARSLEY	PERSIL	0	95–100	0	21	4–8 w	US, NL, DE	Perforated bags Icing	Sacs perforés Glaçage
				10	11	8 w	US		
PEA	POIS	-1 to 0	98	0	21	1–3 w	US, AU, NL, DE	Precooling; Icing	Préréfrigération ; Glaçage
PEPPER									
– sweet	POIVRON	7 to 12	90–95	0	21	2–3 w	US, AU, CA, NL, IT	CI ! C_2H_4 ! Rapid cooling Polybags; Waxing	CI ! C_2H_4 ! Refroidissement rapide Polybags; Enduction cireuse
		13		6	6	4–5 w	FR		
– dry (hot)	PIMENT (sec)	0 to 10	60–70	0	21	6 m	US	Drying (RH < 15%) Polybags (9 m at 0°C)	Séchage (RH < 15 %) Polybags (9 m à 0°C)
POTATO	POMME DE TERRE								
– late	– tardive	4 to 6	90–95	0	21	5–9 m	CH	CI light !! Curing (2 w at 95% RH - 20°C)	CI lumière !! Salaison (2 w à 95 % RH - 20°C)
		7 to 10	90	0	21	9 m	IT, US, NL, AR	Growth inhibitor if t > 7°C	Inhibiteur de croissance si t > 7°C
– early	– précoce	10	90	0	21	3–8 w	DE, CA	Wounds ! Light ! Heat !	Blessures ! Lumière ! Chaleur !
PUMPKIN	POTIRON	10 to 13	50–70	0	21	2–3 m	US, AU, IT	Cult. ! C_2H_4 ! High RH	Cult. ! C_2H_4 ! RH élevée
RADISH	RADIS								
– bunched	– en botte	0	90–95	0	21	1–2 w	NL, US, AU	Icing	Glaçage
– topped	– sans fanes	0	90–95	0	21	3–4 w	US, AR	Hydrocooling; Icing; Polybags	Hydrocooling; Glaçage;
– black	– noir	0	90–95	0	21	3–4 m	US	(same conditions as carrots)	Polybags (mêmes conditions que les carottes)

COMMODITY CULTIVAR	LEGUMES CULTIVAR	t (°C)	RH (%)	CO_2 (%)	O_2 (%)	PSL	SOURCES	NOTES	OBSERVATIONS
RHUBARB	RHUBARBE	0	95–100	0	21	2–4 w	ZA, US, AU, CA	Hydrocooling; Aeration; Perforated polybags	Hydrocooling; Aération; Polybags perforés
SALSIFY	SALSIFIS	0	95–98	0	21	2–4 m	US, CA, DE, NL	(see carrots)	(voir carottes)
SPINACH	EPINARD	0	95–100	0	21	1–2 w	US	Vacuum or hydrocooling; Perforated polybags; CO_2 retards yellowing	Vacuum ou hydrocooling; Polybags perforés CO_2 retarde le jaunissement
				40	10	1–2 w	JP		
SQUASH	COURGE								
– summer	– d'été	8 to 10	85–90	0	21	1–2 w	US, AU	Cult. !	Cult. !
– winter	– d'hiver	10 to 12	60–70	0	21	2–6 w	US, AU	Cult. !	Cult. !
SWEET POTATO	PATATE DOUCE	13 to 16	85–90	0	21	4–7 m	US, CA, AU, AR	CI ! Aeration Curing (1 week at 30°C)	CI ! Aération "Curing" (1 semaine à 30°C)
SWISS CHARD	BETTE	0	98	0	21	2 w	US	Precooling	Prérefrigération
		0		3	10	2 w	IT		
TOMATO	TOMATE								
– mature-green	– verte (adulte)	14 to 16	90–95	0	21	1–2 w	US, AU		
		10	85–90	0	21	5–6 w	AR		
		12	95	10	3	3 w	AU		
– turning	– tournante	12 to 15	85–90	0	21	2–3 w	IT, DE	Cult. ! CI ! Decay ! 6 w with CO_2 pretreatment (3 d at 20%)	Cult. ! CI ! Pourritures 6 w avec prétraitement au CO_2 (3 d à 20%)
		12	95	0	21	3–4 w	GR		
– ¾ ripe	– ¾ mûre	8 to 10	85–90	0	21	1–2 w	US, IL, AU, ZA		
		14	85–90	3	4	2 w	DE		
– ripe	– mûre	8 to 10	85–90	0	21	1 w	US, DE		
		4 to 5	85–90	0	21	2–3 w	GR		
TURNIP	NAVET	0	95	0	21	4–5 m	US, CA	Air circulation; Waxing	Aération ; Enduction cireuse
WATERCRESS	CRESSON	0	95–100	0	21	2–3 w	US	Vacuum or hydrocooling Perforated polybags	Vacuum ou hydrocooling Polybags perforés
YAMS	IGNAMES							CI !! (t < 15°C) Aeration Curing	CI !! (t < 15°C) Aération "Curing"
		16	70–80	0	21	6–7 m	US		
		30		0	21	3–4 w	US		

Chapter 6

Meat and poultry

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6.1 RAW MATERIALS

There are many factors in meat and poultry processing that influence the quality and safety of the final product.

Optimum meat quality is obtained from animals, which at the time of slaughter are in good condition, i.e. well fed and well handled. Different breeds do not always give the same meat quality. The type of feeding will influence the sensory quality of the meat and the susceptibility to rancidity and other oxidation reactions.

If the animals are badly handled and exposed to stress during collection and transportation to the slaughter facility, it will often have a negative effect on the eating quality of the meat. It can produce DFD (Dark-Firm-Dry) or PSE (Pale-Soft-Exudative) meat. It may also negatively impact the technological quality of meat, such as reducing the storage life and the quality of meat products (Savell *et al.*, 2005). Many countries have

legislation with minimum requirements (space, air ventilation, etc.) for the transportation of live animals from the farm to the slaughterhouse.

The animals must be handled correctly at the slaughterhouse to minimise stress, and all measures must be taken to eliminate, or at least reduce, the number of pathogenic micro-organisms in meat and poultry products (Warriss, 1990). Poultry in particular should rest for 1–2 hours prior to slaughter; this step plays a crucial role in reducing stress and allows their heart rate and breathing to return to normal. Resting ungulates at the slaughtering plant after transporting will not necessarily reduce stress, as they may become agitated by new surroundings and the presence of other animals. However, in some countries, a resting period of at least two hours is recommended for pigs, while it should not exceed 1 hour for young bulls.

Where animals are held for a short time before slaughter, they should have access to water. If held longer, such as a day or more, they should be fed. Withdrawing feed prior to slaughter is particularly important for poultry, to allow them time to empty their intestines and to reduce the risk of faecal contamination during evisceration. For broilers, this period should be 8 to 12 hours, while for turkeys, it should be 6 to 10 hours (Barbut, 2015).

6.2 SLAUGHTERING

6.2.1 Slaughtering processes

Stunning, sticking, bleeding, evisceration and dressing should be carried out quickly and hygienically to ensure a low load of microorganisms. It is very important to reduce or prevent cross-contamination of pathogenic bacteria.

The chilling of the hot carcass should normally start as soon as practicable after dressing, while avoiding cold shortening.

Poultry Scalding Loosening the feathers by immersing the birds in hot water after slaughter is an important step that facilitates de-feathering or plucking (Barbut, 2015). Large plants often use a continuous line where the birds are submerged in a long hot water tank while suspended by a moving shackle line. A higher scalding temperature better loosens the feathers but is also the harshest on the bird's skin. There are three commonly used scalding schemes: soft/semi-scalding used for broilers and young turkeys (50–53°C for 1–3 minutes), sub/medium scalding used for mature birds (50–53°C for 1–2 minutes), and hard scalding commonly used for waterfowl (59–61°C for 0.75–1.5 minutes). In the case of hard scalding, the outer layer of skin is removed during the plucking stage. Removing the epidermis often results in the skin appearing lighter, but can cause discolouration if dehydration occurs during subsequent air chilling.

6.2.2 pH decline and *rigor mortis*

In live animals, glycogen stored in muscle is used with oxygen circulating in the blood to produce energy in the form of ATP (adenosine triphosphate). ATP is used to drive and support many processes in living cells. Upon slaughter, the oxygen supply ceases, and glycogen is converted into lactic acid, causing a fall in muscle pH from 7 in the live animal to an ultimate value of between 5.5 and 6.0 in meat, and 5.9 and 6.4 in poultry.

At the same time, the ATP in the muscles is depleted and leads to the development of *rigor mortis*. *Rigor mortis* (death stiffness) is developed in about 10–30 h for beef, 8–16 h for lamb, 4–8 h for pigs, and 2–4 h for chicken.

DFD meat If an animal is subjected to severe exhaustion shortly before slaughter, the glycogen reserves decrease and the ultimate pH is higher than normal because less lactic acid is formed. An ultimate pH above 6.4 can result in DFD meat; the meat becomes dark, firm and dry. DFD meat is less suited for direct retail sale, since dark meat is considered undesirable, and the storage life in the chilled form is shorter than that of normal pH meat. DFD meat has a higher water–binding capacity than meat with a normal pH and so may be used with good results in the production of sausages and canned meat products. DFD problems can occur in beef, veal, lamb and pork.

PSE meat The problem of pale, soft, exudative meat (PSE) is confined almost entirely to pigs. Different breeds exhibit different PSE susceptibility and by removing the halothane gene, the PSE susceptibility can be reduced. The condition is caused by a low pH value in the carcass while it is still warm. The quick fall in pH immediately after slaughter is ascribed to stress immediately before slaughter.
PSE meat is of a reduced quality (modified structure, uneven colour) and has a lower water binding capacity, which results in smaller yields when pork is used in processed products.

Cold shortening Lowering the temperature of a hot carcass too rapidly, especially for beef, veal and lamb, may result in a severe localised contraction of muscle fibres, a phenomenon known as "cold shortening". This is an irreversible process that may cause considerable toughness in the meat after cooking. For beef, veal, and lamb, such toughening will occur if the meat temperature is reduced below 10°C before the pH has fallen below about 6.2. In practical terms and in the absence of electrical stimulation, the temperature of any part of beef, veal or lamb should not be permitted to fall below 10°C within 10 hours after slaughter.
Cold shortening may occur during very rapid chilling of pigs, i.e. at air temperatures below -24°C with high air velocity. However, different types of pigs in different countries do not have the same degree of susceptibility to cold shortening. Very lean pigs with a slow pH fall are the most susceptible.
Cold shortening may occur in poultry when hot boning or cutting immediately after chilling is used.
For beef, veal and lamb, electrical stimulation (▶ **Section 6.2.3**) may reduce or eliminate the problem of cold shortening.

Ageing Ageing (also called ripening or maturing) of chilled meat is accompanied by a gradual increase in tenderness. This process takes a few hours for poultry and several days or weeks for beef. The ageing time depends on the temperature, and is longer at lower temperatures.
Full ageing, at 4°C, may require up to 2 weeks for beef and 1 week for veal. During this period, the chilled carcasses are hung in chilled rooms at a relative humidity of 85% to 95%. Higher relative humidity may lead to excessive bacterial growth and lower relative humidity to unnecessarily high evaporative losses (see ▶ **Section 3.2.2**). Beef may be aged at

higher temperatures in shorter times but, under such temperature conditions, it needs to be carefully controlled to avoid excessive microbial growth.
Ageing of other meats requires different periods, such as 4 days for lamb carcasses, 2–4 days for pigs, a few hours for chickens, and about 12 hours for turkeys, all at a temperature of 4°C. As a separate process, ageing is necessary to develop the tenderness of beef and lamb, whereas it is not normally used for pork, turkey and chicken, as ageing takes place during distribution.
Chilled beef is often cut into pieces. The most valuable joints are vacuum-packed for further ageing.

6.2.3 Electrical stimulation

Immediately after bleeding, electrical stimulation of the carcass can be used for beef and lamb. This technique causes the pH to drop to about 6.4 within minutes and *rigor mortis* is sufficiently advanced within a few hours to allow rapid chilling to be applied without the risk of cold shortening. If direct freezing is required, a longer dwell period may be necessary to avoid toughening.

Electrical stimulation is especially valuable when used before hot boning or in ultra-rapid chilling processes.

In poultry, electrical stimulation is used to accelerate the time to *rigor mortis* so that tender breast meat fillets can be harvested immediately after chilling (within 3 hours of slaughter), thereby making in-line slaughter, chilling and deboning possible.

6.2.4 Boning

Splitting, cutting up, and boning of carcasses are normally carried out after the chilling process, which should take place in temperature-controlled rooms. Most countries require air temperatures in these rooms of 10°C or less to be maintained.

In this temperature range, air velocity must be kept low for the comfort of personnel (a maximum of around 0.2 m/s). Such conditions may be expensive to attain, unless air socks or similar air distribution systems are used.

Due to ergonomic concerns, a temperature above 16°C may be required in meat cutting rooms. Even at 10°C, the meat will normally be colder than the surrounding air. Therefore, air humidity must be low enough to prevent condensation on meat surfaces (see ► **Section 3.2.6**). Also, the objective is to move the meat quickly through such operations to minimise any increase in temperature, and to ensure compliance with relevant regulations. For example, making sure the EU maximum permitted temperatures of 7°C for meat from ungulates and 4°C for meat from poultry or lagomorphs are not exceeded.

Cutting rooms and equipment therein must be cleaned frequently to prevent microbial growth on any contaminated spots.

Hot boning Cutting up carcasses, especially beef, before complete chilling may result in economic advantages due to energy savings, lesser quantities of the product needing chilling, the removal of most fat and bones before chilling, and a higher yield of meat. In addition, the space occupied by the boxed, vacuum-packed boned-out meat only

requires 15% of the space of the hanging carcass sides in the chill room; consequently, which will reduce the capital cost. By using hot boning, the risk of cold shortening is increased, and joints should be held at 10–15°C for several hours before chilling begins (conditioning). Under well-controlled conditions, good quality will be preserved.
As mentioned above, electrical stimulation is especially valuable when hot boning is used. However, cutting meat into pieces implies that areas susceptible to contamination increase; thereby raising the risk of microbial growth.

6.2.5 Further processing

Meat and poultry are often further processed. Cutting and mincing are widely used processes for fresh meat and poultry. Other methods, such as curing, slicing, heat processing (pasteurisation), smoking are also frequently used in the meat industry. All processing must be carried out according to GMP (Good Manufacturing Practices), to ensure appropriate quality, stability and safety of meat and poultry products. In most countries, the HACCP system has been introduced (see ► **Section 2.1**).

6.3 CHILLING PROCESS

6.3.1 Beef, veal, lamb and pork

Typically, the chilling of these species is carried out by circulating cold air (see ► **Section 3.1.1**). Air temperature and velocity should be as uniform as possible in the chilling installations (James and James, 2002; North and Lovatt, 2012).

Rapid chilling immediately after dressing is beneficial in reducing bacterial growth, evaporative weight loss and subsequent drip on cutting. The chilling should not be so rapid as to cause cold shortening, unless the carcasses are electrically stimulated.

For chilling beef and veal or lamb, unless electrical stimulation is applied, the air temperature should not be lower than 6°C or 10°C, respectively, during the first 10 hours after slaughtering to avoid cold shortening.

For pigs the fat layer protects the meat against cold shortening, and temperatures below 10°C are often used with an air velocity of about 2 m/s in the first 2–3 hours of chilling. Cold shortening does not occur unless very cold air at high velocity is used in the chilling process. Rapid chilling in pigs, such as that achieved in multi-stage quick cooling tunnels, can result in faster cooling and less evaporative loss during the cooling stage.

Tenderstretch Hot carcasses, especially beef, are sometimes hung from the hip (H-bone) instead of the hind leg. This stretches the major muscles in the hindquarter during chilling, leading to greater tenderness in some of the most desirable cuts.

Spray chilling Evaporative weight loss during air chilling is a significant economic concern for the meat industry. Spray chilling systems have been implemented in North America, Europe and elsewhere in the world for beef, lamb and pork (Savell *et al.*, 2005). Spray chilling involves intermittent spraying of cold water on the carcasses during the first 3–8 hours post-slaughter to replace moisture lost by evaporation. The surface remains

wet, allowing for maximum mass transfer and evaporative cooling effect without increasing carcass weight loss.

6.3.2 Poultry

Sometimes, poultry is chilled in water. In some countries, air chilling is also used, almost exclusively.

Water chilling Water chilling (immersion chilling) under carefully controlled conditions is approved in Canada, the United States, the EU, etc. In many countries, regulations require monitoring and/or controlling water uptake in the carcasses, etc. Water chilling may result in water uptake from 4% to 10%.
Larger birds, such as turkeys, are often held overnight in tanks with ice water, and agitation by compressed air is blown in through pipes on the bottom for further chilling.
In the EU, chemical treatments, such as chlorine, are not allowed and a counter-current system is required, with prescribed amounts of potable water for washing eviscerated birds prior to chilling and for the chillers. The water at the bird's exit point must be below 4°C. These challenges make air chilling more common in Europe.

Air chilling Birds that are air-chilled and sold fresh are scalded at 50°C–53°C to avoid discolouration of the skin.
Air chilling is carried out in many different systems. Most systems chill the birds whilst suspended upside down on a shackle attached to a moving chain conveyor through a chilling room or tunnel (the same conveyor is often used from slaughter, to scalding and then chilling). Some systems have the birds placed on racks that move horizontally through a chiller tunnel. Air is often ducted through the bird cavity to accelerate core temperature reduction; this is called vent chilling.
Air chilling in poultry results in an evaporative weight loss of about 1%–2%. To minimise the impact of this weight loss, spray chilling (explained in ► **Section 6.3.1**) is also commonly used in poultry processing.
Crust-freezing systems may also be used. Birds wrapped in plastic are placed in chilling rooms where the air circulates with a temperature of -10°C or lower. The chilling process should be stopped when the bird's average temperature drops to about -0.5°C. The birds are then transferred to a storage room for temperature equalisation.

Combination chilling Some poultry processors use a two-stage "combination chilling" system, where the carcasses are initially chilled in cold water and subsequently cooled in cold air. This two-stage solution is often employed when a processor aims to enhance the capacity of their existing air-cooling system, especially if they have limited space for more air cooling. Adding a water-cooling system to increase total cooling capacity is often a good solution.

Second-stage cooling Chilling is normally followed by cutting, further processing, grading, and/or packaging. A second and final stage of cooling to the intended storage or transportation temperature is indicated.
A special air chilling system may be used, but often the products are placed in a storage room.

6.4 STORAGE, TRANSPORT AND DISPLAY

If previously chilled meat is to be kept in optimal conditions for a maximum possible length of time, the temperature should be maintained as low as possible, short of freezing (except in superchilling), throughout storage, transportation and display.

It is important to recognise that the refrigeration systems used in storage rooms, in transportation (and distribution) vehicles, and in retail cabinets are only designed to maintain the temperature of previously cooled meat. Loading such systems with partly cooled meat may cause problems (e.g. disruptions, reduction in meat quality), if the subsequent stages of the cold chain are incapable of pulling the temperature down to the design value (see ▶ **Section 3.1**).

6.4.1 Storage

In cold storage rooms for meat, the air temperature has traditionally been about 4°C, but for longer storage, it should be 0°C to 2°C, and more recently as low as -1.5°C has been used.

In storage rooms for unprotected carcasses and sides, it is of great importance to have uniform air distribution and only moderate air velocities, such as 0.1 to 0.3 m/s, in order to prevent excessive evaporative weight losses from large, unprotected carcass surfaces. Care should be exercised to avoid condensation on the meat surface when it is taken out of cold rooms.

In cold storage rooms, meat is usually hung from hooks on rails as half or quarter carcasses, without protection against superficial desiccation. The relative humidity should range from 90 to 95% (see ▶ **Section 3.2.2**).

6.4.2 Transportation and display

Transportation must be carried out in insulated vehicles with a low K-value, i.e. 0.70 W/(m^2.K) or less (see ▶ **Section 3.3**).

For chilled meat being shipped overseas, the uniformity requirements for temperature and air circulation are stricter to avoid microbial spoilage.

In supermarkets, meat and poultry are often placed in chilled display cabinets.

6.5 PACKAGING

Further information on packaging material and methods is given in ▶ **Section 2.3**.

6.5.1 Packaging of meat

Prime and subprime cuts and boneless joints, particularly of beef, are often vacuum-packed in plastic bags with low permeability for water vapour and gases, especially oxygen. This results in a lower weight loss and reduces the rate of growth of aerobic microorganisms. This packaging method is used for storage or transportation over long periods. It is often used for ageing of beef.

Where vacuum packaging is used, a greatly increased storage life is obtained over unwrapped meat or meat packed in air-permeable films. This effect is due to the biochemical processes in the meat and the bacteria already present, which will quickly use up any available oxygen. Thus, a microclimate of oxygen-free, high-carbon dioxide conditions prevails, inhibitory to many microorganisms. When growth does occur, this will mainly be lactic-acid-forming bacteria, which will extend storage life.

The removal of oxygen will cause the reduction of oxymyoglobin into myoglobin with a purple colour. The bright red colour (oxymyoglobin) usually attributed to fresh beef is restored when the package is opened and the meat exposed to the atmosphere for 15 to 30 minutes. However, the unfamiliar purple colour makes vacuum-packed meat less appealing in a retail context and may interfere with consumer acceptability.

Vacuum-packed meat is mainly used for further processing, such as cutting and retail packaging in supermarkets.

Modified atmosphere packaging (see also ► **Section 2.3.1**) For storage and transport of large cuts of meat, modified atmosphere packaging may be used instead of vacuum packaging. The packaging material has a very low permeability to water vapour and gases; the gas mixture does not contain any oxygen and is often above 50% CO_2.
A very long storage life, about 16 weeks for lamb and beef, can be obtained if the meat is packed in an impermeable alufoil laminate, filled with 100% CO_2, and maintained at about -1.5°C. The oxygen concentration must be kept very low to prevent changes in meat colour.

Retail packaging Traditionally, meat has been packed using overwrap with high oxygen permeability plastic films, typically above 4–5000 ml/(m^2.day.bar), in order to maintain the bright red colour of meat during display. Practical storage life of meat cuts is about 1 to 4 days at a temperature range between 2°C and 4°C.
Today, modified atmosphere packaging is commonly used, especially for beef. The packaging material has a very low permeability to water vapour and gases; the packages are filled with mixtures such as about 80% oxygen and 20% carbon dioxide.
This maintains the bright red colour and reduces microbial growth. The storage life of minced beef is increased from between 1 and 2 days up to between 3 and 5 days at 2°C or below. For beef cuts, it increases from between 2 and 5 days to between 8 and 12 days at the same temperature.
The increased storage life highly depends on the initial bacterial count and on strict maintenance of low temperature, particularly in the display cabinet. In the case of minced meat in particular, exposure to high oxygen concentrations for several days may lead to oxidative changes, such as rancidity.

Cured meat products Cured meat products such as ham and bacon may be vacuum-packed in order to obtain a reasonable storage life. The growth of most spoilage bacteria is reduced by creating a low oxygen and high CO_2 environment. It also avoids colour fading, as the colour of cured meat, mostly in pork, turns brown or grey in the presence of oxygen. Modified atmosphere packaging, e.g. 50% nitrogen and 50% CO_2, offers the same

storage life as vacuum packaging and has some advantages, such as improved appearance of the package, and easier slice separation.
In some cured meat products, lighting over display cabinets can accelerate colour fading. This can be reduced by using a plastic with a very low oxygen permeability and by creating a very low residual amount of oxygen after packaging.

6.5.2 Packaging of poultry

For wholesale distribution, poultry is sometimes packed with crushed ice (ice-packed) or with dry ice (dry pack).

Modified atmosphere packaging is also used: several chickens are placed in a large plastic bag, filled with a mixture of nitrogen and at least 20% CO_2. The storage life lasts 2 to 3 weeks at about 2°C.

Retail packaging The conventional packaging method for chilled poultry is as described for meat, i.e. in plastic bags or trays with plastic overwrap. Vacuum packaging or modified atmosphere packaging can be used for poultry cuts or portions.

6.6 QUALITY-INFLUENCING FACTORS

Microorganisms are generally the main agents of spoilage in chilled meat and poultry. They are primarily present on the meat surface after slaughter. The microorganisms may multiply on the meat surface, and their main deteriorating effect is to produce unpleasant smelling and tasting compounds, ultimately making the meat inedible.

It is therefore essential that the number of spoilage microorganisms present on the product at the start of storage is as low as practical.

Generally, meat with a high pH, e.g. DFD meat, has a reduced storage life. It is recommended or prescribed that beef with a pH above 6 (in some countries 5.8) should not be vacuum-packed.

Although microbial growth is the main problem, rancidity can also be a storage life-limiting factor in meat and poultry products. This will depend on the concentration of unsaturated fatty acids and their degree of unsaturation. Thus, rancidity is a greater issue in pork than in beef or lamb. Rancidity can be reduced or avoided by preventing oxygen from coming into contact with the product, for example, by vacuum packaging or modified atmosphere packaging with a low oxygen concentration (0.5% or less).

Colour changes may also reduce the storage life of meat and meat products. The packaging's influence has been discussed above (▶ **Section 6.5.1**). It is crucial to consider both the colour shelf life and the microbiological shelf life, as they are not necessarily identical.

Manufacturing processes such as slicing and mincing will increase the risk of oxidative reactions (and of microbial growth), thus shortening the storage life. Curing reduces water activity, which in turn extends the storage life.

Heating, such as in pasteurisation, reduces the number of bacteria and can extend the storage life, but problems with the so-called "Warmed-Over-Flavour" may occur for some meat and poultry products.

6.7 RECOMMENDED STORAGE CONDITIONS

Generally, meat and poultry should be stored as close to the initial freezing point as possible; about -1.5°C for raw meat and -3°C or below for cured meat. Storage at temperatures below the initial freezing point is used in processes such as superchilling. In superchilling, the precooled product is stored at temperatures down to -2°C and up to 20% of the available water is frozen.

6.8 PRACTICAL STORAGE LIFE TABLE

Relative humidity should be above 90%, unless otherwise stated in the notes or if the product is packed in impermeable (tight) plastic materials.

► **Table 6.1** shows the practical storage life of certain widely consumed meat products.

Table 6.1 Chilled animal products

Product	Temperature °C	Packaging	PSL	Notes
Beef carcasses	4	unwrapped	10–14 d	
Beef carcasses	-1.5–0	unwrapped	3–5 w	
Beef, boneless joints	-1.5–0	vacuum-packed	12 w	
Beef, retail cuts	4	oxygen permeable packaging	2–5 d	
Beef, retail cuts	4	vacuum-packed	2 w	
Beef, retail cuts	2	modified atmosphere packaging	9–12 d	80% O_2 + 20% CO_2
Minced beef	4	oxygen permeable packaging	1–2 d	
Minced beef	4	vacuum-packed	7–14 d	
Minced beef	2	modified atmosphere packaging	3–5 d	80% O_2 + 20% CO_2
Pork carcasses	4	unwrapped	8 d	
Pork carcasses	-1.5–0	unwrapped	3 w	
Pork, joints	-1.5–0	vacuum-packed	3–5w	
Pork, retail cuts	4	oxygen permeable packaging	3 d	
Cured, sliced pork products	4	vacuum–packed	3–6w	Depend on a_w, etc.

Product	Temperature °C	Packaging	PSL	Notes
Cured, sliced pork products	4	modified atmosphere packaging	3–6w	<1% O_2, 20% CO_2
Wiltshire bacon	4	unwrapped	3–5w	
Lamb	-1.5–0	unwrapped	3–4 w	
Lamb	-1.5	controlled atmosphere packaging (100% CO_2)	16 w	
Lamb and mutton	-1.5–0	vacuum-packed	10 w	
Veal	-1.5–0	unwrapped	3 w	
Edible offal	-1.5–0	unwrapped	1 w	
Lard, without antioxidant	-1–0	paper	4–8 m	
Chicken, eviscerated	4	oxygen permeable plastic packaging	1 w	
Chicken, eviscerated	0	oxygen permeable plastic packaging	2 w	
Chicken, eviscerated	-2	oxygen permeable plastic packaging	3–4 w	

Keys:
d = day w = week m = month

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Chapter 7

Eggs

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Eggs are a staple food consumed globally, recognised for their high nutritional value, affordability, and broad cultural acceptance. In addition to being a source of protein with a well-balanced amino acid profile, they provide essential vitamins (A, D, E, K, B-complex) and minerals (iron, phosphorus, selenium, and zinc), along with antioxidant carotenoids such as lutein and zeaxanthin. Maintaining these nutritional qualities during storage is critical, highlighting the role of proper refrigeration in preserving both the safety and health benefits of eggs.

In recent decades, global egg production has seen significant growth, with favourable expectations for continued increases in yield. Although there have been significant improvements in poultry genetics, nutrition, and the automation of housing facilities, the post-laying phase receives less attention than production efficiency. In this phase, refrigeration is the primary method to slow the rate of deterioration and preserve the internal quality of eggs during storage. From a commercial perspective, the best strategy is to store eggs chilled at temperatures above their initial freezing point, avoiding freezing, in accordance with local legislation.

7.1 EGGSHELL MICROBIOLOGY

Eggs are protected by multiple natural barriers that help maintain quality and limit microbial contamination. The eggshell, composed primarily of calcium carbonate, is a porous structure that allows gas exchange while serving as a physical barrier, and it is covered by the cuticle, a thin protective layer that further reduces microbial penetration. Below the eggshell, the inner and outer membranes provide additional protection, while the albumen contains antimicrobial proteins that inhibit the growth of both naturally occurring and pathogenic microorganisms (Oliveira and Oliveira, 2013). Understanding these anatomical and biochemical defences is essential for assessing contamination routes and mechanisms of quality deterioration. Proper handling and refrigeration play a critical role in preserving egg safety and nutritional quality.

Even eggs with low or no initial contamination may become contaminated during the laying process, primarily through contact with contaminated environments or utensils. Excreta, soil, and dust are the main sources of contamination, as they can carry pathogenic microorganisms that are transferred to the eggshell during or shortly after laying. This process can compromise the sanitary quality of the product, facilitating the entry of harmful bacteria such as *Salmonella*, thereby posing a public health risk.

Maintaining eggshell integrity and the protective cuticle layer is important for preventing bacterial invasion, as these physical barriers work in concert with the inner membranes and antimicrobial components of the albumen to limit microbial penetration. However, bacteria can still penetrate the eggshell under specific circumstances. Mechanisms of trans-shell penetration include temperature gradients that create condensation on the shell's surface, pressure differentials that drive microbial movement, and localised breaches in the cuticle or eggshell structure. The quality of the shell, particularly its thickness, hinders pathogen entry. Factors such as the egg's origin, hen vaccination and the hygiene conditions at the laying site significantly influence product safety and quality.

Microbial contamination can occur at different stages:

- **Laying** The egg may become contaminated through contact with hen's excreta or materials present in the nest.
- **Storage and transport** Contact with dirty surfaces, improper handling, and high humidity promote microorganism adhesion.
- **Processing and consumption** Broken eggs can release microorganisms onto food and surfaces, increasing the risk of cross-contamination.

Although bacteria are present on the eggshell immediately after laying, bacterial penetration becomes more significant after 4 to 5 days of storage. Egg storage must be carefully controlled to prevent unwanted condensation. In particular, temperature fluctuations, which cause surface condensation and retraction of egg contents, can facilitate bacterial penetration by allowing the absorption of water and microorganisms from the shell.

Among the various microorganisms inhabiting the eggshell, some alter the egg's characteristics, while others are potential pathogens responsible for foodborne illnesses in

humans. Gram-positive bacteria, such as *Staphylococcus* and *Bacillus*, often predominate in the eggshell microbiota, likely due to their thicker peptidoglycan cell walls, which confer greater resistance to environmental stressors, including desiccation and organic matter (Oliveira and Oliveira, 2013). In contrast, Gram-negative bacteria are mainly associated with the contamination of spoiled eggs.

The primary bacteria found on eggshells belong to genera such as *Pseudomonas, Alcaligenes, Proteus, Arthrobacter, Escherichia, Serratia, Aeromonas, Hafnia, Citrobacter, Salmonella, Micrococcus, Staphylococcus,* and *Bacillus*. The most relevant bacteria in the context of foodborne diseases, particularly those linked to the consumption of chicken eggs, include *Salmonella spp., Campylobacter spp., Listeria spp., Staphylococcus spp.,* and *Escherichia spp*. Additionally, fungi such *as Candida spp., Penicillium spp.,* and *Aspergillus spp.* may also be present.

Low temperatures reduce enzymatic activity and bacterial growth. When combined with controlled relative humidity during refrigeration, moisture on the eggshell surface is minimised, thereby reducing bacterial penetration through eggshell pores. Under these conditions, eggs present a lower risk of releasing bacteria into the environment, reducing the potential for cross-contamination of other foods.

7.2 EGG QUALITY

Egg quality is defined by the set of external and internal attributes that determine its market acceptability. Key quality factors include characteristic flavour and odour, eggshell appearance, albumen consistency, air cell size, and yolk colour. Both external attributes, such as eggshell integrity and hygiene, and internal attributes, such as albumen and yolk quality, are important in egg classification. Egg quality is influenced by several factors, including genetics, age, nutrition, housing, and storage conditions. Among these, storage conditions, such as temperature control, humidity, and duration, are often overlooked in both farm-level handling and post-harvest distribution, even though they play a decisive role in preserving sensory and nutritional quality as well as microbial safety.

7.3 SHELF LIFE

The shelf life of eggs is directly influenced by storage conditions, proper handling (such as segregation of damaged eggs), and packaging. The expiration date should be determined based on these factors, as well as the condition of the eggs at the time of receipt, including transportation and storage duration. Currently, there is no universal mandatory expiration date for shell eggs. The “best before” date is determined by the grading centre, and its inclusion on packaging may vary depending on national legislation. Scientifically, egg shelf life is influenced by changes in albumen pH, thinning of the albumen, air cell enlargement, and microbial growth, all of which can affect both quality and safety. It is important to distinguish between terms: a “best before” date indicates the period during which the egg maintains optimal quality, an “expiration date” refers to the end of safe consumption, and a “consume-by” date provides guidance on when eggs should be used to minimise health risks.

In the United States, the expiration date is calculated up to 30 days after packaging, and the "best before" date cannot exceed 45 days. In India, eggs stored at 28°C are deemed fresh for up to 12 days. In Europe, the expiration date must be indicated, with a maximum of 28 days after laying, and delivery to the consumer must occur within 21 days. In Japan, date labelling for foods is regulated; however, there is no uniform, rigid standard for "expiration" or "consume-by" dates specifically applied to shell eggs, as observed in other regions. In South Africa, the expiration date is 40 days after laying for regular eggs and 56 days for pasteurised eggs, with variations depending on seasonal conditions. In Brazil, the legislation establishes a maximum expiration date of about 28 days, with mandatory inclusion of packaging and expiration dates.

7.4 PHYSICOCHEMICAL CHANGES AND QUALITY DETERIORATION DURING STORAGE

Beyond its well-balanced nutritional composition, the egg stands out as an economical source of high-quality protein. However, as an animal-derived product, it is perishable and may lose quality if not properly handled and stored. From the moment of oviposition, eggs undergo physicochemical changes in the albumen and yolk, which can affect their flavour, freshness, and palatability. Storage time and temperature directly influence this degradation, as increased carbon dioxide exchange through the eggshell accelerates quality loss, particularly at ambient temperature.

Quality loss is an inevitable and ongoing process that can be exacerbated by various factors, such as microbiological contamination, as well as high humidity and temperature during storage. The longer the storage period, the greater the deterioration of internal quality due to carbon dioxide movement through the eggshell, particularly under environmental conditions that accelerate these processes.

Fresh eggs are characterised by a clear, transparent, dense, and elevated albumen, with only a small portion of liquid fraction. As storage time increases, the proportion of liquid albumen rises at the expense of the dense fraction. The liquefaction and loss of viscosity in the thick albumen result from the hydrolysis of amino acid chains, which, when degraded, release bound water from large protein molecules.

Albumen liquefaction is one of the easiest ways to identify egg deterioration and quality loss, and it is easily recognised by consumers. ▶ **Table 7.1** presents quality attributes that change during egg storage, along with the ideal parameters observed in fresh eggs.

7.4.1 Weight loss

Weight loss in eggs is one of the primary indicators used to assess their freshness, making it essential for monitoring the degradation of egg quality during storage under controlled conditions. However, determining weight loss under practical conditions can be challenging. Controlling weight loss is important, as eggs are classified based on their weight, and deviations can affect grading and labelling.

Table 7.1 Main quality factors affected during storage

Parameter	Cause	Indicators
Egg weight (↓)	Loss of ammonia, nitrogen and hydrogen sulphide are products of the chemical degradation of their organic constituents.	2 to 3% loss of egg weight during storage is acceptable.
Haugh unit (↓)	Liquefaction and loss of viscosity of dense albumen occur because of the hydrolysis of amino acid chains, which, when degraded, release water linked to large protein molecules	Class AA (>72), Class A (72–60), B (59–31); or Class C (30).
Albumen and yolk pH (↑)	Biochemical changes in the yolk and the transfer of water from the albumen.	The albumen pH varies between 7.5 and 8.5 immediately after oviposition
Yolk index (↑)	The water released during the hydrolysis reaction of the albumen's amino acids is transferred to the yolk, which consequently increases in weight, becoming decentralised and less dense.	A fresh egg of good quality has a yolk index of around 0.45.

Eggs are typically classified at the time of packaging, a few hours after laying. If storage is inadequate, they may reach the consumer with a weight lower than that declared on the label. Weight loss occurs gradually during storage, primarily due to the high porosity of the eggshell, which facilitates water evaporation to the external environment. This process is accelerated at higher temperatures, whereas proper refrigeration slows moisture loss and helps preserve internal quality. Acceptable weight loss for maintaining egg quality generally ranges from 3% to 5% over standard storage periods (FAO, 2003).

Chilling is effective in maintaining the internal quality of eggs for a longer period. The data presented in ▶ **Table 7.2** illustrates the impact of storage conditions on the egg weight.

Table 7.2 Weight loss of eggs (%) after 28 days of storage

	Fresh egg	28 days
Room temperature (24°C)	0	4.08%
Refrigeration (4°C)	0	1.78%

Experimental data by da Silva Pires (unpublished). These results were obtained under controlled laboratory conditions and are provided for illustrative purposes.

7.4.2 Albumen pH

Albumen pH is a more reliable indicator for assessing egg freshness during storage, as it is not influenced by the age or breed of the hen (▶ **Table 7.3**). A fresh egg typically has an albumen pH ranging from 7.5 to 8.5. During storage, eggs lose carbon dioxide through the eggshell, leading to an increase in albumen pH. The rise in albumen alkalinity is associated with a decrease in egg quality. Eggs stored at high temperatures can exhibit pH values above 9 after 30 days of storage.

Chilling reduces the rate of CO_2 loss from the egg's interior, thereby slowing the deterioration of albumen quality.

Table 7.3 Albumen pH of eggs after 28 days of storage

	Fresh egg	28 days
Room temperature (24°C)	7.8	9.2
Refrigeration (4°C)	7.8	9.0

Experimental data by da Silva Pires (unpublished). These results were obtained under controlled laboratory conditions and are provided for illustrative purposes.

The difference in pH between chilled and room-temperature eggs reflects the reduced rate of CO_2 loss under cold storage. The analysis of the results reinforces the importance of controlling storage conditions as a key factor in preserving egg quality.

7.4.3 Haugh unit

The Haugh unit (HU) is a measure used to evaluate albumen quality and is widely employed for commercial egg classification and freshness determination. The Haugh unit relates the height of the dense albumen to the egg's weight. The greater the albumen height, the better the egg quality, as it indicates greater freshness. Older eggs tend to have more liquid albumen with a lower height, resulting in a lower HU score.

During storage, liquefaction and loss of viscosity of the dense albumen occur because of amino acid chain hydrolysis, which releases water when degraded. However, the HU uses egg weight as one of its parameters, and this factor may be influenced by other variables, such as the hen's genetics and age.

The data in ▶ **Table 7.4** reveals the importance of chilling in preserving the internal characteristics of eggs.

Table 7.4 Haugh unit of eggs after 28 days of storage

	Fresh egg	28 days
Room temperature (24°C)	82	66
Refrigeration (4°C)	82	74

Experimental data by da Silva Pires (unpublished). These results were obtained under controlled laboratory conditions and are provided for illustrative purposes.

7.4.4 Yolk index

The yolk index is a measure used to evaluate yolk quality. It is calculated as the ratio between yolk height and yolk diameter serving as an indicator of egg freshness and yolk quality. During the egg storage period, water from the albumen diffuses into the yolk by osmosis. This causes the yolk to increase in volume and become more fluid, leading to an increase in its diameter and a reduction in its height. Consequently, the yolk index decreases (▶ **Table 7.5**).

Table 7.5 Yolk index of eggs after 28 days of storage

	Fresh egg	28 days
Room temperature (24°C)	0.42	0.33
Refrigeration (4°C)	0.42	0.38

Experimental data by da Silva Pires (unpublished). These results were obtained under controlled laboratory conditions and are provided for illustrative purposes.

7.5 EGG CLEANING/WASHING

Another factor that can impact the quality and shelf life of eggs is the eggshell washing process. Eggs are washed before packaging to remove dirt and poultry excreta and to reduce microbial contamination of the eggshell. Characteristics of the eggshell, such as thickness, the amount of cuticle present, and the thickness of the individual layers, may be altered by washing, potentially resulting in partial or total removal of the cuticle.

The practice of egg washing remains a controversial issue in terms of its impact on shell integrity and microbial safety. In Brazil, egg washing before breaking for industrial processing is recommended and should be performed using mechanical devices that follow procedures designed to prevent microbial penetration into the egg. The United States, Japan, and Australia also employ egg washing practices, while many countries, including the European Union members and the United Kingdom, have resisted this practice.

7.6 ON-FARM EGG STORAGE

Although egg storage at the farm level represents one of the last handling stages within the production phase, its importance should not be underestimated, as it can compromise all the work previously done. Storage can be performed at room temperature or under refrigeration, depending on the regulations of each country. However, two factors essential to internal egg quality need to be highlighted: temperature and storage duration.

Even over short periods, proper storage conditions are essential to maintain egg quality. While refrigeration helps preserve eggs, internal quality tends to decrease over time, regardless of storage conditions. In countries where eggs are stored at room temperature, it is recommended that the storage area be dry, well-ventilated, free from unpleasant odours, and pest-free. When chilled to 0°C, eggs can successfully be maintained

for up to six months. However, interruptions in the cold chain should be avoided. Abrupt temperature fluctuations can cause condensation on the shell, increasing the risk of contamination.

In cases where refrigeration is necessary, attention should be given to the quality of primary and secondary packaging, with preference given to trays and cartons with low water absorption capacity.

7.7 TRANSPORTATION TEMPERATURE

During loading and transport, eggs must be continuously protected from temperatures that could compromise their quality, accelerate deterioration, or increase the risk of contamination (▶ **Table 7.6**).

Table 7.6 Recommended temperatures for egg loading and transport

	Transportation within 2–3 days	Transportation within 5–6 days
Max. temperature during loading	6°C	3°C
Recommended temperature during transportation	-1 to 3°C	-1 to 1°C
Acceptable temperature during transportation	1 to 6°C	1 to 3°C

Source: FAO (2003)

7.8 REGIONAL DIFFERENCES IN EGG REFRIGERATION

Latin America and Brazil

In Latin America, including Brazil, refrigeration of shell eggs is not legally required. In Brazil, eggs are commonly stored at room temperature in markets. However, the Brazilian Health Regulatory Agency does recommend refrigeration for domestic storage (ANVISA, 2009).

Premium eggs, such as free-range or organic, are more frequently kept refrigerated, especially in urban supermarkets. Once brought home, though, they are often stored in the refrigerator door, a common but unsuitable practice, since frequent opening leads to temperature fluctuations that can negatively affect egg quality and reduce shelf life.

Europe

In the European Union, refrigeration of eggs prior to retail sale is not mandatory. Historically, EC Regulation No. 589/2008 discouraged refrigeration before retail (EC, 2008) with the presumption that condensation caused by temperature fluctuations may facilitate bacterial ingress into the eggshell. Regulation (EC) 589/2008 has been

repealed and replaced by Regulation (EU) 2023/2465, which similarly prescribes that Class A eggs should not be treated for preservation or chilled at temperatures below 5°C. However, eggs kept below 5°C during transport for up to 24 hours or at retail premises (or attached annexes) for up to 72 hours are not considered as chilled (EC, 2023).

In many European countries, strict hygiene regulations and relatively mild climates permit the practice of ambient storage until retail, with refrigeration used selectively in warmer seasons or southern regions of Europe. Although legislation restricts chilling practices, the European Food Safety Authority has issued scientific opinions and policy documents that strongly endorse the refrigeration of eggs (EFSA, 2009, 2014).

United States

In contrast to Europe and Latin America, the United States requires that shell eggs be refrigerated and maintained at an ambient air temperature of 7.2°C (45°F) or lower during storage, transportation, and retail display (► **Figure 7.1**) for eggs that have not been treated to destroy Salmonella. This requirement, established through FDA (2009) regulations, particularly the FDA Egg Safety Rule (21 CFR Part 118), forms part of the national strategy to reduce the risk of *Salmonella enteritidis* infection associated with shell eggs.



Figure 7.1 Washed and packaged eggs stored in chilled state prior to distribution. (Courtesy of the American Egg Board and USDA; D3993-1)

This integrated approach in the United States combines mandatory egg washing, rapid cooling and refrigeration, and microbial safety controls, reflecting a public health, focused egg safety system that is frequently cited internationally as a reference regulatory model. In contrast, many European countries and the United Kingdom prioritise egg integrity and limit washing practices, relying instead on strict handling, labelling, and storage regulations to ensure safety. These regional differences highlight the variety of strategies used worldwide to maintain egg quality and protect public health.

▶ **Table 7.7** summarises the main regulatory differences and refrigeration practices observed across key regions:

Table 7.7 Comparative overview of egg refrigeration policies by region

Region	Refrigeration Policy	Temperature Range	Notes
USA	Mandatory	< 7.2°C	Cold chain and egg washing required
European Union	Not mandatory before retail; chilling below 5°C prohibited	≥ 5°C (Regulation 2023/2465)	Focus on condensation prevention
Brazil / Latin America	Not required	Ambient (retail), 0–4°C (recommended domestic)	Refrigeration typically reserved for premium products

7.9 CHALLENGES IN INTERNATIONAL EGG TRADE

The varying legislations on egg refrigeration worldwide reflect different scientific and regulatory approaches to food safety (Guyonnet, 2023). Divergent chilling requirements, such as mandatory refrigeration versus ambient storage, represent a major challenge in international egg trade, particularly when eggs are exported between countries with contrasting temperature regulations.

These differences often require adjustments in packaging, transportation, and cold chain logistics to comply with importing country standards. The need for temperature-controlled transport, continuous monitoring, and strict cold chain maintenance increases operational complexity and costs and raises the risk of shipment rejection in cases of temperature deviations.

Historical Salmonella outbreaks have strongly influenced national chilling policies for shell eggs, reinforcing refrigeration as a key public health strategy (Bermudez-Aguirre *et al*., 2025). Although harmonisation of international standards remains challenging due to climatic and regulatory diversity, alignment of refrigeration practices is critical to ensure egg safety and facilitate international trade.

7.10 KEY RECOMMENDATIONS FOR EGG CHILLING

Storage Temperature Eggs should be stored between 0 and 4°C to preserve internal quality, inhibit microbial growth, and reduce moisture loss. However, regional legislation must be considered.

Regulatory frameworks

European Union Regulation (EC, 2023) Eggs are not recommended for systematic

chilling below 5°C along the supply chain, although short-term exposure (up to 24 h during transport and 72 h at retail) is acceptable.

United States Regulation Refrigeration is mandatory from laying to retail. Maintain temperatures below 7.2°C.

Technical recommendations

Follow ASHRAE standards:

- Washing: Use water 11°C warmer than the egg, at 43–52°C.
- Drying: Immediate drying is mandatory to prevent microbial ingress.
- Cold chain: Ensure uninterrupted refrigeration with forced-air systems for rapid chilling.

Minimum Temperature Limit Avoid temperatures approaching freezing, as ice crystal formation may cause cracks and compromise shell integrity. The initial freezing point of egg white and yolk is reported to be -0.45°C and -0.58°C, respectively (Musil and Orel, 1958). In the shell, the intact egg contents may be chilled to a temperature of -3°C without becoming frozen. Thus, for transport and storage purposes, the practical freezing point of whole raw eggs in the shell is generally assumed to be -2.2°C (Ashby, 1995).

Condensation Control To prevent surface condensation, avoid abrupt temperature fluctuations. Eggs should not be transferred directly from cold storage to warmer environments without transition protocols.

Packaging and farm storage Use low-absorption trays. Store in dry, well-ventilated, odour-free environments. When chilled, eggs may be kept for up to 6 months if freezing is avoided.

Transport Maintain egg temperature during transport at -1°C to 3°C, depending on duration, with loading temperatures not exceeding 6°C to avoid quality loss and microbial proliferation. This threshold is based on internationally recognised technical guidelines for refrigerated egg transport, which recommend a maximum loading temperature of 6°C to minimise deterioration (FAO, 2003).

The production and commercialisation of high-quality eggs are essential for ensuring food safety and meeting global protein demands. Refrigeration plays a central role, not only in maintaining internal quality parameters, but also in reducing microbial growth, particularly of *Salmonella enteritidis*. While the benefits of refrigeration are well documented, practices and regulations still vary widely across regions (Fikiin *et al*., 2020). The United States has implemented a mandatory cold chain system with temperature thresholds established to mitigate microbial risk and quality deterioration. In contrast, under Regulation (EU) 2023/2465, the European Union prevents the premium Class A eggs from being chilled below 5°C, due to concerns regarding possible condensation-related contamination throughout the food supply chain.

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Chapter 8

Fishery products

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8.1 INTRODUCTION

In most markets, there is a high demand for fresh fish. The chilling of fresh fish is a critical process for maintaining the quality and safety of fish products from catch to consumption. Fish are highly perishable, and without proper chilling, quality can quickly deteriorate. Ideally, the storage's ambient temperature should be maintained at -1 to 0°C to preserve quality. However, achieving this ideal condition for the diverse array of

fish species, fish products, processing methods, and technologies remains challenging. Different species exhibit substantial differences in their initial properties, and they may originate from warm, temperate, or cold waters. Consequently, the chilling method must be adapted to the product, process, and market.

Fish quality is a complex concept involving many factors, such as food safety, nutritional quality, availability, product type and convenience, freshness and sensory quality. Several factors influence the quality of chilled fish, including the freshness of the catch, temperature control and hygiene. Effective chilling of fresh fish is essential to ensure consumers receive high-quality and safe-to-eat products. Maintaining a strict cold chain and following the best handling and storage practices preserves the fish's original quality as much as possible.

Traditional preservation processes, such as curing, salting, drying, and fermentation, are most often used in combination with chilling. The interactions between chilling and these processes, as well as the addition of chemical preservatives are important, especially for processed, chilled fishery products.

8.2 RAW MATERIAL

8.2.1 Intrinsic quality

As previously mentioned, fish include a wide variety of species, and different methods and technologies are available for farming, harvesting, and processing of raw material. Furthermore, fish is used in a wide range of products, from whole fish and fresh fillets to processed fish like salted fish, oils, and by-products. The quality and characteristics of fish as a raw material depend on intrinsic factors, as well as the fishing ground and catching method.

The intrinsic quality of fish refers to the sum of attributes inherent to the raw material. These attributes include the species, size, sexual maturity, and the habitat where the fish was caught or harvested, such as the fishing ground, feed, and seasonal variations (Castell, 1971). The biological status of the fish is important as the state of feeding leads to variations in ultimate pH and in enzyme activity, which have large effects on shelf life. For example, small, ungutted fish have a very short storage life, because enzyme activity may result in rapid belly bursting, rendering them unfit for human consumption.

Proper handling from the moment of catch or harvest is essential to preserve the intrinsic quality of fish. This includes immediate chilling and hygienic processing, because poor handling practices can lead to a rapid decline in quality. Fishing is a hunting operation, and the catch can only be predicted to some extent. In aquaculture, the harvest is easier to plan, allowing a choice of size and other characteristics such as colour and fatness.

Freshness is a primary indicator of fish quality. Fresh fish should have a clean, ocean-like smell, bright eyes, and the gills should be red or pink. The visual appeal of fish, including its colour, size and shape, is important for consumer acceptance and is a critical aspect of its intrinsic quality. High-quality fish should have a pleasant flavour and a texture that is appropriate for the species.

8.2.2 Quality influencing factors

Fish are highly perishable due to their high moisture content, neutral pH, and abundant resident microbiota, all of which facilitate microbial and biochemical spoilage (Amit *et al.*, 2017). Analyses of the proximate composition of raw fish muscle show that most species contain between 60% and 80% water. Species with high fat content, like mackerel and herring, exhibit lower moisture content, whereas lean species, such as cod, have higher moisture contents. Spoilage activities occurring in fish after harvest cause significant changes in their sensory and nutritional properties, which limit their shelf-life and are perceived by consumers as a loss in freshness.

The loss of freshness and quality in chilled fish, which induce unfavourable changes in fish odour, flavour and texture, and raise food safety concerns is caused by three main processes: autolysis, microbial growth, and oxidation. These processes are temperature dependent, generally slowing down as the temperature decreases. This explains the need to chill fish and fish products rapidly and to maintain low temperatures during handling and further processing. The early chemical and biochemical changes are described as autolytic. The later changes are dominated by microbial action and are described as spoilage, subsequently resulting in putrefaction. In addition, the degree of oxidative changes of fat is important when the freshness and quality of fatty fish are considered.

The primary cause of spoilage in chilled fish and fishery products is microbial growth. Microorganisms naturally exist on the skin and gills, and in the intestines of fish, as well as on processing equipment. They transfer to the flesh, which is initially sterile in healthy fish, during handling and processing, and may enter the flesh more easily as autolytic degradation weakens tissue structure. Bacteria multiply rapidly, influenced by temperature and available nutrients. As they grow, they produce compounds that result in unpleasant odours and flavours, leading to deterioration.

Fish and shellfish contain varied microflora, the composition of which is dependent on environmental factors. Fish caught in colder waters have a predominance of psychrophilic or psychrotrophic microorganisms, and the specific spoilage organisms for cold-water species are dominated by *Shewanella*, *Photobacterium*, and *Pseudomonas*. This means they grow at temperatures between 0°C and 5°C, and therefore traditional chilling is less efficient at preventing microbial growth as it is for other products. In fish from cold waters, this microflora is already present on the fish and will increase in number during storage. In fish from warmer waters, the microflora is mainly mesophilic, and therefore the change in environment towards 0°C storage has a positive effect. The initial number of psychrophilic bacteria is low in fish from warmer waters. Therefore, warm-water species generally have a longer shelf life than cold-water species when stored in ice.

In fatty fish species rich in polyunsaturated fatty acids, such as sardine, herring, mackerel, trout, and Atlantic salmon, lipid oxidation is a major concern. The nutritionally valuable n-3 fatty acids are especially prone to oxidation, which can lead to undesirable changes such as rancidity. These effects tend to become more pronounced as storage time or temperature increases.

Handling fish after catch means working with raw flesh, and the rate of the deteriorative reactions is highly dependent on temperature. Furthermore, good hygiene and cleanliness positively affect storage life. Filleting, cutting, and other processing operations bring microorganisms, enzymes, and oxygen into contact with the fish flesh, which may reduce storage life. The best way to maintain the intrinsic quality of fish during storage is to lower the temperature towards -1 to 0°C immediately after catch and slaughter, and to remove blood and intestines, which can otherwise supply substrates for bacteria or enzymatic deterioration.

8.2.3 Weight changes

The weight of fish can vary during chilled storage depending on the species and the chilling method used. This is a commercially important factor, especially for fish sold by weight. Optimising chilling practices is essential to minimise weight losses and associated quality degradation. Chilling white, lean fish, like cod and haddock in refrigerated seawater (RSW; see ► **Sections 8.4** and **8.6**) can lead to initial weight gain but may result in higher drip loss later, especially if not followed by proper handling. Ice storage generally results in gradual weight loss that is more stable over time and cod has shown a drip loss of 2–3% over 10 days. This loss is not only due to water but also includes leaching soluble proteins and flavour compounds, which can negatively affect product quality. In the case of fatty fish, like salmon, the drip loss may also contain fat. Moreover, the drip creates an environment that can promote microbial growth and accelerate spoilage.

8.3 QUALITY TESTS

Fish quality testing is important in both the commercial and consumer sectors to ensure freshness, safety, and compliance with legislation. Quality tests help assess various factors such as sensory characteristics, including overall freshness and microbial quality.

Sensory evaluation involves the human assessment of the fish's appearance, odour, texture, and taste, and is one of the most common ways to evaluate the freshness and quality of fish. The Quality Index Method (QIM) is a scientifically-developed and standardised sensory assessment tool used to evaluate the freshness and shelf-life of fish (Sveinsdottir *et al.*, 2002). It is based on the systematic observation and scoring of specific, easily observable quality attributes that change as the fish deteriorates. For example, the colour and smell of the gills and the colour of the eyes are important factors in evaluating whole fish.

Physicochemical tests are used to analyse the chemical composition of fish and detect signs of spoilage. When fish deteriorates, its pH decreases *postmortem* due to the breakdown of muscle proteins into acidic compounds. However, it may increase later due to microbial spoilage and production of alkaline compounds such as ammonia and amines. Total volatile basic nitrogen (TVB-N) is another important parameter because high levels of TVB-N indicate the progression of microbial spoilage. TBARS (thiobarbituric acid reactive substances) and PV (peroxide value) measure lipid oxidation in fish, particularly the breakdown of fats into rancid compounds. The K-value is a commonly used freshness indicator based on ATP (adenosine triphosphate) degradation products

that starts after death. ATP is a molecule found in all living cells, including fish muscle, and it plays a central role in energy metabolism. ATP degradation rates vary between species; for example, it degrades faster in mackerel than in cod (Mozuraityte *et al.*, 2021).

Non-invasive methods for analysing product quality are under development and becoming more prevalent within the seafood industry. Common methods include spectroscopic techniques such as near-infrared spectroscopy (NIR), as well as impedance methods and tools like the Torrymeter. Impedance spectroscopy is a physical test used to evaluate the freshness of fish, though it is not as popular as other methods. Additionally, impedance analysis can determine fat content by measuring the difference in electrical conductivity between fat and water. A significant development in the field of impedance measurement as a non-destructive method of testing fish quality commenced in the 1970s at the Torry Research Station in the UK (Lees and Smith, 1979), leading to the popularisation of the Torrymeter. In Japan, a measuring tool called the fish analyser was developed that functions on the same principle and is currently used in the fishing industry.

Fish is a high-risk product for microbial contamination. Microbial testing ensures that fish is free from harmful pathogens and within the safe microbial limits for consumption. Total plate count (TPC) measures the overall bacterial load on fish. A high bacterial count may indicate improper handling, storage, or transportation conditions. In many European countries, specific shelflife limit values are no longer used. The responsibility for performing risk assessments and establishing and documenting shelf-life rests with the manufacturers. The microorganisms commonly linked to human foodborne diseases caused by fish products are *Vibrio* spp., *Listeria monocytogenes*, *Yersinia* spp., *Salmonella* and *Clostridium botulinum* (Novoslavskij *et al.*, 2016). Other bacteria, such as *Morganella*, when present in high numbers, produce histamine from fish, such as tuna, that contain high levels of histidine resulting in scombrotoxin poisoning.

Environmental testing of some microbial indicators on processing equipment is an important part of food safety management in the seafood industry. Since fish is a highly perishable and protein-rich product, it provides an ideal environment for microbial growth if hygienic conditions are not strictly maintained. Contaminated surfaces and equipment can become sources of cross-contamination, leading to spoilage, foodborne illness, and regulatory non-compliance. By systematically monitoring hygiene, seafood producers can reduce the risk of contamination, extend product shelf life, and ensure compliance with regulations.

Shelf-life tests are carried out by storing fish or fish products under different conditions (e.g., different temperature conditions or simulated cold chains) and periodically evaluating the product for quality indicators like sensory characteristics or microbial content. Shelf-life tests help determine how long fish can be safely stored under different conditions.

8.4 FISH HANDLING

The main goal during fishing, slaughtering and handling is to treat the fish in such a way that its initial quality is maintained and degradation processes are slowed down. Chilling

is one of the most critical steps in maintaining the quality, safety, and shelf life of fish after it is caught. Gentle handling is necessary and, depending on the slaughter method, induced stress and *post-mortem* changes may vary and affect the quality of the product.

Refrigerated seawater (RSW) or chilled brine systems can be used to chill the fish and maintain optimal water temperature, depending on the species and the duration of transport. After stunning and cutting the gills, the fish can be transferred to tanks for bleeding and chilling, before being gutted and, in some cases, headed. The fish can then be packed in boxes with ice or further processed into fillets or portions. Gentle handling, rapid chilling and hygienic processing practices, both before and after slaughter, are essential for maintaining product quality.

8.4.1 Fishing

Fishing is the activity of catching or harvesting fish and other seafood from natural or artificial waters. Fishing methods refer to the techniques and gear used to catch fish and other seafood. These methods vary based on the targeted species, fishing environment (marine or freshwater), and scale of operation. The choice of fishing gear is important, because it has a variety of impacts on fish quality and may result in a deterioration of the product delivered to the fish factory and/or consumer. Many features of fish damage are specific to certain types of fishing gear, as described in a review by Veldhuizen *et al.* (2018).

After harvesting, the fish must be handled carefully on board to maintain quality. The on-board handling largely depends on the fishing area, species and traditions, and it varies from harvesting small amounts of whole fish on small boats to processing large volumes of fillets or consumer-packed products on-board industrial trawlers at sea. If the fish are not processed on board, the value chain includes landing and post-harvest processing in a land-based factory. Regardless of the harvesting method, it is critical to promptly and effectively chill the fish to preserve quality and extend shelf life.

8.4.2 Aquaculture

Effective fish handling in aquaculture is essential for maintaining fish health, improving production efficiency, and ensuring high-quality products. Well boats, which are specialised vessels designed to transport live fish in tanks filled with seawater, play a crucial role in the industry by moving live fish between farms and processing facilities. Proper chilling during transport helps maintain fish welfare, reduce stress, and preserve product quality. Pre-cooling the fish on board can also reduce the required cooling capacity at the processing plant. However, pre-cooled fish typically needs to be processed immediately upon arrival unless there is a chilled storage tank for live fish.

8.4.3 Live fish storage and transport

Storage of live fish is a traditional practice in many countries when the supply of fish exceeds demand, but chilling during live storage is seldom applied to large quantities due to biological limitations or logistical challenges. However, as mentioned in ► **Section 8.4.2**,

large-scale live transport is common for some species like Atlantic salmon, where well boats are routinely used to move live fish between farms and processing plants.

Smaller fish may be chilled in closed containers or water-filled bags with controlled oxygen levels at temperatures between 5°C and 10°C. Flatfish, such as plaice and sole, are particularly well-suited for this method due to their low activity levels and body shape. For live shellfish, such as lobsters and shrimp, partial chilling is quite common during both storage and transport. They are typically kept in specially designed transport boxes or containers with elevated oxygen levels.

Storage temperatures must not drop below critical limits for the species, and the fish should be slowly acclimatised to avoid temperature shock. In addition, salt levels must also be carefully controlled. The optimal salt level varies depending on the species and the salinity of the water from which they originate. Circulating holding tanks should also ensure adequate water flow rates.

8.5 PACKAGING

The primary function of food packaging is to maintain the quality and safety of fresh or processed fish. Packaging serves as a barrier against environmental factors, limiting physical, chemical, and microbial contamination during transport, distribution and storage. Packaging also serves as a method to convey information (see ▶ **Section 2.3** on Packaging).

The selection of packaging methods and materials is influenced by the target market, whether the product is intended for industrial processing or direct consumer use, as well as by storage parameters, including time and temperature. Whole fish skin serves as a natural barrier, whereas processed or cut fish products require additional protection to prevent contamination and rapid spoilage. Wrappings and closed bags, usually made of plastic material, can protect against contamination, while modified atmosphere packaging (MAP) and vacuum packaging can prolong the shelf life. Due to the wide range of both products and materials available, it is difficult to provide precise recommendations on the shelf life for each packaging method and material.

Fish are typically transported in bulk using various packaging methods for industrial processing or for sale at fish markets, depending on the type of fish, product, market, and distance. The fish industry relies heavily on polystyrene boxes, where whole gutted fish or fillets are packed with crushed or flaked ice to maintain low temperatures. However, these boxes present environmental and waste issues, prompting the industry to search for more sustainable alternatives such as fibre-based insulated boxes. Despite these concerns, polystyrene boxes remain the preferred choice due to their insulating capacity and ease of handling. Melting ice can maintain the temperature of fish close to 0°C for 24 to 48 hours, or even longer, provided the boxes are properly filled with ice and stored in cool conditions. As long as there is still ice in the box, the temperature will remain stable at around 0°C. Once the ice has completely melted, the temperature rises quickly. Saltwater (brine) can maintain even lower temperatures, e.g. -1°C, a temperature at which fish will not freeze but shelf life is even longer than at 0°C.

Wrappings, vacuum packs, skin- and MAP-packs are ways of presenting fillets and other fish products to consumers. Vacuum and MAP packs can be chilled in air, and vacuum packs can also be chilled in iced water. Most packaged products are distributed in master cartons made of fibre material in the cold chain. Temperatures are usually close to 4°C in a typical cold chain for packaged fish products, although lower temperatures (e.g. 0°C) would be ideal. These low temperatures increase the shelf life compared to higher temperatures, especially for fish from cold-water species.

8.5.1 Modified atmosphere packaging

Modified atmosphere packaging (MAP) involves introducing a controlled mixture of gases into the package (see ► **Section 2.3.1**). Carbon dioxide (CO_2) is commonly included in packages of fresh seafood. Carbon dioxide inhibits the growth of spoilage bacteria, such as *Pseudomonas*, *Shewanella*, and *Photobacterium*, by reducing the pH value in the product. In addition, there is an absence of oxygen for microorganisms to grow. To achieve an antimicrobial effect, there must be at least 20% carbon dioxide in the package, but higher concentrations up to 60% are commonly used (Cann, 1980). For lean (white) fish, the recommended modified atmosphere is: 40% CO_2, 30% N_2 and 30% O_2. For fatty fish, the recommended modified atmosphere is: 60% CO_2 and 40% N_2 (Cann, 1980). The effect of CO_2 is temperature dependent since its solubility increases with lower temperatures. Therefore, fish products in MAP should be kept below 5°C to obtain a prolonged shelf life. Depending on the species, shelf life at 0°C has been reported to range from a few days to 10 days.

Nitrogen is used as a filler gas in MAP packages. Nitrogen replaces carbon dioxide and prevents the package from looking collapsed since it does not dissolve in the product's water phase. Unlike carbon dioxide, nitrogen gas does not have any inhibitory effect on microorganisms. For fatty fish, removal of oxygen from the package reduces oxidation rates. When oxygen is removed, the package becomes anaerobic, allowing anaerobic bacteria to grow. The *Clostridium botulinum* type E strain can produce a very strong toxin if the temperature is above 3.5°C and the salt concentration is less than 3 g per 100 g of water. Strict temperature control and regulatory guidance are therefore necessary when using MAP for fish.

Cooling modified atmosphere packaging may pose challenges, as the atmosphere in the package acts as an insulator around the product, and the package's volume is much greater than that of the product (Hauzoukim and Mohanty, 2020). To avoid this issue, the product should be at 0°C before packaging, and the gas should be chilled.

Active packaging refers to packaging systems that interact with the product to extend its shelf life by reducing the rate at which its quality degrades (see ► **Section 2.3.1**). For example, oxygen scavengers reduce the oxygen levels inside the package to slow oxidation and microbial growth. This is particularly useful for fatty fish, like salmon and mackerel, which are prone to lipid oxidation. Absorbents are often used in trays to absorb excess moisture, reduce visible drip loss, and prevent microbial growth. By combining modern packaging methods, such as chilling and active packaging (the hurdle concept), it is possible to preserve fresh quality and extend shelf life considerably.

8.6 CHILLING METHODS

Effective chilling is essential for preserving the quality and safety of fish and seafood products, reducing spoilage, and maintaining optimal freshness throughout the cold chain. Several chilling methods are employed in the seafood industry, each offering advantages depending on factors such as species, transport conditions, equipment, requirement for rapid temperature reduction, and fish welfare. This section covers various chilling techniques, including ice-based systems, refrigerated seawater (RSW), and slurry ice. Air chilling is generally not used during fish processing because it offers a slow cooling rate, which allows spoilage processes to begin during chilling.

8.6.1 Chilling in water

Water-based chilling methods offer efficient heat transfer, which can significantly improve chilling speed and effectiveness. These methods can be achieved using ice-water mixtures, fresh or seawater in containers, or by employing refrigerated seawater (RSW) systems in onboard tanks, aquaculture operations, or land-based facilities to chill fish before processing. Because of its salinity, RSW allows temperatures to fall below 0°C, which enables faster chilling compared to ice alone. RSW is a suitable and common method for fast chilling large quantities of fish typically found on board purse seiners and trawlers equipped for pelagic fishing. The system consists of several tanks, tubes, pumps, and valves, in which seawater is mechanically refrigerated and circulated. Herring and mackerel are species that are typically transported in RSW tanks, while species like blue whiting are stored in refrigerated fresh water. These species are used for fish oil and meal production. Using fresh water reduces salt uptake in the fish.

In fisheries, tubs and insulated containers with water or seawater offer a flexible and effective chilling solution. Containers fit into small boats and provide the advantages of rapid chilling and easy handling. After landing, the containers can be stored at the factory before processing. In aquaculture, water-based chilling methods are widely and successfully used. The HeliX tank is a high-performance chilling system designed for efficient and gentle cooling and handling of fish, widely used in the seafood industry. It supports rapid chilling, bleeding, and storage, and can operate with both RSW and slurry ice as cooling media. To ensure hygienic operation, water based chilling systems must be designed with efficient circulation, effective filtration, and easy cleaning of pipes and holding tanks after each use.

However, prolonged storage in water can negatively affect the quality of fish products. Extended exposure may cause bleaching of the gills and changes to the skin. When stored in containers on board fishing boats, the movements of the vessel can lead to physical damage, especially to the skin.

By adding salt to fresh water, a brine with a lower freezing point is created. This results in a higher temperature difference between the fish and the water, enhancing the heat transfer efficiency. The drawback of brine chilling is that it can lead to elevated salt content in the fish if they are immersed in the brine for too long. There is also a risk that the fish may freeze if the immersion time is not properly controlled.

8.6.2 Chilling in ice

Ice is one of the most used methods for chilling fish and seafood. A key principle is to reduce the product temperature to near 0°C as quickly as possible. Ice also maintains low temperatures by absorbing heat during storage and transport. It is crucial that the ice be made from fresh, clean water, because contaminated ice can compromise hygiene and product safety. Ice should never be reused, as it may carry a high microbiological load.

Onboard, vessels commonly store fish in boxes or containers filled with ice. When done properly, this method is highly effective. For ice to function as an effective cooling agent, it must be in direct contact with the fish, and the product should be surrounded by ice particles or flakes. The amount of ice used should be sufficient not only to rapidly chill the fish, but also to prevent the temperature from rising during storage. For long storage times, re-icing may be necessary to maintain low temperatures. In many fisheries, vessels may remain at sea for extended periods, requiring sufficient ice to be carried from shore or produced onboard. To avoid mechanical damage, containers should not be overloaded, as the fish at the bottom may be compressed, leading to flesh damage and weight loss. Containers should have adequate drainage to remove meltwater.

For fresh gutted fish and fillets, icing is also widely used. Gutted fish and fillets are typically placed in polystyrene boxes with ice. In some cases, the fish is lined with a thin sheet of plastic or paper to prevent direct contact with meltwater, which can lead to the loss of water-soluble nutrients. Fillets may also be vacuum packed before being placed in boxes with ice.

Fish stored in slow-melting ice keeps a lower temperature compared to fish kept in conditions where ice does not melt, due to the more stable, consistently low temperatures of melting ice. When storing iced fish in a chill room or in refrigerated transport, the surrounding air temperature should not drop below 1°C. If the air is too cold, the ice will not melt, reducing its ability to absorb heat. A slow, controlled melting process ensures continuous cooling and maintains good ice-to-fish contact, especially on exposed surfaces. Moreover, operating refrigeration systems at unnecessarily low air temperatures also increases compressor energy use due to lower evaporation temperatures.

In recent years, gel packs have emerged as a replacement for ice. Gel packs are plastic bags filled with sodium-based gel (water and sodium polyacrylate), which lowers the freezing point of the mixture. These gel packs are placed on top of the fish instead of crushed ice.

8.6.3 Chilling in slurry ice

Slurry ice is an effective method for chilling fish and seafood. It consists of a suspension of fine ice crystals in an aqueous solution, typically seawater or freshwater chilled at a subzero temperature. One of the key advantages of slurry ice is that it behaves like a liquid, allowing it to be pumped and distributed, and ensuring close and uniform contact with the fish surface for rapid and efficient cooling. Slurry ice provides a faster chilling rate because of its higher heat exchange capacity compared to flake-ice and RSW. It enables faster chilling of the catch compared to traditional refrigerated seawater (RSW) systems and ice.

Regarding quality, slurry ice minimises mechanical damage to fish products due to its spherical microscopic particles. Compared with flake ice, this advantage is particularly relevant for species with soft tissues. The complete coverage of the fish surface by the slurry ice mixture also protects against oxygen exposure, helping prevent oxidation and flesh dehydration. In addition, slurry ice enables precise temperature control, reducing the risk of freezing — a particularly important consideration when handling delicate or high-value species.

Slurry ice systems can be designed for different capacities and temperature ranges, depending on the chilling needs. An ice slurry installation typically includes a refrigeration unit, an ice slurry generator, a storage tank, and a delivery and circulation system. This setup provides operational flexibility, as the slurry can be produced in advance and stored until needed, for example in fish holding tanks. However, temperature and concentration controls are critical. Ice concentrations can be as high as 60%, which increases viscosity and energy requirements for pumping. The refrigeration unit must also operate at lower evaporation temperatures, especially when producing slurry from seawater, which begins to freeze at around -1.8°C (at 3.5% salt content).

8.6.4 Superchilling

Superchilling involves keeping the product at a temperature between -0.5 and -4°C, which causes a partial freezing of the water content in the product (5–30%). Superchilling is not as commonly used in the fish industry as traditional chilling, but there is potential for increased use. A major advantage of superchilling is that it slows down microbial growth and enzymatic activity more effectively than traditional chilling does, thereby extending the product's shelf life. Superchilling can also reduce the need for ice in transport boxes, which saves space and reduces weight. Disadvantages may include practical challenges in accurately controlling the temperature to prevent the product from freezing. Additionally, the surfaces of the fish can tend to dry out. However, it may be possible to use protective layers on the fish skin or individual packaging for high-value fish to mitigate these issues.

8.6.5 Dried and salted fish

Fish can be preserved through salting and/or drying. Due to their high salt content and low water activity, the demand for refrigeration is lower than for fresh fish. However, when stored at elevated temperatures, a red discolouration can develop due to the growth of extreme halophile bacteria. The halophiles cannot grow below 8°C, but they may survive and grow if the temperature exceeds 8°C. Many markets for salted fish, such as those in Africa, do not have adequate refrigeration facilities. If this red discolouration appears, the product is considered to have exceeded its shelf life and unfit for sale.

Drying is a common method of preserving fish. Dried fish exists in many different cultures with different species and drying methods used. Stockfish, for example, is an unsalted dried fish product made from Arctic cod (*Gadus morhua*) and dried in air. Smoke-dried fish is common in Asian countries, especially Japan and Bangladesh. The drying process is generally determined by a decrease in water activity (a_W), which subsequently decreases or inhibits microbial activity in the fish. Each microorganism requires a specific

a_W to grow on the dried fish. Almost no microbial growth can occur at a_W levels below 0.60, while most bacteria require a_W levels above 0.85 to grow.

For salted fish products, low relative humidity levels in the storage chambers are recommended, typically lower than 76%. For dried products an even lower relative humidity is recommended, less than 50%, to avoid excessive absorption of moisture. If the relative humidity is higher than the recommended value, moisture-proof packaging is advisable. In chilled storage rooms, dried and salted fish should be kept separate from other food products due to their odour and low relative humidity requirements.

8.7 REGULATIONS AND CERTIFICATIONS

Governmental regulations differ from country to country. The main legal framework in the EU and EEA is Regulation (EC) No. 853/2004, which sets specific hygiene rules for food of animal origin, including fishery products. These rules were updated in Regulation (EU) 2022/2258, which clarified the temperature and transportation conditions for fishery products. In the United States, the FDA and USDA primarily regulate the chilling and transportation of fish and seafood products, with a strong emphasis on temperature control in the cold chain and hazard analysis and critical control points (HACCP). Japan has stringent food safety regulations under its Food Sanitation Law, which was enacted in 1947 and has been amended many times. For example, the standard storage temperature for most fishery products is below 5°C, while most other foods are allowed to be stored below 10°C. To kill parasites, some fish species must be frozen at -20°C for 24 hours before being eaten raw as sushi.

Certifications often referred to in the fishing industry include:

- MSC (Marine Stewardship Council): for sustainable wild-caught fish.
- ASC (Aquaculture Stewardship Council): for responsibly farmed seafood.
- Global G.A.P.: covers food safety and sustainability in aquaculture.
- ISO 22000 / FSSC22000 or BRC: covers food safety management systems and risk management.

8.8 CHALLENGES AND DEVELOPMENT PERSPECTIVES

As described in this chapter, fish can be chilled using several well-established methods that have been refined over time and are generally reliable. Nevertheless, there remain areas where further development and innovation are needed. The following sections highlight some of these challenges, which may require solutions at local, national, or international levels, often through collaborative projects.

8.8.1 Meltwater management during transport

Traditionally, whole fish are stored in boxes with ice before processing and during transport to market. However, the meltwater from these boxes has become a growing concern for authorities, not only due to hygiene and environmental issues but also because, in winter, the water discharged from trucks can freeze on roads and create hazardous driving conditions.

Several methods have been proposed to reduce meltwater, such as using sealed containers and absorbent liners, but commercial adoption remains limited. One key approach is **effective precooling** of fish at the processing facility, which reduces the amount of ice required during transport. While this seems straightforward, it can be challenging when large volumes of fish need to be chilled simultaneously. Improved temperature control at the factory, supported by a solid understanding of thermodynamic principles, is essential. Enhanced staff training and the use of software tools for process optimisation may also help achieve consistent and efficient cooling.

8.8.2 Energy-efficient operation

Refrigeration is energy-intensive, particularly when large volumes of fish require rapid precooling. Storage also demands continuous cooling. However, if the fish are properly precooled to the storage temperature beforehand, the refrigeration system only needs to compensate for external heat loads.

Energy efficiency depends on several factors. Good insulation and minimising door openings are critical, as each opening introduces warm, moist air. Moisture leads to frost formation on evaporators, reducing heat transfer and system performance. Defrosting, whether by electric heaters or hot gas, restores efficiency, but it consumes energy and adds heat to the storage room. Therefore, it should be optimised.

System design also matters. A single large refrigeration system serving multiple rooms is generally more efficient than several smaller units. Smart controls for temperature regulation and defrost cycles can further reduce energy use.

Lower energy consumption not only cuts costs but also reduces greenhouse gas emissions. Transitioning from fossil fuels to renewable energy sources, such as installing solar panels on factory roofs, offers additional sustainability benefits. When investing in new technology, it is essential to consider payback time and cost-benefit analysis. Some companies accept longer payback periods for energy-saving measures, and government funding may be available to support such initiatives.

8.8.3 Sustainable refrigerants

The refrigeration industry is transitioning away from refrigerants with high global warming potential (GWP), such as hydrofluorocarbons (HFCs). This shift is being driven by international agreements and national regulations. This phase-out is essential to reduce greenhouse gas emissions and align with climate targets.

Natural refrigerants, including carbon dioxide (CO_2) and ammonia (NH_3), are increasingly adopted as sustainable alternatives. These options offer low or zero global warming potential and have been used in various sectors for many years. Ammonia, in particular, has long been common in large industrial processing plants. Proper system design, operator training, and compliance with safety standards are essential for handling all refrigerants, whether natural or synthetic, due to safety considerations.

Regulatory frameworks, such as the EU F-Gas Regulation and the Kigali Amendment, are accelerating the shift towards low-GWP refrigerants. A growing concern is that many

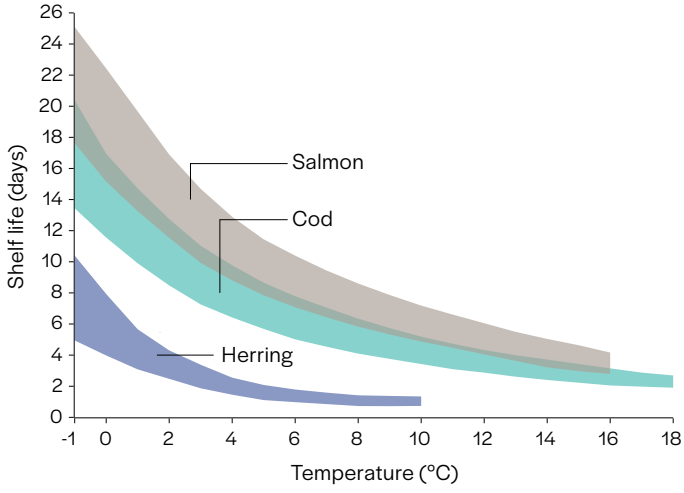
synthetic refrigerants can degrade into per- and polyfluoroalkyl substances (PFAS), which pose significant health and environmental risks. The European Union is currently considering a ban on PFAS-containing substances, which would further restrict the use of certain synthetic refrigerants. Industry readiness for this transition varies: large-scale facilities often lead the adoption, while smaller operators face challenges related to cost, technical expertise, and infrastructure. Continued innovation, training, and financial incentives are essential to ensure a smooth shift towards sustainable refrigerant solutions.

8.9 RECOMMENDED STORAGE CONDITIONS

Maintaining low temperatures is critical for preserving the shelf life of chilled fish products. While temperatures close to 0°C can often be achieved during storage and bulk transport, local distribution and retail display frequently expose products to higher temperatures, typically around 4°C or more. This significantly reduces shelf life: at 0°C, shelf life is roughly twice as long as at 4.5°C, and about four times as long as at 10°C, as shown in ► **Figure 8.1**.

Most display cabinets use cold air and can be designed to maintain temperatures near 0°C. However, in practice, settings often prioritise other products with less stringent requirements, which compromises fish quality. To ensure compliance and maintain product integrity, it is recommended to use separate fish cabinets with continuous temperature monitoring using data loggers or time-temperature integrators.

Additional treatments, such as mild heat processing or preservative dips, can extend the shelf life of products distributed through supermarket chains. While these products remain chilled, they do not meet the definition of "fresh". All such interventions must comply with the relevant laws and regulations of the target market.



► **Figure 8.1** Generally accepted shelf life for different species at different temperature levels (adapted from Magnussen *et al.* 1993).

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Chapter 9

Dairy products

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Raw and pasteurised milk as well as many processed dairy products are nutrient-rich foods ideal for the growth of many microbial species. Many dairy products have high fat content, so fat rancidity reactions also often need to be minimised. Therefore, refrigeration of dairy products to slow microbial growth and deterioration reactions, such as fat oxidation, is a very common preservation method used to lengthen Practical Shelf Lives (PSLs). Drying is the other most common preservation method used for dairy products.

9.1 REGULATIONS

Most countries have detailed national regulations on dairy products, prescribing that milk should be produced under hygienic conditions by healthy animals and should be free from unacceptable levels of antibiotics and chemical residues, laying down requirements for cooling, transport, and storage, and prescribing the composition, especially the fat content, of various products, especially milk and butter.

There are also international recommendations, e.g., on hygienic manufacture of milk and milk-based products. Standards or requirements for milk and dairy products'

temperatures are specified in various international and national documents. However, it must be borne in mind that these temperature requirements differ depending on the authority because the ideal situation of global standardisation has not yet been reached. The temperature limits for cooling, transport, storage, etc. of chilled dairy products can range between 4°C and 7°C, or even 10°C. The temperature limits given below differ from one country to another and this can have a significant impact on the PSLs of products.

Some countries have regulations on the maximum allowable number of microorganisms in milk at the beginning of the production cycle, and it has been recommended that the price of milk should be based on its microbial quality upon arrival at the dairy plant. This should motivate milk producers to increase their efforts in hygienic milking practices and raw milk handling.

9.2 COOLING OF RAW MILK

Raw milk must have a high microbiological quality that does not deteriorate between milking and processing at the dairy plant. In order to stop or slow the rate of bacterial multiplication, it is important to immediately cool the milk and maintain a low temperature.

9.2.1 Cooling on the farm

Milk starts out at 35°C and should be cooled as soon as possible after milking to a temperature low enough to stop rapid bacterial development. This temperature varies between 4°C and 8°C, depending on the frequency of milk collection (every 24, 48, or 72 hours) and on the country. The chilled storage temperature should be achieved within 2 to 3 hours and maintained until collection. Collection should be carried out using vehicles capable of maintaining the required temperature (insulated and/or refrigerated).

Daily collection is required for some uses of milk, such as the manufacturing of certain cheeses, in which the presence of psychrotrophic flora gives a bitter flavour.

On large farms, milk is often cooled, sometimes with chilled water as the primary refrigerant, in a special cooler (heat exchanger) before it is pumped into an insulated or refrigerated tank. Ice banks can be used to provide the chilled water.

Some farms pre-cool the milk in heat exchangers using ambient cold water before final cooling using refrigeration.

9.2.2 Cooling of raw milk at the dairy

Raw milk is often transported over short distances in insulated, sometimes non-insulated, tankers, at 8°C–10°C or below. If the transportation time exceeds 24 hours, raw milk should be carried at 4°C or below.

Especially if the milk cannot be processed within a few hours of farm collection, it is once again cooled upon arrival at the plant in plate or tubular heat exchangers, in order to ensure a temperature below 4°C. These heat exchangers are usually supplied with chilled water. Jacketed tanks, cooled by chilled water flowing through the jacket, are used only for cooling small volumes.

After chilling, milk is stored in insulated tanks. If the milk is to be stored for more than 24 hours, it should be immediately pasteurised and cooled to about 4°C. The temperature of milk meant for direct processing is adjusted at the end of pasteurisation to meet the requirements of its intended use.

9.3 PASTEURISED MILK FOR DIRECT CONSUMPTION

Milk is pasteurised in plate or tubular heat exchangers. Many countries set legal standardised duration and temperature requirements for pasteurising raw milk intended for direct consumption.

The minimum requirements are normally 72°C for 15 seconds. This should result in a negative alkaline phosphatase (ALP) test immediately after the heat treatment. Phosphatase is an enzyme in raw milk that is denatured at temperatures just below the pasteurisation temperature, so the absence of phosphatase is used to check that the pasteurisation process is adequate. To save heating and refrigeration energy consumption, the heat content of the pasteurised milk is often used to prewarm the cold, raw milk, thus cooling the pasteurised milk. The pasteurised milk is then chilled, first with cold water (unless the temperature of the milk has already been reduced to about 8°C–10°C). Then, chilled water, brine, or another refrigerant is used to achieve the desired/required temperature. This temperature, e.g., usually 6°C or below, is maintained until filling and packaging.

Packaging The packaging for pasteurised milk should be impervious to light and with a low permeability to water vapour, gases, etc. Glass bottles (relatively heavy returnable packaging) disappeared from many markets starting in the 1960s. Nowadays, either plastic-coated cardboard cartons, or plastic bottles, or pouches are mainly used.

Storage In retail shops, pasteurised milk should be kept at 5°C or below.

Ultra-High Temperature (UHT) milk is pasteurised at 140°C–150°C for 2–5 seconds and packed under aseptic conditions. It can be kept at ambient temperature for up to 9 months. Chilled storage of UHT milk further slows down quality-reducing processes and prolongs storage life.

9.4 COOLING OF CREAM AND BUTTER

9.4.1 Cream

After the whole milk has been separated by centrifuge into skim milk and cream, the cream undergoes more intense pasteurisation than the milk, such as 10–20 seconds at 85°C–90°C, resulting in no detectable Lactoperoxidase (LPO) activity. LPO is an enzyme in raw milk and its absence due to heat denaturation is used to indicate whether the cream pasteurisation process is adequate.

After cooling, the cream is kept in a tank at around 5°C. Whipping cream should be ripened for at least 24 hours at about 6°C, in order to allow the fat to crystallise and give the cream its physical structure.

9.4.2 Butter

Butter contains 80%–82% fat. It is usually classified into two categories, sweet-cream butter and soured (or cultured) cream butter. Both can be salted or unsalted. Cream for butter production is usually pasteurised at temperatures above 90°C. The cooling rate of cream (post-pasteurisation) has a significant impact on the final fat crystal structure and texture of butter once churned.

If butter is manufactured using a continuous process, the churning of the cream necessitates intensive cooling of the churn cylinder. The butter is shaped into small blocks or into large cubes if it has to be stored over a long period or used in an industrial process. For short-term storage, which typically lasts a few weeks, the butter is stored at 0°C to 4°C. For long-term storage, up to one year, the butter is frozen and kept at -15°C to -20°C.

Packaging for butter should be greaseproof, impervious to light as well as flavouring and aromatic substances, and have a low water vapour transmission rate.

Butter fat intended for industrial use, and cream or butter of low quality, can be further fractionated to produce butter oil or anhydrous milk fat.

9.5 FERMENTED MILK AND CHEESE

9.5.1 Fermented milk and desserts

Refrigeration is necessary in order to limit the acidification of yoghurt and to stabilise desserts after manufacture. Typically, this is done after packaging for set yoghurts in a cold room with vigorous air circulation or prior to packaging for stirred yoghurt, but some stirred yoghurts are packed at temperatures up to 15°C to ensure pumpability. All fermented milk and dessert products must be kept cold until sold. At temperatures below 5°C, the storage period can be longer than 3 weeks.

9.5.2 Cheese

Refrigeration requirements for cheese depend on its type and the manufacturing process.

9.5.2.1 Fresh cheese

Fresh cheeses, like cottage cheese and cream cheese, which have a high water content, must be kept below 5°C and stored for no more than 3 weeks before being sold to avoid spoilage. Such cheeses are sometimes cooled in a continuous cooler before packaging, using tubular coolers; sometimes the curd is stored in a cold room.

9.5.2.2 Other cheeses

For many other types of cheese, refrigeration is usually necessary only at the salting and maturation stages shown in ► **Table 9.1**. The temperature ranges from 8°C to 25°C, depending on the type of cheese.

For bulk manufacture of some cheeses, large blocks (e.g., 20 kg) are wrapped in plastic film and placed in a carton, before being cooled (from 30 to 35°C in the case of cheddar, or 50 to 70°C in the case of mozzarella) down to 10 to 20°C within 24 hours, prior to storage and maturation. While the packaging acts as a barrier to heat transfer, it provides

a rigid mould, ensuring that the cheese forms into uniform blocks. The cooling rate must be sufficient to ensure that microbial and enzymatic activity is restricted to desirable levels, while allowing flavours and textures to develop. Blast chillers or brine/coolant baths can be used for this purpose. In the case of slice-on-slice processed cheese, chilling is achieved by contact with metal belts or drums.

If the cheese is ripened under plastic films, temperature control alone is necessary. However, if no plastic cover is used, the humidity of the ripening cellar must also be regulated.

Soft cheeses are ripened over 2 to 6 weeks. Boiled and hard cheese can take between 3 months and 1–2 years.

After ripening, the cheese should be kept at a temperature between the ripening temperature and 0°C, depending on how long it will be stored.

Some types of cheese, particularly soft cheese, can be kept only for very brief storage periods. Conversely, cheese such as Cheddar or "cooked" curd cheese, can be cold-stored for long periods, provided that the packages prevent desiccation. Sudden temperature changes are detrimental to the cheese texture and appearance, especially when the cheese contains cavities, such as in Gruyère (Swiss cheese).

Packaging For display in supermarkets, cheese is often packed in plastic containers. Increasing use of vacuum packaging or modified atmosphere packaging (mainly CO_2, sometimes also N_2, but with a maximum of 1%–2% O_2) is being used to extend storage life. In particular, for fresh cheese sliced or cut into portions, modified atmosphere packaging provides significant benefits.

While some cheese should not be frozen, since it modifies its texture and thus harms its aspect and quality, for other varieties (e.g., mozzarella and cheddar), it may be beneficial for preserving their flavour and texture. It is important to slowly thaw frozen cheese in order to prevent it from crumbling (in the case of cheddar) or to prevent damage to the microstructure and minimise moisture separation (in the case of mozzarella). This allows for proper shredding and uniform melting (e.g., for pizza making). It should be noted that most pizza cheese is currently sold shredded and individually quick frozen (IQF) and can be used directly frozen rather than as a chilled product after thawing.

Table 9.1 Processing and storage of cheese

Type	Salting	Controlled drying	Ripening	Storage temperature and duration
Soft cheeses:				
(e.g., Camembert)	13–15°C (1 day)	12–14°C RH: 85–90% (10 days)	8–10°C RH: 90% (2–3 weeks)	Camembert (France): 4–8°C; RH: 90% Brie (France): 0–2°C; RH 82–85% (USA): -1–1 °C RH: 85–90% (2 months)
Blue-veined cheeses:				
Roquefort, Bleu d'Auvergne and other blue cheese	8–10°C RH: 95%	—	5–10°C RH: 95%	0°C RH: 75–80% Roquefort (USA): -1–1°C RH: 80–85% (2–3 months) 4-8°C (France)
Gorgonzola	15–21°C (20–24 days)	13–16°C RH: 75–80% (20–30 days)	First stage: 9–11°C RH: 85–90% (about 2 months) Second stage: 5–7°C RH: 90°C (about 1 month)	5–7°C RH: 90°C (USA): -1–1°C RH: 80–85% (3–6 months)

Keys:
RH = relative humidity

Source: IIR (2000)

Type	Salting	Ripening	Storage temperature and time
Hard cheeses not subjected to high-temperature treatment:			
Tilsit (unpressed)	12–15°C RH: 95% (2–3 days)	12–16°C RH: 95% (about 5 months)	2°C RH: 90%
Bel Paese (unpressed)	12–15°C in brine (10 to 12h)	4.5°C RH: 90% (30–45 days)	(USA): -1–1°C RH: 85–90% (2–3 months)
St Paulin (pressed)	12–15°C (3-5 days)	12–15°C RH: 90% (3–4 weeks)	(France): 0–5°C RH: 90%
Edam (pressed), Dutch	12–15°C (3-5 days)	12–15°C RH: 90% (3–4 weeks)	(Netherlands): 12–15°C
Cheddar (pressed)	—	slow: 4°C, RH: 75% (8–18 months) normal: 7–10°C, RH: 85% (2–5 months) accelerated: 12–16°C RH: 85–90% (about 2 months)	(USA): -1–1°C RH: 70–75% (12 months)
Cheshire (pressed)	21°C 1%	12–15°C (1-3 months)	
Cooked cheeses:			
Emmenthal	10–15°C in brine (2–3 days)	Cold cellar: 10–15°C, RH: 85% (10–20 days) Warm cellar: 16–25°C, RH: 85% (30–45 days)	10–12°C RH: 80% (several months)
Gruyère de Comté	10–15°C in brine (2–3 days)	Cold cellar: 10–15°C, RH: 90% (10–20 days) Warm cellar: 16–18°C, RH: 90% (30–40 days)	10–12°C RH: 80–85% (several months)
Parmesan	15–16°C (30 days)	16–18°C RH: 80% (about 1 year)	(USA): -1–1°C RH: 70–75% (12–24 months)

Keys:
RH = relative humidity

Source: IIR (2000)

9.6 CANNED AND POWDERED MILK

9.6.1 Canned milk

Sweetened or unsweetened concentrated milk deteriorates when kept at high temperatures due to browning or coagulation. In temperate climates, it can be safely kept at room temperature, 20°C, for up to one year. In warmer climates and over long storage periods, low-temperature storage is recommended.

9.6.2 Powdered milk

Powdered milk has a longer shelf life than concentrated milk, especially if it is vacuum-packed or packed with an inert gas. The shelf life of nitrogen-packed infant formula powder can be up to 3 years. Skimmed milk spoils less easily than full-fat milk and instant milk (regardless of whether it is skimmed or not).

For long-term storage in warm climates, powdered milk must be kept in cool spaces (10°C). There are many factors to consider when determining the shelf life of powdered milk. For industrial products, these factors include residual moisture, yeast content, mould, total fat content, free-fatty-acid content, the packaging's permeability to protect against oxygen and moisture, as well as storage temperature.

9.7 PRACTICAL STORAGE LIFE OF DAIRY PRODUCTS

▶ **Table 9.2** shows the typical practical storage lives of certain widely consumed dairy products. Specific products may have practical storage lives that are considerably longer than those stated in ▶ **Table 9.2**, depending on formulations, manufacturing methods, and packaging systems used.

Table 9.2 Practical storage life of dairy products

Product	Storage temperature	Practical storage life
Milk:		
– pasteurised	4°C	10 to 15 days
– UHT-sterilised	10°C	6 to 9 months
Yoghurt	4°C	30 to 45 days
Fromage frais	4°C	30 days
Sour cream	4°C	20 days
Butter	4°C	60 days

Source: IIR (2000)

References

IIR, 2000. *Recommendations for chilled storage of perishable produce*. International Institute of Refrigeration.

Chapter **10**

Pre-cooked ready prepared products

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10.1 INTRODUCTION

There is a growing range of prepared, normally pre-cooked, products that rely on chilling to maintain both their organoleptic quality and safety. These include sweet and savoury pies, pasties, quiches, flans, pizzas, and convenience (or ready-to-eat) meals.

There is no agreed definition of a ready-to-eat or convenience meal. The term is generally applied to a pack containing a complete meal or a main course based on meat, fish, or plant ingredients, which requires little further preparation and cooking and can be consumed without any additional items. Although they are often reheated before consumption, some convenience meals consist of only a single meal item (for example, fish fingers) that the consumer supplements with other fresh or prepared items to make a complete meal.

Some ready-to-eat or convenience meals are stored frozen; however, these recommendations concern only chilled products. In industry practice, a distinction is often made between ready-to-eat (RTE) and ready-to-heat (RTH) food. RTE foods can be consumed without further processing, whereas RTH products require reheating before consumption to achieve optimal quality or safety. Many chilled convenience meals fall into the RTH category even though they are often described generically as ready-to-eat products in the retail market.

The majority of current processing plants have evolved around existing factories and produce a large range of ready-to-eat meals as well as snack products for both retail and catering outlets. A number of specialised units use cook-chill methods to produce food for institutions such as hospitals, airlines, schools and prisons. Others use sous-vide systems to supply hotels and restaurants.

10.2 RAW MATERIALS

Factories producing a range of chilled products, especially those producing ready-to-eat meals, have to handle raw materials of many different types, including meat, fish, vegetables, fruits, cereals, etc. The raw materials can arrive at the plant as liquid, solid or solid/liquid mixtures, in many forms, such as chilled, frozen, canned, dried, bottled or ambient-stable packs. The microbiological quality of raw materials can vary widely, ranging from sterile canned food to heavily contaminated unprepared vegetables.

Raw materials must be stored at appropriate temperature and humidity levels to minimise the growth of microorganisms and prevent the loss of nutrients while maintaining their sensory quality. Preparation of raw materials should take place in areas physically separated from the cooking and post-cooking areas. Preparation should take place on suitable working surfaces and under hygienic conditions. Particular care should be taken with raw food that are likely to be contaminated with pathogenic microorganisms.

To prevent the transfer of microorganisms from raw to prepared food, personnel handling raw materials should be confined to the raw-material handling area. They should not enter or handle food or equipment in other areas without changing protective clothing and washing their hands. To help prevent cross contamination, air pressure differentials should also be maintained so that airflow moves from the cooked/finished product areas (which are kept at a positive pressure) towards the raw-material-handling area. This reduces the risk of airborne contamination.

10.3 SPECIFIC PROCESSES

10.3.1 Cook-chill

Cook-chill is a catering method for producing large quantities of meals of a reasonable eating quality in a cost-effective manner. The prepared food is fully cooked, i.e. to a minimum temperature of 70°C for at least 2 minutes or its antimicrobial equivalent. After cooking, it is rapidly cooled and stored at a low temperature (typically 0°C to +3°C), which is above its initial freezing point, for a maximum of 5 days.

If the storage temperature rises above 5°C but remains below 10°C, good practice cook-chill recommendations require the food to be consumed within 12 hours. If the air temperature rises above 10°C, it is advisable to destroy food. After storage, the food is thoroughly reheated, again to a minimum temperature of 70°C for at least 2 minutes or its antimicrobial equivalent, right before consumption.

The basic principles of a cook-chill system are that:

- Raw materials must be of a good microbial quality;
- Cooking should ensure the destruction of vegetative cells of any pathogenic microorganisms that are present;
- Rapid cooling after cooking should control the growth of microorganisms;
- Cross contamination should be avoided between raw and cooked produce;
- Low storage temperatures and good hygiene are necessary in order to maintain quality and safety;
- Reheating should maintain quality and safety.

Products can be centrally prepared in advance using unskilled labour supervised by a small number of skilled chefs.

In institutions, such as schools or hospitals, food is often reheated in large quantities in steam or hot-air regeneration units before being placed on individual plates for consumption. Another option is to transfer the cold food to individual plates and reheat it in a microwave or other small oven when required.

10.3.2 Sous-vide

Sous-vide was developed in 1975 by Georges Pralus, a French chef, to produce high-quality cooked dishes with low weight losses for catering establishments. More recently, sous-vide products are being produced on an industrial scale for retail distribution.

In sous-vide, food is immersed in vacuum-sealed bags at low temperatures for long periods of time, resulting in a weight loss of 2% to 8%, compared to 25% to 30% with conventional air ovens. Products can be centrally prepared in advance using unskilled labour supervised by a small number of skilled chefs. Only small kitchens with minimal equipment are required to reheat the food at the point of sale.

The sous-vide process consists of specific operations:

- Packing prepared raw or partially cooked food in bags or pouches specifically designed for vacuum sealing;
- Sealing the bags or pouches under vacuum;
- Cooking the vacuum-sealed food to a controlled pasteurisation temperature;
- Rapidly chilling the cooked product;
- Storing under controlled conditions;
- Reheating in a controlled manner and serving.

The claimed advantages of sous-vide are that the cooking stabilises and maximises the quality, aroma, flavour, texture and nutritional qualities of the product. In sous-vide cooking, the product is vacuum-sealed, and moisture does not evaporate to the external environment. Instead, fluid release occurs within the pouch and remains available to the consumer.

10.3.3 Ready-to-eat meals

In the kitchen or raw material preparation area of a ready-to-eat meal plant, raw materials are assembled and processed to make them ready for cooking. In some cases, cooking follows immediately after preparation, whilst in others the prepared material may be stored before cooking.

After cooking, the material is transferred to the high-risk area. Ideally, the outlet from the cooking equipment is directly connected to the high-risk area. The material is either further processed hot (such as blending or component mixing), transferred to the assembly line for hot depositing into meal trays, or chilled for further processing or meal assembly in its chilled state. A number of different methods of meal assembly are employed depending on the product requirements and manufacturers' preferences.

In food processing, microbial safety is commonly achieved by **cooking** at **70°C for at least 2 minutes** (or an equivalent time-temperature combination). In some industrial processes and for certain meal components, higher cooking temperatures of **85°C** are used to ensure uniform pathogen destruction.

Some manufacturers employ a totally cold-fill approach — all product ingredients are chilled to between 0°C and 5°C before assembly into the meal tray. The tray is then sealed with plastic film at the end of the line before being transferred to a product-holding chill before subsequent secondary (outer) packaging.

Some employ a totally hot-fill technique where all meal components are packaged at a "hot" temperature (65°C–90°C) depending on product specifications.

Often, the properties of the meal components dictate that some are added hot, then blast chilled, before the addition of further hot or cold components. For instance, hot-filled meat or sauce is blast chilled before the addition of mashed potato topping to prevent "bleeding" of the sauce into the potato.

Some products are further heat-treated after assembly, e.g. grilling or browning the top layer of a meal.

After the meal has been assembled and the primary (inner) packaging is completed, the product exits the high-risk area ready for any secondary (outer) packaging. This step is carried out prior to it being placed in the low-risk dispatch holding chill (0°C–5°C). Typically, the final product would be in the form of a 350-gram portion in a plastic tray suitable for one person.

Many meals are in single-compartment trays, whilst others are in multi-compartment trays with rice, pasta or vegetables in one compartment and the meat or fish component in a sauce in another compartment. Further components may be in other compartments. Individual meals are usually placed in a cardboard sleeve that is printed with nutritional information and cooking instructions.

The meals are either packed into cardboard boxes (typically six meals to a box), with the boxes assembled into 1-tonne pallet loads or directly packed into plastic stacking trays. Chilled products should be held for no longer than 24 hours before being loaded onto refrigerated vehicles for delivery to retail stores or catering outlets.

10.3.4 Bakery products

Refrigeration is used in several stages of bread and pastry processing. It plays a crucial role in controlling the dough temperature during mixing, the kinetics of fermentation, the dough and fat textures and also the cooling stage after baking.

10.3.4.1 Bread dough mixing

For bread, the final dough temperature at the end of mixing should ideally be similar to the fermentation temperature, as this suppresses any temperature equilibration at the start of fermentation. Dough structure is progressively developed during mixing, and this results in heat dissipation throughout the mixing stage.

Refrigerated water is often used during mixing to control and reach the desired final temperature. A rule of thumb sometimes applied is that the sum of the room temperature (assumed to be the mixing equipment temperature), the flour temperature (the main ingredient) and the water temperature should remain constant to reach a target final temperature at the end of mixing. Thus, as the room and the flour temperatures vary, the water temperature is adjusted.

In some equipment, a double jacket is installed around the mixing bowl. Within the jacket, a secondary refrigerant is circulated to maintain the dough at a constant temperature.

10.3.4.2 Bread dough fermentation

Fermentation is carried out in a temperature and humidity-controlled cabinet or chamber. Typically, the air humidity is provided by moist air generated by a boiler. Refrigeration is then used to adjust the final air temperature. The air is then circulated around the dough pieces at a low velocity. Ultrasound mist generators are sometimes used; they produce tiny water droplets, which remain suspended in the air if their diameter stays in the range of a few micrometres.

Refrigeration can also be used to retard the onset of bread dough fermentation. This is a method used daily by most craft bakers, who prepare the dough for the next day, at the end of the previous day. The prepared dough is then placed in the fermentation cabinet, and chilled (usually with air around 4°C) to block or slow the yeast fermentation. Then, during the night, the temperature rises, initiating fermentation, so that the dough pieces will be ready for baking by morning.

10.3.4.3 Post-baking bread cooling

After baking, bread is cooled via a combination of evaporation (evaporative cooling) and air convection (convective cooling). Evaporative cooling reaches its peak from around 90°C until the bread reaches around 40°C, after which evaporation becomes negligible. Bread chilling can, therefore, be split into two stages: a first stage during which evaporative cooling predominates and a second stage during which convective cooling is the main phenomenon involved. Typically, the first stage represents one third of the total cooling time, and the second stage the remaining two thirds. Bread packaging can begin once the temperature drops below around 25°C; to avoid water condensation forming in

the packaging. The total cooling time varies depending on bread shape, size, and structure, but it is typically 1–2 hours for sliced bread.

Bread chilling equipment can be either continuous systems or batch chillers.

- Continuous chilling often uses ambient air, with the bread moving on circular belt conveyors or linear conveyors, and fans ensuring air convection around the product. Refrigerated air is then sometimes used for the second stage of bread cooling to accelerate its completion.
- Batch chillers are typically used in medium-sized bakeries. In this case, the bread is placed on shelves on a trolley, which is wheeled into the chiller, where a refrigeration unit equipped with fans blows cold air over the bread. Frequently, the trolley and shelves have also supported the bread during baking, so they are also hot and represent an additional refrigeration load, which can be substantial.

For bread baked in a pan, bread depanning is done as soon as possible, after exiting the oven and before cooling, to prevent moisture condensation on the surface of the pan, as this would result in the bread adhering to the pan.

The evaporative cooling stage can be improved by spraying sterile water onto the bread when freshly baked. This process effectively accelerates bread chilling while also reducing the net mass loss occurring during bread chilling. Mass loss during cooling typically ranges from 3% to 6%. It is usually at the lower end of this range, as moisture diffusion towards the bread surface takes time and water evaporation phenomenon is limited by the lack of water at the surface.

An alternative approach, called adiabatic cooling, has been successfully implemented in continuous systems with conveyors. Its goal is to reduce water loss. There are usually two stages (three stages are sometimes used) with an airflow circulating countercurrent to the direction of the bread conveyors. The airflow is ambient air into which a mist of water is sprayed. The mist cools the air as it evaporates and a relative humidity target of 90% is set. The cold air then flows over the bread, cooling the bread and heating the air. The water loss in the bread is minimised due to the air staying close to saturation. A second (and sometimes third) water mist is sprayed into the air, also with a 90% relative humidity target, prior to the second or subsequent stage. This ensures that the air remains cool and close to saturation. This system mitigates water loss compared to conventional cooling and it applies well to soft bakery products.

10.3.4.4 Vacuum chilling of bread

Vacuum chilling can be applied to breads such as brioche, Panettone, Danish pastries and cakes.

Generally, a batch process is used; the product is placed on a trolley or rack in a pressure vessel, and the pressure is decreased. The rate of cooling depends on the pump's volume flow rate, which evacuates the lost moisture from the product, and the total cooling time may be only a few minutes. In vacuum cooling, the bread is cooled almost entirely by evaporative cooling, resulting in a water mass loss of up to 10% of its initial mass. Sometimes, sterile water is sprayed on the product during the process to mitigate the net water loss.

The product temperature follows the saturation temperature of water, as a function of the pressure, and the centre temperature drops faster than the edge temperature. This is caused by the moisture flux travelling from the centre to the edge of the bread. The final temperature of the product is controlled by the final pressure level reached inside the pressure vessel.

For the vacuum pump, liquid ring pumps are preferred, as they are very robust and relatively insensitive to the moisture content of the evacuated gases from the pressure vessel. However, this pumping technology consumes water, which should be treated and reused. Other pumping technologies can be used but require condensation units to prevent moisture from entering the mechanical parts of the pump.

The rapid cooling experienced in vacuum cooling results in a hardening of the bread crust (this is explained by the vitrification of the crust), and this can be a quality drawback for bread slicing, for example. However, a multi-stage vacuum cooling process (with the pressure lowered in several steps) can prevent this problem.

Vacuum cooling can result in an expanded structure of the baked product, occurring when the moisture evaporates. This can be a quality advantage in some cakes, brioche and Danish pastries.

Vacuum cooling has been observed to have no significant effect on staling for part baked frozen bread.

10.4 CHILLING PROCESS

The majority of plants rely on air blast cooling systems for the chilling of precooked products or ready-to-eat meals. In batch systems, the products, packs or trays of cooked material are placed directly on racks in the chiller or on trolleys that, when fully loaded, can be wheeled into the chiller. Continuous systems range from trolleys pulled through tunnels to conveyorised spiral or tunnel air-blast chillers.

Some meals and products are chilled using cryogenic tunnels, although care must be taken to avoid surface freezing. Sous-vide and other imperviously packed products are often chilled by immersion in cooled water or another suitable liquid.

With some cooked products, such as large hams in moulds and sausages, chlorinated water sprays can be used in the initial stages of cooling. Increasingly, pie and ready-to-eat meal fillings are pressure-cooked and vacuum-chilled, the main advantage being shorter heating and chilling times, which result in higher throughputs. However, care must be taken, as the quality of some products can deteriorate if cooked at too high a temperature or chilled too rapidly.

Sometimes, when the product's initial temperature is high (i.e. immediately after cooking), there is an initial pre-cooling stage whereby ambient air is circulated as the cooling medium. Taking advantage of this "free" pre-cooling can substantially reduce the chilling load that must be met by the mechanical refrigeration system.

High-risk products (for example, cook-chill processes for meats or alternative meat/plant-based products) should have their core temperature continuously monitored during cooling. This can be achieved by logging a worst-case pack with a calibrated probe. Where the worst-case pack is defined as the thermal centre, product with the warmest initial temperature, in the warmest position within the load. Establishing this may require temperature records from various product load configurations of the chiller or modelling (see ► **Chapter 4**). Electronic data loggers and integrated chiller controls with stored records are becoming increasingly common and often required for regulatory audits.

The aim of any pre-cooking process for chilled food is to ensure the destruction of vegetative cells of pathogenic microorganisms. However, there is a risk that some microorganisms which produce spores may survive the cooking process or that the food may become recontaminated. To prevent further growth, food temperature should be rapidly reduced from 80°C to 3°C. Different jurisdictions have slightly specific guidelines and regulatory requirements for implementing this general principle. The relevant jurisdiction(s) for a specific production facility should be consulted (examples are given in ► **Table 10.1**). Some jurisdictions also allow for alternative cooling processes if available data demonstrates its efficacy (for example, for cooling large cuts of cooked meat).

In addition to microbiological factors, a rapid reduction in product temperature promotes retention of nutrients, which is vital in systems such as cook-chill, which are often used for the preparation of meals for the elderly, people with disabilities and children.

Table 10.1 Example requirements for chilling times for cooked food

Country	Chilling time	Chilling rate (°C/min)	Storage temperature (°C)
EU and GB[1]	none prescribed (food placed on the market must be safe)	n/a	n/a
U.S.[2]	from 57°C to 21°C in 2 hours (from 21°C to 5°C in 4 hours)	0.30 (0.07)	5°C
Australia/NZ[3]	from 60°C to 21°C in 2 hours (from 21°C to 5°C in 4 hours)	0.33 (0.07)	5°C

1 Article 14 of EU Regulation 178/2002 prohibits placing unsafe food — defined as injurious to health or unfit for human consumption — on the market (Regulation (EC) No. 178/2002, 2002). Supporting this, Regulation 852/2004 (often cited as 852/2005) places the primary responsibility for this safety squarely on the Food Business Operator (FBO) at all stages of production, processing, and distribution (Regulation (EC) No. 852/2004, 2004).

2 (US Food and Drug Administration — FDA, 2017).

3 (Food Standards Australia New Zealand, 2023).

In simple single-stage batch chilling systems, the risk of surface freezing limits the lowest air temperature that can be used.

The problem is complicated in multi-compartment ready-to-eat meal consumer packs, which typically contain rice or pasta in one compartment and a meat or fish product in the second, because the thermal properties of the different items are often very different and they may also be filled to different depths. Trials have indicated that, due to the limits on the lowest air temperature that can be used, chilling such packs takes about 1 h if surface freezing is to be completely avoided (see ▶ **Table 10.2**). Using air at -10°C and a velocity of 5.0 m/s resulted in a cooling time of 34 minutes, but substantial quantities of the product in both compartments were frozen. Reducing the air velocity below 0.5 m/s more than doubled the cooling time but produced a situation where only a small area of the rice was frozen. With higher air temperatures, the extent of freezing was reduced. At an air temperature of -5°C, only a small amount of freezing occurred at 5.0 m/s, but this still resulted in a cooling time of approximately 0.75 h.

Table 10.2 Effect of air temperature and velocity on cooling time from 80°C to 4°C in 30-mm thick, two-compartment ready-to-eat meals

Air temperature	Velocity	Time to 4°C	Minimum temperature	
(°C)	(m/s)	(min)	(°C)	
			Meat	Rice
-10	5.0	34	-4.2	-3.8
-10	1.0	58	-1.4	-4.8
-10	0.5	78	-0.2	-2.2
-5	5.0	42	-2.2	-3.0

Based on (James, 1990)

Table 10.3 Cooling time to 10°C for different cooked meats

Type of meat	Weight	Initial temperature	Cooling time to 10°C in:		
	(kg)	(°C)	(min)		
			Air	Immersion	Vacuum
Beef					
M. semitendinosus	0.9	75	150	100	52
Forequarter	2.7	75	390	282	43
Silverside	2.7	75	338	240	61
Boneless turkey	6.4	85	526	411	36
Boned out ham	7.1	80	761	456	57

Air conditions: 0°C, 1.2 m/s; Immersion conditions: water at 0°C; Vacuum conditions: 5 mbar.

Extracted from (Burfoot *et al.*, 1990)

Typical cooling times in air, immersion and vacuum systems for a range of cooked meat joints are given in ► **Table 10.3**. Although cooling times are much faster under vacuum, weight losses (typically 7.5% to 9.5%) are much higher than those in the air (typically 2% to 3%).

Product thickness has a substantial influence on the chilling time of products in trays, as used in cook-chill systems (see ► **Figure 10.1**). In this example, based on an infinite slab model, increasing the air velocity during air chilling from 0.5 to 3.0 m/s reduced the cooling time by a factor of between 1.7 and 2 times (see ► **Figures 10.1a** and **10.1b**). ► **Figures 10.1a** and **10.1b** can be used to predict the effect of different air temperatures on cooling time provided that the surface temperature of the product is not below its initial freezing point. For example, from ► **Figure 10.1a**, if air at -2°C is used instead of +2°C, the cooling time to 3°C in the centre of an 80-mm tray is reduced from 20 to 12.5 hours.

Most products of interest have an initial freezing point between -1°C and -2°C. Surface freezing is undesirable in many products in cook-chill systems and the temperature at which freezing occurs is usually a limiting factor during chilling.

Air distribution, especially in batch chillers, can also have a large impact on chilling times. This is due to poor air distribution, which can result in a large variation in air velocity flowing past individual product packs. Care must be taken both during chiller design and installation and during operation to ensure adequate air distribution. Air diffusers, turning vanes, and other airflow directing devices can assist in ensuring even airflow. When loading racks, empty spaces where there is no product (for example, above and below the racks) should be blocked to prevent air bypass. Particular care must be taken when a chiller is in a partially loaded configuration (e.g. a half batch) to ensure that the airflow doesn't bypass the product.

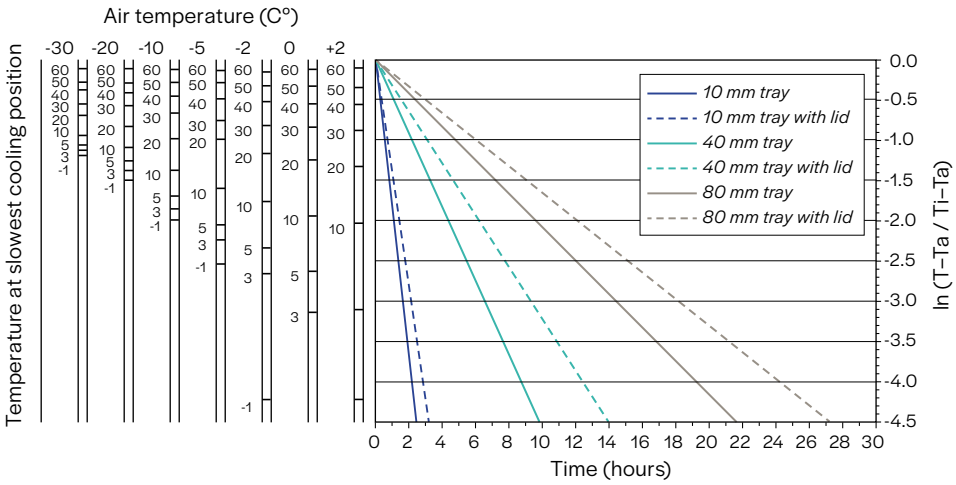


Figure 10.1a Time required to cool centre of bolognese sauce in an air velocity of 0.5 m/s (IIR, 2000)

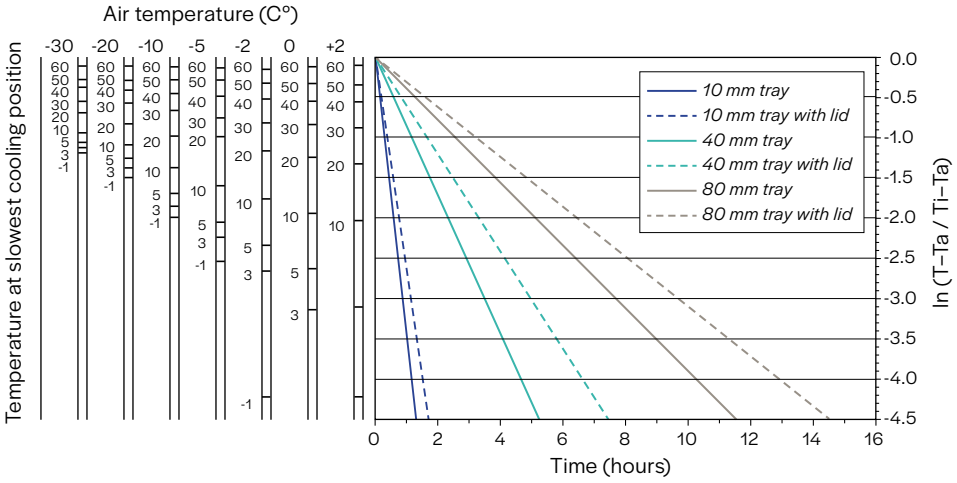


Figure 10.1.b Time required to cool centre of bolognese sauce in an air velocity of 3 m/s (IIR, 2000)

10.5 STORAGE, TRANSPORT AND DISPLAY

All chilled products, especially those that have been cooked, are very susceptible to contamination and growth of food spoilage or pathogenic microorganisms. The temperature of these products should, therefore, be maintained below 5°C during storage, transport and display. Sous-vide and cook-chill products are especially at risk, and these should be kept below 3°C after initial cooling.

It is important that all the required heat is removed from the ready-to-eat meals before they are sleeved (placed in a printed slip-on cover), packed in cartons and solid stacked on pallets. Similarly, heat should be removed from pies, pizzas, quiches, etc. before they are boxed or stacked in trays. Once the products are solid stacked, it is difficult to reduce their temperature. Conversely, it is easier to maintain the temperature of a correctly chilled product once it is bulk stacked. Once the stacks have been broken up for retail sales, it becomes more difficult to maintain the temperature of individual products below desired limits.

10.6 PACKAGING

Most ready-to-eat meals are packed immediately after assembly in PET packs with heat-sealed lids. These range in size from individual portions (150 to 500 g) for retail sale to catering packs (up to 5 kg). Retail packs are placed in either printed cardboard packs or sleeves. Retail and catering packs are usually boxed in bulk and stacked on pallets for storage and distribution. Most individual products such as pies, pizzas and quiches are packed in cardboard boxes or in plastic trays for storage and distribution.

Sous-vide products should be vacuum-sealed in high quality, and O_2 impermeable pouches or bags before cooking, chilling, storage and distribution.

Cook-chill products are usually cooked, chilled and stored in stainless steel trays. The trays are fitted with lids to stop drying out during processing and storage. The food can either be reheated in bulk on the trays before consumption or plated out as individual meals and microwave reheated.

10.7 QUALITY-INFLUENCING FACTORS

The growth of microorganisms is usually the main factor limiting the storage life of cooked products and ready-to-eat meals. However, in some ready-to-eat meals, flavour and textural changes can also limit storage life.

Similarly, changes in the texture of the pastry and separation of components can sometimes influence the storage life of products such as pies, pizzas and quiches. In some unwrapped products, e.g. sliced cooked meat, surface drying will produce detrimental changes in the appearance of the food.

In all cases, strict control of the cooking process and the use of rapid cooling techniques will maximise both organoleptic quality and nutrient retention.

In some cases, pasteurisation of ready-to-eat meals after the packs have been sealed can produce substantial increases in storage life. This process requires heating all the contents to a minimum temperature of 85°C whilst retaining pack integrity. The process can be achieved using hot air, steam or microwaves. There is a growing interest in **non-thermal preservation technologies**. Among these, **high-pressure processing (HPP)** and **ultraviolet (UV) surface treatment** are commercially established, while **pulsed light**, **ionising radiation**, and **cold plasma** have more limited industrial applications. Some of these processes only produce surface decontamination, whilst others need to be developed further before they become commercially viable for large-scale operations.

10.8 RECOMMENDED STORAGE CONDITIONS

To reduce the risk of growth of pathogenic and spoilage microorganisms, it is desirable that ready-to-eat meals and other precooked products should be stored, transported and displayed at a temperature of 5°C or less.

For wrapped products, the air velocity and relative humidity are of less importance. With unwrapped food, such as sliced cooked meats, on retail display, high relative humidities (above 85%) and low air velocities (0.2 m/s) are required in order to maximise display life. Air distribution and the defrost strategy should also minimise drying and condensation on product surfaces. Even for wrapped products, surface condensation may be an issue, especially for packaging materials that can absorb moisture (that is, cardboard-based packaging).

Cook-chill and sous-vide products should be stored at or below +3°C throughout the period between initial cooling and the preheating phase prior to consumption, although temperatures up to 5°C are allowed in some countries.

10.9 PRACTICAL STORAGE LIFE

The PSL of cooked products such as pies, pizzas, quiches and especially ready-to-eat meals is very variable and depends on the ingredients and processes used. In general, the PSL will range from 2 to 8 days for products that have not been subjected to in-pack pasteurisation and up to 21 days for in-pack pasteurised food. The strictest requirements specify a maximum storage time for both cook-chill and sous-vide products of 5 days, including both the day of production and the day of consumption. If the temperature of the food exceeds +5°C but not +10°C during storage and distribution, it should be consumed within 12 hours. If its temperature exceeds 10°C, it should be regarded as unsuitable for use and destroyed.

Commodity bread products such as sandwiches are often stored at around 4°C to prevent any microbial growth of the filling contained in the sandwich (i.e. meat-based products, and sauces). However, storage at such a temperature tends to accelerate bread staling, limiting the practical storage life.

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Chapter 11

Brewing and not-fruit juice drinks

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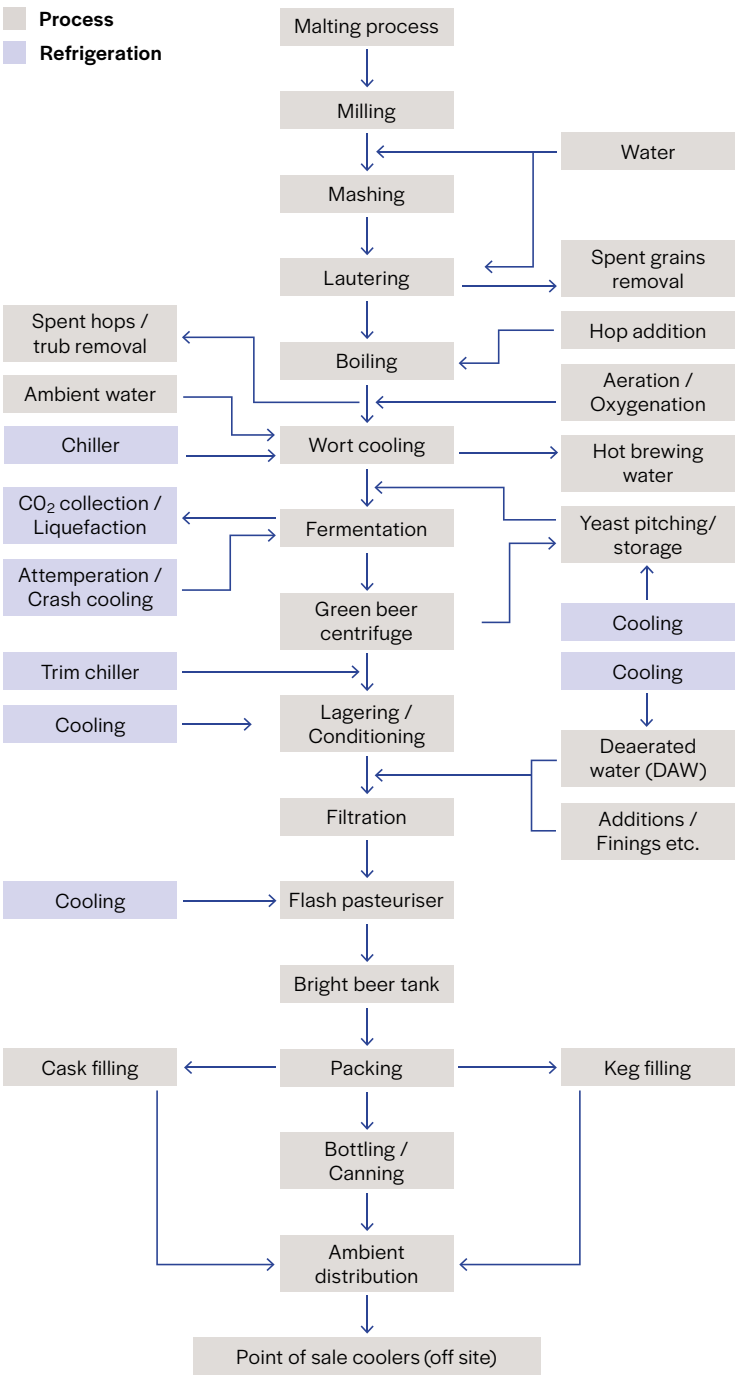


Figure 11.1 Flow sheet showing brewery processes and refrigeration.
(Source: Author's elaboration)

11.1 BREWING PROCESS

In order to understand the refrigeration processes used in beer production, it is necessary to first understand the basic brewing process.

Brewing involves producing a sugar solution (wort) from grain and its conversion to alcohol and CO_2 during a fermentation process.

There are various beer categories, including ales and lagers, but the traditional process involves only four main ingredients: water, malted barley, yeast and hops. However, in modern breweries, other types of grain, starch or sugars are added to supplement the grain charge, and to produce certain characteristics such as flavour, colour and mouthfeel.

The basics of brewing include malting and the hot and cold processes, as described in the following sections and shown in ▶ **Figure 11.1**.

11.1.1 Malting process

Barley seeds are allowed to germinate under controlled conditions in order to activate natural enzymes, which are used in the growing process. Germination is then stopped by "kilning", so that the seeds do not grow into new plants but instead become a major ingredient of beer.

The enzymes (α-amylase and ß-amylase) are a key part of the barley cycle, converting starch into useful food, and promoting new plant growth. However, these enzymes are fundamental to the brewing process, where they are used to convert the starch in the endosperm into fermentable sugars such as glucose, sucrose and maltose. Other, less fermentable sugars are also formed, such as maltotriose.

The brewing process is generally considered to fit into two main sections, namely "hot process" and "cold process". In order to establish the refrigeration requirements of a brewery, this chapter briefly explains the hot process.

11.2 HOT PROCESS

11.2.1 Wort production

"Wort" is the brewer's name for the basic sugar solution, which will be fermented. The alcohol content of the beer produced is based on the specific gravity of this sugar solution, less the amount of residual sugar, remaining after fermentation. In general terms, wort is produced in a batch process, by converting starch from the malted barley and other grains, into a sugar solution by action of the aforementioned enzymes produced during the malting process.

11.2.2 Milling

Malted barley and other grains are crushed by a mill into a "grist case", breaking up the starch into a blend of grits and flour, whilst keeping the husks as intact as possible. The husks are used later, to form a filter bed, to clarify the wort.

In general, the smaller the particulate size after milling, the more fermentable sugars are released; – known as "extract" and measured against a laboratory optimum figure called the fine-grind extract. To increase extract, a mash filter can be used to separate the

wort, when there is a "hammer mill" to pulverise the grain to a fine consistency. It should be noted that hammer milling produces very fine material which can be flammable and must be protected by regulations such as ATEX and Dangerous Substances and Explosive Atmospheres Regulations (DSEAR), which apply in the UK. Similar regulations apply in other countries. Care must be taken to prevent stones or metal passing through the mill, where sparks may form. The use of magnets and destoners is a prerequisite before milling, in a modern brewery.

11.2.3 Wort separation

The crushed grain is blended with hot water (hot brewing liquor), in a mash mixer, to form a porridge-like mash, at an optimum temperature that best allows the enzymes to work. Once converted, the wort (sugar solution) is then separated from the husks.

11.2.3.1 Mashing and lautering

In a traditional ale brewery, the mash is collected into a "mash tun" which operates at a single temperature, typically 67°C, to allow the starch to convert to sugar over a set period (say 1 hour). The base of this vessel contains a slotted metal support plate over an underplate space where the wort is filtered through the husks and then collected before transferring to a kettle.

Larger breweries and more modern brewhouses heat the wort in a separate "conversion vessel" using a stepped heating regime, aimed at gaining the most effective conversion of the starch into sugars — each enzyme working at its optimal operating temperature. Once the wort is "fully converted" that is, when the maximum amount of fermentable sugars has been released, a "mash-out" stand is often carried out at a temperature, typically 73–75°C, to deactivate the enzymes.

The wort is then pumped to a "lauter tun" where the contents are filtered through the husks sitting on a false bottom. The lauter tun is a separate, unheated vessel with a base, similar in design to the mush tun. Here, the sugar solution (wort) is strained and, after the solids are removed, runs off to a heating vessel known as a "kettle" or "wort copper".

The maximum extract is achieved by spraying the grain with warm water, known as "sparging", to remove as much of the sugar as possible from the husks, leaving the husks themselves behind, for use as "spent grains", an animal feed supplement for cattle.

11.2.3 Cereal cooker

When using certain raw materials, such as maize and rice, to supplement the malted barley, the grain needs to be heated to a higher temperature in order to convert starch into sugar. Rice, for example, needs to be boiled so that the starch is gelatinised, with the cereal then returned to the mash conversion vessel. This blending of temperatures is known as "decoction".

These "adjuncts" are not only used to replace costly malt, but they also modify the colour and mouthfeel of beer.

11.2.4 Mash filter

Over 25% of the world's beers are produced using a mash filter (BRAUWELT International, 2023; Mörtl, 2022). The main reason for using such a machine is that it can operate on

very fine powders and small grains and, thereby, may be used with indigenous grains such as sorghum or millet. It can also be used to obtain a very high extract, often greater than the predicted laboratory extract.

Mash filters with flexible plates can also squeeze the mash, producing very dry spent grains and recovering the maximum amount of wort.

11.2.4 Wort boiling

Within the kettle (wort copper), the wort is raised to boiling point, using steam to sterilise it, using vessel jackets, coils or an external shell and tube heater, known generically as a "calandria". Hops are added in this vessel, and the extracted hop oils give a bittering flavour to the finished product. Hops also help to keep the wort free from microbial spoilage.

A proportion of the liquid is evaporated, removing unwanted hop volatiles and adjusting the wort strength to the required original gravity, which is a measure of the sugar concentration before fermentation. The wort is finally ready for transfer to the fermenter, following the removal of hop debris, either using a Whirlpool, a Hop Back or other filtration device, to clarify the wort and remove proteins. This protein separation is known as "hot break".

11.3 COLD PROCESS

11.3.1 Wort cooling

The bitter-flavoured sugar solution (or wort) has to be cooled to a temperature at which yeast can be introduced (or pitched) without being damaged and to gain the best fermentation effect.

Wort cooling reduces the temperature of the wort and its volume shrinks by approximately 4% as it cools. Haze-forming proteins flocculate and drop out of solution. This cold break is diverted to drain or mixed with the spent grains as animal feed. Breweries measure the volume of wort produced at the lower temperature (post wort cooler) and not as a hot liquid.

For English ales and similar beers, the pitching temperature, dependent on strain, is typically in the range of 12–14°C. For lagers, the temperature is lower, nearer 8–10°C, and for porters and stouts, approximately 18–20°C, as they are stronger, darker beers.

The cooling process starts in a plate heat exchanger, where the hot wort is cooled by transferring its heat to the incoming ambient brewing water (liquor) (▶ **Figure 11.2**). This recovered heat raises the temperature of the water to that required for mashing and sparging, improving energy efficiency. The required wort temperature is achieved by an additional stage on the plate heat exchanger, using a secondary refrigerant (coolant) such as propylene glycol solution or an industrial methylated spirits solution (IMS).

Brewers of lager beers often cool the incoming brewing liquor from ambient to a temperature of around 1°C +/- 0.5°C and use this very low temperature brewing liquor as the only coolant, minimising the risk of cross-plate contamination. The wort is cooled to pitching temperature without using glycol or IMS solution. It should be noted that when using a plate heat exchanger for heating or cooling liquid foodstuffs and beverages, care must be taken to prevent cross-plate contamination, either due to plate perforations or damaged seals.

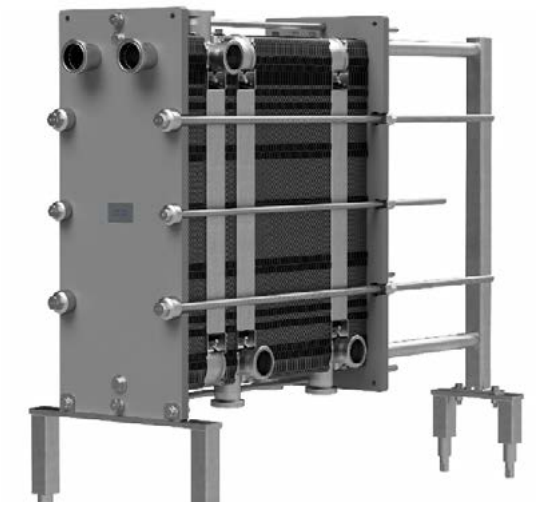


Figure 11.2 Typical wort cooler. (*Courtesy of Alfa Laval*)

The materials of construction should be suitable for both the product and the heating/cooling medium and that there is a positive pressure differential between the product and the heating/cooling medium, to ensure no leakage into the product. Pressure testing should be carried out on a regular basis to check for any leaks.

To ensure fouling of the plate pack remains minimal, regular CIP of the beer side is required, depending on the type of beer produced and the brewing programme itself. Pressure gauges located before and after each stage of the process will alert the brewer to any reduction in flow.

For safety reasons, a plate heat exchanger should be fitted with a removable cover to contain any leakage should the rubber seals rupture, or the plate pack tightening screws loosen.

11.3.2 Yeast pitching

Yeast is a unicellular fungus that drives alcoholic fermentation during the brewing process. Immediately before the wort cooler, the wort is aerated (or oxygenated) in order to promote the growth of the yeast at the early (aerobic) stage of fermentation. The plate pack offers a tortuous path in order to saturate the wort with air or oxygen.

Yeast is pitched into the wort immediately after the plate heat exchanger, en-route to a fermentation vessel ready to start the fermentation process. Yeast, like hops, helps to keep the wort free from infection, so the sooner the yeast is added the better.

In brewing, yeast management is an important science on its own, but from a refrigeration perspective, it is simply the addition of the correct quantity of good quality liquid yeast into the wort at the optimum combined, pitching temperature. Yeast is usually collected and stored at low temperature, around 4°C, making sure that it is not frozen and that ice crystals do not form.

In smaller breweries, yeast in powder form may be used, sometimes in a single trip process. In this case, the reproduction or growth stage may take longer.

11.3.3 Fermentation

The standard time for the fermentation process ranges from 4 to 5 days for ales and 7 days for lager beers.

Once yeast is added to the wort, fermentation, an exothermic reaction, begins. This causes the temperature to rise and after a few days, the yeast turns the wort (sugar solution) into beer, containing both alcohol and carbon dioxide.

Fermentation occurs within a jacketed vessel, known as a fermentation vessel, although many modern brewers use one vessel for both fermentation and lagering (cold maturation and clarification), otherwise known as a dual-purpose vessel (DPV).

At the start of fermentation, the process is aerobic and allows the yeast to reproduce up to approximately 5 times the original volume. In order to contain the additional yeast, a fermentation vessel is normally designed with a 25% headspace to allow for foam production.

After a period of time, once all the oxygen has been consumed, the process becomes anaerobic and the sugars are then converted to alcohol and carbon dioxide.

Modern breweries tend to use vertical cylindro-conical vessels (see ▶ **Figure 11.3**) using a bottom-fermenting yeast, where the yeast will settle to the bottom of the vessel once fermentation has finished.



Figure 11.3 Vertical cylindro-conical vessels. (*Photo: James Jennings*)

In older/traditional breweries, square vessels with internal cooling coils are often used (see ▶ **Figure 11.4**) — these vessels are more suited to top-fermenting yeast.

Cylindro-conical vessels are ideal for collecting carbon dioxide, which is used to carbonate the packaged product to taste and for point-of-sale dispense.

A liquid coolant, often a glycol solution or industrial methylated spirit (IMS) solution, is normally used for attemperation (temperature control) during fermentation. However,

a primary refrigerant gas, such as ammonia, can also be used for direct cooling of fermenters using a high-pressure cooling jacket. It is normal for direct cooled vessels to be located outdoors, to reduce the risk of gas leakage into production areas.



Figure 11.4 Open square fermenter with a yeast crust on top.
(*Photo: Roger Putman, Chartered Institute of Brewers and Distillers*)

When a primary refrigerant is used, the system must be designed to accommodate increases in jacket pressure corresponding to the rise in temperature from the lowest working temperature up to the highest ambient temperature. Climate change must be considered with expected ambient temperatures likely to be much higher than current levels.

In order not to damage the yeast, which can be collected and used to pitch future brews, the temperature of the coolant is controlled to ensure that ice crystals do not form on the vessel internal surfaces.

If a secondary refrigerant system is used, the coolant temperature is controlled by mixing cold supply coolant with warmer return coolant via a three-way control valve.

The normal procedure is to allow the fermentation temperature to rise by a few degrees to remove diacetyl off-flavours, then control the temperature of the vessel content to ensure the correct flavour profile. This temperature is controlled within a specific profile until the available sugar has been converted to alcohol. This temperature control process, known as attemperation, uses jackets on the vertical sides of the fermentation vessel to maintain the temperature within the required limits of the beer recipe.

For sweeter, less bitter beers, such as “mild” or brown ale, fermentation can be stopped early by crash cooling, leaving a proportion of the fermentable sugars unfermented.

11.3.4 Crash cooling

Once fermentation is complete and the alcohol content has been achieved, the emphasis turns to conditioning (often called “lagering”, “maturation” or “storage”). The purpose of this stage is to develop the flavours and to clarify the beer whilst keeping the temperature low.

By opening the valve to the cone jacket on the fermentation vessel, the beer is "crash-cooled" to a temperature of around -2°C, over a 24-hour period, causing the yeast to form clumps (flocs) and settle at the bottom of the tank. The alcohol acts as a mild antifreeze and prevents the bulk of the vessel from freezing.

11.3.5 Yeast collection

In vertical vessels, where yeast falls to the bottom of the tank, a small quantity of soiled yeast is removed from the fermentation vessel to drain. The remaining yeast can be collected and stored in a yeast storage vessel where it can be used for future pitching, as a food ingredient or sold to farmers as spent yeast, a high protein feed supplement for animals.

In open square fermenters, where the yeast rises to the top, the yeast is skimmed using a vacuum extraction device. The product after fermentation is now called "green beer" and it is followed by the lagering process.

A typical lager yeast collection after fermentation would be approximately 5% of the fermenter volume, with the first 1% being mixed with trub and tipped to drain, the next 3% being collected for use in future pitching and the final 1% sent to a "piggy" tank for use as pig food. A small residue of yeast is left in the beer to aid maturation and "secondary" fermentation during storage.

For yeast that does not flocculate well, or when maximising beer recovery for blending, yeast can be removed using a green beer centrifuge with a bypass, to ensure some yeast remains in solution. During this transfer, the green beer centrifuge removes as much of the yeast as possible and any residual protein that drops out of solution. The temperature during this process must be low and the beer should not be allowed to rise above -1°C, a plate heat exchanger often being used to maintain this low temperature. Any filtrate from the separation can be dosed back into the fermenter for further processing.

See ► **Section 11.4.4 Yeast handling**.

11.3.6 Lagering

In the German language, the term "lagering" means "storing" and refers to the time the beer remains in vessel to develop flavours and to clarify the product. Nowadays, alternative techniques are also used to stabilise the beer and these are not necessarily "time related".

Beer has to be cold conditioned to remove haze forming proteins and settle out any residual yeast after secondary fermentation. After crash cooling, the fermented "green beer" is transferred to a conditioning vessel (CV) or into another dual-purpose vessel (DPV).

Conditioning vessels are generally smaller than fermenters, as there is minimal foaming at this stage, and a headspace of around 5–10% would be adequate. Alternatively, in a DPV, the 25% headspace can be used to top up and blend beers.

Lagering will be carried out in a lagering vessel or dual-purpose vessel (DPV), where the same design of the vessel can be used for both fermentation and lagering. However, after the yeast is removed, the headspace required in a lagering tank is much lower, typically 5–10% freeboard. As crash cooling is not required, smaller refrigerating jackets can be fitted to maintain the low temperature.

Throughout the entire lagering process, the beer should be kept at a low temperature, usually slightly below 0°C, using a coolant in a cooling jacket.

The length of conditioning time depends on a number of factors, including beer type and the shelf life required for the finished beer. The container used for dispensing (bottle, can, keg or cask) will also influence the shelf life. For example, a traditional lager might require 28 days in a conditioning vessel with three months in keg, whereas a traditional British keg ale requires only around 7 days in a conditioning vessel.

For British cask ales, the beer can be filled directly into a cask from the fermenter and matured in the dispense container — known as "cask conditioning".

Modern brewing methods and improved technology, such as in-vessel mixing, can reduce the tank conditioning time, with some lagers being ready for dispense in just a few days, subject to cold filtration.

11.3.7 Filtration

Apart from cask-conditioned beer, which is stored in its container at 11 to 13°C, other beers are sold in kegs, bottles and cans. Prior to packaging, this "tank-conditioned" beer needs to be filtered at low temperature to remove any residual protein haze.

Additives may also be added to the conditioned beer prior to filtration. These additives may include hop oils for flavour, finings, preservatives, e.g. ascorbic acid, additional colouring and filter aids such as diatomaceous earth (Kieselguhr) and pearlite.

In recent years, the use of powdered filter aids such as diatomaceous earth and perlite has become less preferred due to health, environmental, and operational concerns. Handling these materials poses inhalation risks associated with respirable silica and generates large volumes of solid waste. Powder filtration systems also result in higher product losses and require significant manual handling and cleaning. Membrane filtration has therefore become a preferred alternative, as it is a closed, fully clean-in-place system that improves operator safety, reduces waste, increases beer recovery, and provides more consistent filtration performance and microbiological control.

In all cases, a final plate heat exchanger is used to trim the temperature in order to ensure that the beer temperature remains below 0°C, when the beer is transferred to the packaging tank. Traditionally, a packaging tank is otherwise known as a "bright beer tank" (BBT). A carbonation device can also be incorporated to increase the CO_2 in solution to the correct level for the beer type.

British ale has a typical carbonation level of 2.4 vol/vol with lagers up to 3 vol/vol. Wheat beers and carbonated soft drinks can be 5 vol/vol or higher.

11.3.8 Bright Beer Tank

Depending on the retention time required in the BBT, this tank will usually be well insulated, keeping the temperature rise to less than 1°C per 24 hours. Cooling jackets are not usually required unless the brewer needs beers to be blended in the BBT, in which case a cooling jacket could prove useful.

The beer in the BBT is held under CO_2 top pressure to retain its carbonation and exclude oxygen, in order to reduce the risk of oxidation and off-flavours.

11.4 ADDITIONAL PROCESSES WITHIN A BREWERY

11.4.1 High Gravity Brewing

Some brewers produce their wort at a much higher specific gravity than their sales require. This allows them to cut (dilute) the product to increase the output of the brewery.

The High Gravity Brewing (HGB) process reduces the number of fermentation vessels required and decreases the number of transfers between sites in a multi-site operation. The finished beer needs to be "cut", or diluted to the required sales alcohol content.

De-aerated water, or in brewing terms de-aerated liquor (DAL), is used to cut the product.

Cutting/dilution is often misunderstood as "watering down" — a term frowned upon in brewing circles — hence the traditional brewing term for water is "liquor".

11.4.2 De-Aerated Liquor production

DAL is usually produced by bubbling CO_2 or nitrogen through brewing quality water, to sparge out air and then storing it under an inert gas blanket. This de-aerated liquor can then be blended with the high gravity beer to produce beer at the required sales alcohol level for packaging.

11.4.3 Carbon dioxide collection and liquefaction

During fermentation, CO_2 is absorbed into the beer to give it its gassy characteristic. However, an excess of CO_2 is produced, which can be collected for use in packaging and dispensing.

In the past, the in-house collection of CO_2 was carried out only by large-scale brewers. However, in recent years, due to the high cost of CO_2, a number of engineering companies have developed collection and liquefaction plants for small-scale breweries.

Collecting, cleaning and pressurising the gas requires no refrigeration; however, for liquefaction, it is normal to cool the gas using a refrigerant. This can be a primary or secondary refrigerant, depending on the make of plant used and the temperature of liquefaction.

11.4.4 Yeast handling

11.4.4.1 Yeast storage

Breweries that use liquid yeast can collect excess yeast at the end of fermentation and use it for pitching future brews, up to an approved number of generations. The exact number of generations allowed will depend on the brand owner's requirements and the way that yeast might mutate over time.

Once the brewer has sufficient yeast for their brewing programme, any further excess, or any out of specification yeast, can be disposed of as a pig feed supplement. It can also be autolysed and sold with the spent grains for animal feed in general.

Good-quality waste yeast might also be sold as a brewery by-product for pharmaceutical use or as foodstuff for human consumption, for example, Marmite and Bovril.

Yeast for reuse must be kept refrigerated to a temperature of approximately 4°C, and stored in a jacketed tank with a coolant. Yeast should not be frozen, as this may damage the cells.

11.4.4.2 Yeast propagation

Fresh yeast can be grown from laboratory culture in a custom-made propagation plant.

Wort is first sterilised by heating to boiling point using a steam jacket or by direct steam contact. It is then cooled to a pitching temperature that allows the yeast to propagate without damaging it.

The actual pitching temperature, typically in the range of 18 to 24°C but can be higher, depends on the yeast strain. This information can be obtained from the yeast supplier or from the brewer's own custom and practice.

This cooling phase uses a coolant to cool down the wort as quickly as possible, either using a refrigerated jacket on the propagator or circulating it via a plate heat exchanger.

Sterile air or oxygen is injected into the wort, to promote aerobic growth of the yeast.

11.4.5 Beer packaging

11.4.5.1 Pack types

Beers may be packaged into either **large** packs or **small** packs.

The term "large pack" includes unpressurised **cask** beers, usually sold as firkins (9 imp. gallons) and pins (4.5 imp. gallons), dispensed under gravity or by handpump; and **keg** beers, usually sold as pressurised in 30 litres, 10 imp. gallons and 11 imp. gallons (50 litres) sizes, dispensed using gas top pressure.

In both cases, larger sizes are sometimes available for sale depending on shelf life and manual-handling issues.

The recommended dispense time for both cask and keg beers is 5–7 days from tapping to consumption; hence the size of large pack purchased will usually depend on the outlet and the time required to sell the beer.

In previous years, larger cask sizes such as a barrel (36 imp. gallons) were regularly used, but at a total weight of approximately 170 kg, the manual handling of these heavy loads causes concern under health and safety regulations. In fact, even a standard 50 litre (11 imp. gallons) keg at an all-up weight of approximately 120 kg, is not preferred due to the problems of manual handling.

Cask beers should be stored in a cellar at a controlled temperature of between 12 and 14°C and dispensed directly. Keg beers, however, can be stored in a cellar or at room temperature, with the final dispense temperature achieved using an under-bar chiller.

The term "small pack" includes glass bottles and aluminium cans of any size. Less popular is polyethylene terephthalate (PET) packaging, considered to be one-trip plastic, although some beers are filled into larger PET bottles as a relatively short shelf-life product.

The refrigeration requirement for small pack in the packaging area is covered in ▶ **Section 11.9** and includes beers, ciders, carbonated soft drinks, energy drinks and ready to drink (RTD) products.

11.4.5.2 Flash pasteurisation

Prior to packing into keg or small pack, beers are often flash pasteurised in order to increase shelf life. The beer is heated to pasteurisation temperature in a plate heat exchanger, held for the appropriate time in holding tubes, and then cooled to packaging temperature using a secondary refrigerant.

11.5 GROWTH OF NO- AND LOW-ALCOHOL BEERS

According to the British Beer and Pub Association (BBPA), no and low-alcohol beer is now the fastest growing drinks segment (British Beer & Pub Association — BBPA, 2024). Younger drinkers, Generation Z, are leading the way, and their move away from alcohol towards a "healthier" lifestyle is one of the main reasons for the popularity of this market segment. There is also a significant market for no and low-alcohol wines and spirits.

It is possible to produce no and low-alcohol drinks in a number of ways. The most common method is to produce beer as per the standard brewing process and then remove the alcohol by boiling/vacuum distillation or by reverse osmosis membrane filtration. More recent developments in the production of special yeasts have also meant that beers with a low alcohol content can be produced using a standard brewing process.

11.5.1 Boiling or vacuum distillation

This method of alcohol removal is currently the only one capable of achieving full alcohol removal and providing a true 0.0% alcohol by volume product.

The boiling method heats the beer until it reaches the boiling point of alcohol (78°C) and then evaporates the alcohol, which is collected in an alcohol safe.

The alcohol itself can then be used in another process, for example, as an additive for vehicle fuels or to fortify alcoholic drinks. However, without a licence to handle or sell alcohol, many smaller brewers will be forced to dispose of the alcohol as waste.

One of the disadvantages of these "hot" methods is that flavour and aroma compounds may also be stripped out.

Excess heat should be removed in a plate heat exchanger just prior to packaging.

11.5.2 Membrane alcohol removal

Membrane filters can also be used to separate the alcohol from the beer. These filters can reduce the alcohol content as low as to 0.05% ABV, which many consider to be "no alcohol". However, it still contains a small proportion of alcohol and is, for that reason, a "low alcohol" product.

11.5.3 Use of specially designed yeasts

It is also possible to ferment wort using a special yeast designed to stop the production of ethanol. Several of these yeasts are genetically modified for this purpose and are designed not to ferment certain sugars such as maltose and maltotriose; these are the primary sugars that conventional yeasts turn into ethanol.

A disadvantage is that these sugars, the maltose and maltotriose, when left

unfermented, create a microbiological stability risk for the packaged beer, requiring significant pasteurisation.

Brewing with these yeasts is currently unlikely to produce 0.0% ABV beers and generally produces beers in the 0.4–0.8% ABV range. However, ongoing development work aims at producing yeast strains that can reduce the alcohol content of beers to 0.05% or lower, generally considered as "no-alcohol" in many markets.

11.6 BREWERY REFRIGERATION SYSTEM

For many years, traditional breweries have used a centralised system to provide their cooling. Nowadays, there is a trend towards a **modular system** due to a range of factors, including:

- **Multiple coolant temperatures required** Many breweries operate their central systems at say -7°C to cover the lowest-temperature duty, for example crash cooling and carbon dioxide liquefaction. The coolant temperature is then increased for the less arduous duties such as wort cooling or fermenter attemperation. With modular systems, a cooling system for each specific temperature duty can be applied, thereby saving the energy required to take all your secondary refrigerant to the lowest common temperature.
- **Geography** A brewery might be spread over a large area and multiple floors. Designers tend to locate a central system at ground floor level, close to the largest refrigerant user, usually near the fermentation vessels. This means that other users, for example wort cooling or yeast handling, might be remote, requiring long pipe runs with associated problems. For example, a high quantity of refrigerant in circuit, risk of leakage, the need for a high standard of insulation, and, of course, the cost of installation. It is also costly to distribute to upper floors. It is possible, for example, to locate a modular unit on each floor, thereby lowering pumping energy and by reducing both installation and maintenance costs.
- **Site expansion** It is beneficial to expand a refrigeration system by simply adding modules. In this way, the initial capital outlay can be minimised to suit the start-up situation, increasing capacity only when required.

Adiabatic chillers, such as the one shown in ► **Figure 11.5**, are considered more energy efficient and can reduce water consumption when compared to standard cooling towers.



Figure 11.5 A modular adiabatic chiller. (*Courtesy of Roberto Sommi, Frigel*)

11.7 SOFT DRINKS

11.7.1 Carbonated soft drinks

The production of carbonated soft drinks is relatively straightforward. In general, a high specific gravity (BRIX), syrup solution is prepared and flavoured, either at room temperature or warm. It is then diluted and carbonated in a suitable plant before pasteurisation, cooling and trim-carbonating to the desired level, prior to filling.

Within the soft drinks sector, the two main methods used to pasteurise and cool soft drinks are "flash pasteurisation" in a plate heat exchanger and in a "tunnel pasteuriser", where the product is first filled into small pack and then pasteurised in a multi-section pasteuriser that heats and then cools the product using ambient water to achieve the correct pasteurisation units (PU's).

Unlike beers, some soft drinks contain a high level of pulp or fibres. To ensure pasteurisation is effective, a plate pack with a larger internal gap is required.

11.7.2 High fibre soft drinks

Wide gap plate packs with countercurrent flow are used for pulp and other high-fibre-content carbonated soft drinks and juices.

11.8 JUICES AND NECTARS

Most juices and nectars, whether freshly squeezed, pressed, milled or processed from concentrate, will be produced warm or at room temperature, and then pasteurised and packed by a method suitable for the required shelf life.

For longer shelf life, Ultra-High Temperature (UHT) processing is a common form of heat treatment for these products, raising the temperature to approximately 140°C in order to kill bacterial endospores.

The product can be packaged using aseptic filling techniques into shelf-stable, aseptic beverage cartons. For shorter shelf-life products, packaging into glass or PET following flash pasteurisation is also an option.

All juices and nectars can then be chilled in the pack at the point of sale or in the home using a commercial cooler or a domestic refrigerator.

11.9 REFRIGERATION AT POINT OF SALE

In order to stabilise the product and ensure the required shelf life in packs, most drinks are packed into small pack, following flash pasteurisation or processing in a tunnel pasteuriser.

Ascorbic acid or other preservatives are used to mop up oxygen and bottled products are to be kept out of direct sunlight.

Once in the pack, there is no need to maintain a low temperature in order to maintain shelf life. There is, however, an ideal serving temperature and this can be achieved within a cold cellar or industrial refrigerator. In the case of keg or cask, an under-bar chiller or refrigerated blanket can be used to achieve the desired temperature at point of sale.

11.10 CONCLUSION

Refrigeration is a critical element in beer production and storage, underpinning both product quality and safety throughout the brewing process. Precise temperature control is essential during fermentation to regulate yeast activity, influence flavour development, and ensure consistent alcohol production, while rapid cooling of wort is necessary to prevent microbial growth and to stabilise the product. During conditioning, filtration, packaging, and storage, refrigeration preserves carbonation, limits oxidation, and slows chemical and biological reactions that can lead to flavour deterioration. Effective refrigeration therefore enables breweries to deliver stable, high-quality beer with predictable shelf life, making it an indispensable component of modern brewing operations.

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Chapter 12

Cut flowers

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12.1 SPECIAL FEATURES OF CUT FLOWERS

Cut flowers are complex and fragile plant organs with considerable commercial value. They are immature, actively growing organs that need water, energy and nutrients to survive, since their separation from the mother plant has deprived them of these materials.

Flower senescence (the process of dying) follows different patterns that are characteristic for each variety: some flowers "shatter", losing their petals; some wilt, some lose colour or become discoloured and if the cut flower has leaves, these may quickly turn yellow, blacken, or abscise. Any of these changes can lead to the end of "vase life".

Flowers contain practically no nutritive reserves, while their metabolism, supported by respiration, is very intense. There is therefore a risk of metabolic disorders immediately after harvest. Additionally, they are also susceptible to bacterial and fungal infections.

They lose a considerable quantity of water through transpiration and are quickly dehydrated, especially when they are in a dry environment, for example, during transport or storage. Moreover, various obstacles to the rise of water in the stem can occur, including air entry into the conducting vessels (leading to "embolism"), the growth of bacteria that can obstruct the vessels or the formation of "tyloses" that deliberately plug vessels.

The physical conditions found indoors are harmful to the survival of cut flowers. Warm temperatures stimulate metabolism and reduce the lifespan of the flowers, while the dryness of the atmosphere accelerates transpiration.

These same considerations apply at the time of harvest. Growers should avoid harvesting in the heat of the day, choose the correct stage of harvest maturity and stem length based on their intended market, move flowers to the shade and remove field heat as soon as possible and chill the flowers overnight in water before packing and shipping. Some flowers, including *Alstroemeria*, *Antirrhinum*, *Dianthus*, *Gypsophila*, orchids and some rose varieties, are very sensitive to ethylene (Woltering and van Doorn, 1988).

12.2 VALUE OF NUTRITIVE AND PRESERVATIVE SOLUTIONS

The purpose of nutritive solutions, or "preservatives", for cut flowers is to extend their vase life. They generally contain a small amount of sugar, glucose or sucrose, as a respiratory substrate; an anti-microbial agent; an acid to support water uptake; and may contain compounds to precipitate calcium carbonate or fluoride out of tap water, since these may be toxic to many flowers. They may also contain plant hormones to keep stems and leaves green. Traditionally, silver thiosulphate (STS) was used to inhibit the action of ethylene, but heavy metal treatments are generally not permitted in supply chains as they lead to disposal problems. Treatments with 1-methylcyclopropene (1-MCP) are now more common for ethylene-sensitive varieties.

Nutritive or preservative solutions are usually applied after harvest before packaging and transport through the supply chain. Each flower species has its own ideal preservative solution but the manufacturers' labels on commercial preservatives will indicate broad suitability of their product. Similar formulations are also used at the consumer phase to extend the vase life (flower food products).

In certain cases, the cold-storage time can be increased by "pulsing" flowers in a sugar-rich solution after harvest. For example, a 2-day treatment at 22°C with a solution containing 10% sucrose, 250 ppm of hydroxyquinoline and 150 ppm of citric acid has been recommended before storing *Strelitzia* flowers for 1 month at 8°C (Halevy et al. 1978).

12.3 VALUE OF REFRIGERATION

By reducing the metabolic activity of cells, refrigeration slows the growth of cut flowers and delays senescence. However, care needs to be exercised because flowers of tropical and sub-tropical origin can suffer from "chilling injury" if treated with too low temperature. These chilling injury temperature limits are characteristic for each variety. ▶ **Table 12.1** gives some examples of flowers that are sensitive to cold temperatures.

Each flower variety has an optimal stage for harvest, and an optimal storage temperature, that would jointly ensure a maximal vase life once removed from cold storage. Few flowers have had the extensive (and expensive) research necessary to develop clear guidelines for these matters (e.g. Eason *et al.*, 2002 for peonies). In the absence of specific information, partly opened buds are the preferred stage for harvest, as they are mature enough to open but are still physically protected by their bracts.

The earlier the flowers are harvested, the more sugar and possibly added plant hormones they will require to support normal development after cold storage. Commercial solutions are available for this purpose.

Controlled atmospheres (CA) or hypobaric storage combined with refrigeration can be beneficial to extend storage life (▶ **Tables 12.2**, **12.3**) but both treatments are expensive to implement and maintain so their use is limited. Nevertheless, the use of reefer container transport (sea freight) as an alternative to air freight is increasing. For long sea transport supply chains, the use of CA may contribute to extend storage life, although it must be noted that some cultivars are sensitive to CO_2 concentrations above 5%. Modified atmosphere packaging (MAP) has been used as a simpler technology for a range of species (Rashed *et al.*, 2024).

Table 12.1 Cold sensitivity of some cut flowers

Marked sensitivity	Low sensitivity
Anthurium	*Allium*
Cattleya	*Aster* (Chinese)
Dendrobium	*Bouvardia*
Eucharis	*Chrysanthemum*
Godetia	*Crocus*
Heliconia	*Cymbidium*
Nerine	*Daffodil*
Phalaenopsis	*Freesia*
Strelitzia (bird of paradise)	*Gardenia*
Vanda	*Gypsophila*
	Hyacinth
	Iris (bulbous)
	Lily
	Lily of the valley
	Peony
	Ranunculus
	Rose
	Sweet pea
	Tulip

Source: Darras (2020)

Table 12.2 Controlled or modified atmospheres proposed by various researchers for the storage of certain cut flowers

Flowers	Atmospheric composition (%)		Storage temperature (°C)	Storage time (days)
	O_2	CO_2		
Carnation	1–3	5	0–1	30
Freesia	21	10	1–2	21
Gladiolus	1–3	5	1–5	21
Lily	21	10–20	1	21
Mimosa	7–8	0	6–8	10
Rose	1–3	5-10	0	20–35
Tulip	21	5	1	10

Source: IIR (2000)

Table 12.3 Storage time of some cut flowers by using simple chilling and hypobaric conditions

Flowers	Storage time (days)	
	simple chilling	hypobaric conditions
Carnation	10	91
Chrysanthemum (in bud)	7–14	42
Rose	7–14	56

Source: IIR (2000)

12.4 VALUE OF PACKAGING

For convenience, harvested flowers are generally packed horizontally in boxes with a plastic liner to reduce water loss. In longer supply chains, a plastic liner can create conditions that stimulate the development of micro-organisms. In those cases, the permeability of the plastic becomes relevant. Some high-value flowers, such as orchids, justify the use of a small self-sealing tube of gel or liquid applied to the cut end. Some researchers recommend vertical storage in water, with dim lighting supplied, for short supply chains. If water is supplied, it should be changed often and treated with an anti-microbial agent.

Due to geotropism (growth response to gravity), some flowers, such as gladiolus, snapdragon, lisianthus, and gerbera, must be packed and transported upright. If shipped horizontally, the stems will bend upward, resulting in distorted flowers. This is particularly relevant for long (intercontinental) supply chains.

The packaging system may also contain special features to protect more fragile flowers from mechanical damage (e.g. Single Faced Kraft sleeves). New smart packaging concepts are entering the market, providing active quality management such as ethylene control.

12.5 RECOMMENDED STORAGE CONDITIONS

▶ **Table 12.4** provides guidelines for storage temperatures and the corresponding expected storage times. In practice, temperatures of -1°C are often recommended yet rarely applied, since they require very close monitoring of conditions; 0°C is preferred. Precise details will vary by variety. For short-term storage (2 to 4 days), temperatures around 5°C are recommended, ideally with the flowers kept in water.

The relative humidity should always be maintained at high values. It is necessary to avoid ethylene accumulation; this can be achieved by equipping the rooms with an atmosphere-replacement device or an ethylene scrubber.

Table 12.4 Recommended conditions for chilled storage of cut flowers

Species	Temperature (°C)	Relative humidity (%)	Expected storage time	Notes
Alstroemeria*	0–1		1 w	
Anemone*	0–1		1 w	
Anthurium	13		3 w	
*Antirrhinum** (Snapdragon)	0–1		8 w	In buds
	7		1–2 d	In water
Aster	0–1		1 w	
Calla	0–1		1–2 w	
Camellia	7	80-85	3–6 d	
Carnation*	-1	95	3 w	Open flowers
	-1	95	12–14 w	In buds
	4		4 w	In a nutritive solution
Sim carnation*	2–5		5 d	
	9		2 d	
Chrysanthemum	0–1	95	3 w	In buds
Crocus	0.5	80-85	1 w	
Cyclamen	0–1		3 w	
Daffodil*	0–1	90	2 w	Cut stems exude slime; hold on their own in water for a few hours before mixing with other species
	10		5–10 d	
Dahlia	4.5		3–5 d	
Delphinium*	0–1		5–7 d	
Freesia*	0		2 w	
	1		9 d	
	5		7 d	
	9		5 d	
Gerbera	-1		10–20 d	Require sugar to keep heads upright in a nutritive solution
	2		2 w	
	4		3-4 w	

Species	Temperature (°C)	Relative humidity (%)	Expected storage time	Notes
Gladiolus	0–1		1 w	
	3–4		9–28 d	
*Gypsophila** (Baby's Breath)	0–1		3 w	
Heliconia	10–12		2 w	
Hyacinth	0.5	80–85	2 w	
Iris	0		2 w	
	5		3 d	
Lilac	4.5	80–85	4–6 d	
Lily*	0–1		4 w	With STS or 1-MCP in a nutritive solution
	1.5	80–85	2 w	
	1		4 w	
Lily of the valley	0	95	5 d	
Lisianthus	0–1		4 d	
Lupin	5		3 d	
Orchid* (including *Cattleya*, *Cymbidium*, *Dendrobium*, *Paphiopedilum*, *Phalaenopsis*, *Vanda*)	13	80–85	2–3 d 12 d	Some varieties are NOT chilling-sensitive in MAP
Peony	1.5	80–85	6 w	In closed buds
Phlox*	5		1–2 d	
Primula	5		15 d	
Protea	0–1			Sugar treatment reduces leaf blackening
Rose*	-1	95	3 w	In tight buds
	2–5		5 d	
	9		2 d	

Species	Temperature (°C)	Relative humidity (%)	Expected storage time	Notes
Strelitzia (Bird of Paradise)	6–7	85–90	1 m	After pulse treatment in a sugar solution
Stock*	0–1		2 w	
Sunflower	0–1			
Tulip	-1	95	1 m	Upright in water
	0		3 w	
Violet	5		7 d	

Data largely sourced from Gross *et al*. (2016).

Keys:
d = day w = week m = month
Note: * ethylene sensitive

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Chapter 13

Seeds

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Refrigeration can be used to preserve edible grains or planting seeds, or to bring planting seeds out of dormancy. It is widely used to extend seed storage life by reducing the rates of deteriorative processes that affect viability and vigour. In practice, however, preservation outcomes cannot be predicted from temperature alone. Seed longevity reflects the combined effects of temperature, seed water status (often expressed as equilibrium relative humidity (ERH), or water activity), and seed storage behaviour (orthodox, intermediate, or recalcitrant seeds). The importance of these interactions is well established in the seed science literature, including predictive viability modelling (Ellis & Roberts, 1980)

and mechanistic analyses emphasising water-dependent changes in deterioration kinetics and molecular mobility across temperature and water status ranges (Walters, 1998; Vertucci & Roos, 1990). As a result, storage policies that assume refrigeration to be universally safe remain scientifically inadequate for mixed collections and may cause avoidable losses, particularly for freeze-sensitive taxa (Chau *et al*., 2019).

This chapter provides a critical scientific basis for the use of refrigeration in seed preservation. It integrates 1) storage behaviour classification, 2) evidence-based setpoint logic spanning cool, refrigerated, frozen, and cryogenic storage, 3) predictive and operational decision frameworks from established models and standards, and 4) condensation thermodynamics as a first-order operational risk in cold environments.

13.1 PRESERVATION OF FOOD GRAINS

Temperatures close to 0°C help delay (inhibit) germination or deterioration of food grains stored in large quantities, "provided that proper dry-air ventilation is applied at the same time". Refrigeration can also kill the larvae of certain insects or completely inhibit their activity.

In cold regions, grains stored in farm bins are routinely exposed to air temperatures well below 0°C. Farmers already use this cold air for aeration and cooling to limit insect activity and mould growth, and there is interest in going further towards sub-zero temperature or atmospheric freeze drying. However, the combinations of grain moisture and temperature that keep seeds viable, and those that lead to ice formation and irreversible damage, have not been clearly quantified. In particular, there is little information on equilibrium moisture contents of grains at sub-zero temperatures and on the moisture thresholds at which freezing inside the kernel becomes lethal.

13.1.1 Sub-zero storage of grain

Studies show that safe use of sub-zero air for grain storage depends strongly on moisture content. Recent studies using canola as a model grain further support this view. Grains dried to ≤12% moisture contained little freezable water and could generally tolerate cooling to -20 to -25°C without major loss of viability, whereas grains above roughly 16 to 18% moisture were more prone to ice formation, structural damage, and reduced germination under deep sub-zero conditions (Tiwari and Jian, 2025, 2026). These findings suggest that sub-zero storage can be effective when grain is sufficiently dried before cooling, although further studies on other grain species are still needed.

13.2 PRESERVATION OF PLANTING SEEDS

Seeds must be kept alive and should remain perfectly capable of germinating.

13.2.1 Orthodox and recalcitrant seeds

There are two broad biological categories of seeds. Those of the more common category are called "orthodox" because they undergo major dehydration while maturing and survive perfectly in this state. Their water content at complete maturity is equivalent to about 10% to 15% of dry matter; they can tolerate even more intense dehydration.

Seeds in the other category remain rich in water and die promptly upon drying out; they are thus called "recalcitrant". Depending on the species, the water content below which they die varies from 20% to 50% of the dry matter (see ▶ **Table 13.1**). Such seeds are found in a few temperate-climate arborescent species (oak, walnut, chestnut, maple) but are much more common in rainforest trees.

Table 13.1 Examples of recalcitrant seeds and the water content below which they die

Species	Minimum water content (% of dry matter)
Acer platanoides (Norway maple)	30–35
Acer saccharinum (silver maple)	30–35
Araucaria angustifolia (Parana pine)	30–35
Citrus grandis (grapefruit tree)	52
Citrus sinensis (orange tree)	25
Euphorbia longan (longan)	25
Hevea brasiliensis (hevea)	20–25
Hopea odorata	20–25
Litchi chinensis (litchi)	30–35
Mangifera indica (mango tree)	30–35
Quercus alba (American durmast)	25
Quercus sessiliflora (sessile oak)	30–40
Shorea roxburghii	25–30
Symphonia globulifera	40–45
Theobroma cacao (cocoa tree)	45–50

13.2.2 Preservation of orthodox seeds

Orthodox seeds remain living, even when they are considerably dehydrated. Moreover, because of this considerable dehydration, they can tolerate very low temperatures. Generally speaking, the drier they are and the lower the temperature, the longer they survive. It is estimated that, at a given storage temperature, whenever their water content is reduced by about 2.5%, their lifespan is doubled. Similarly, for a given water content, each time the temperature is lowered by 6°C, their lifespan is also doubled.

Orthodox seeds tolerate substantial desiccation and generally benefit from reduced temperature, including storage in conventional freezers. For long-term preservation, the baseline for orthodox seeds is freezer storage near -18°C, and FAO gene bank standards specify -18±3°C as the storage temperature for base collections of orthodox seeds (FAO, 2014). This practice is supported by decades of gene bank operation and by the strong

dependence of the deterioration rate on temperature and water status for desiccation-tolerant seeds (Ellis & Roberts, 1980; Walters, 1998).

A critical limitation is that orthodox status does not imply uniform longevity. Large-scale gene bank analyses demonstrate substantial interspecific and familial variability in viability decline even under standardised storage, indicating that long-term stability cannot be inferred solely from the use of low temperature (Walters *et al*., 2005). Accordingly, refrigeration must be coupled with monitoring strategies tailored to species and, where possible, to historically observed decline rates.

In setting up gene banks, it is recommended to dehydrate orthodox seeds as much as practicable and to store them at temperatures of about -20°C or -30°C in a very dry atmosphere, for example, in hermetically closed containers containing silica gel. Particularly fragile orthodox seeds can also be kept for a very long period in liquid nitrogen or in a freeze-dried state.

13.2.3 Preservation of recalcitrant seeds

There is currently no satisfactory method of achieving long-term storage of recalcitrant seeds, since they must be kept in humid surroundings, in order to avoid dehydration, and there is always a risk of germination since they do not normally go into dormancy. Lowering the temperature is not sufficient to prevent them from germinating, because recalcitrant seeds are rich in water and therefore do not tolerate negative temperatures. Moreover, since most of them are of tropical origin, they are susceptible to cold injuries below certain temperatures that are species-dependent (see ► **Table 13.2**).

Table 13.2 Examples of cold-sensitive recalcitrant seeds and the lowest temperature limit that they can tolerate

Species	Temperature limit (°C)
Dryobalanops aromatica (Bornean camphor tree)	5
Hevea brasiliensis (hevea)	15–16
Hopea odorata	12
Mangifera indica (mango tree)	12
Shorea roxburghii	12–15
Shorea talura	4
Symphonia globulifera	15

Recalcitrant seeds are desiccation-sensitive and frequently sensitive to freezing, precluding the dry, low-temperature protocols used for orthodox seeds. For these species, refrigeration typically provides only short-term holding and does not constitute a long-term conservation strategy. FAO gene bank standards recognise the limitations of hydrated storage and describe cryopreservation of excised embryos, embryonic axes, or other tissues as the principal long-term approach for recalcitrant-seeded species (FAO, 2014). Recalcitrant seeds do not acquire the physiological and structural characteristics that

enable safe desiccation and metabolic quiescence, and temperature reduction alone cannot compensate for desiccation intolerance (Berjak & Pammenter, 2013). Consequently, the refrigeration problem for recalcitrant seeds is not the selection of a freezer setpoint for whole seeds; rather, it is the design and validation of cryogenic protocols that manage water distribution and ice formation in the preserved biological unit.

13.2.4 Intermediate (freeze-sensitive) seeds

Intermediate seeds exhibit partial desiccation tolerance but may suffer injury under conventional freezer storage, reflecting freeze sensitivity at relevant water states or damage associated with drying beyond a moderate threshold. This behaviour is frequently underestimated because freeze sensitivity is not always immediate. A large, long-term evaluation of 295 native Hawaiian species demonstrated that 5°C storage can outperform -18°C storage for freeze-sensitive taxa and that freeze sensitivity may only become apparent after 2–5 years of storage (Chau et al., 2019). The study further operationalised recollection intervals using a viability-based criterion (P70), emphasising that a subset of species requires relatively short conservation horizons even under controlled storage (Chau *et al*., 2019).

These results are directly relevant to refrigeration practice. They show that a default institutional policy of -18°C storage for all seed lots is not scientifically defensible in taxonomically diverse collections. Where storage behaviour is uncertain, intermediate behaviour must be treated as a plausible risk, and setpoint selection should be guided by evidence from storage-behaviour testing and, when necessary, by paired multi-year observation.

13.3 THERMAL CONTROL OF SEED DETERIORATION: DEPENDENCE ON WATER STATUS AND PHYSICAL STATE

13.3.1 Predictive longevity modelling and its limitations

Ellis and Roberts (1980) developed improved viability equations integrating the effects of temperature and moisture while accommodating differences in initial seed-lot quality. This framework remains foundational because it supports comparative planning (e.g., estimating time to reach a viability threshold under alternative setpoints) and formalises the empirical observation that longevity is strongly dependent on both temperature and moisture.

The predictive utility of these models is limited by parameter uncertainty and by condition-dependent changes in deterioration kinetics. Walters (1998) emphasised that seed ageing mechanisms and kinetics are influenced by water-dependent changes in molecular mobility and by the loosely defined quality component, which can vary widely among lots due to pre-harvest and post-harvest conditions. Consequently, setpoint decisions and monitoring schedules should not rely on extrapolation alone; they require empirical understanding and periodic verification.

13.3.2 Water status thresholds and ERH-based interpretation

Water status provides an operationally meaningful approach for understanding when refrigeration yields maximal benefit. Vertucci and Roos associated stability transitions with approximate relative humidity zones across species, reporting an onset of respiration

near 91% RH, an increase in thermal-chemical reaction rates near 27% RH, and a region associated with optimal longevity near 19% RH, and they proposed equilibration in the approximate 19–27% RH range as a basis for long-term seed storage protocols (Vertucci & Roos, 1990). The practical implication is that storage systems must be evaluated not only by temperature but also by whether seeds remain in a low water-activity domain consistent with long-term stability. A small increase in water activity can accelerate deterioration even when the average temperature is unchanged.

13.3.3 Cryogenic storage and non-Arrhenius behaviour

Cryogenic storage is frequently presumed to halt ageing. Empirical evidence indicates that this assumption is not universally valid. Walters *et al*. (2004) reported measurable changes in germination after more than a decade of cryogenic storage for some species and observed an Arrhenius discontinuity around -15°C, implying that the temperature dependence of ageing does not necessarily extrapolate across all temperature ranges. Cryogenic storage remains valuable, but it should be validated empirically rather than assumed to confer indefinite stability.

13.4 TEMPERATURE RANGES AND SETPOINT LOGIC FOR MIXED COLLECTIONS

A tiered temperature strategy is required because the optimal setpoint depends on seed storage behaviour and conservation objective.

- Cool storage (10–15°C): Cool storage is suitable for short-to-medium horizons, distribution, and operationally active collections where frequent access is expected. Deterioration proceeds more rapidly than in colder ranges; therefore, longevity expectations must be conservative and monitoring intervals correspondingly shorter (Ellis & Roberts, 1980; Walters, 1998).
- Refrigerated storage (2–8°C): Refrigerated storage is appropriate for medium-term conservation, active collections, and as a default conservative tier when storage behaviour is uncertain or when intermediate behaviour is suspected. The long-term dataset of Chau *et al*. (2019) provides a strong evidentiary basis for this range as an alternative to freezer storage in freeze-sensitive taxa.
- Frozen storage (-18 to -20°C): Frozen storage near -18°C is the standard for long-term conservation of orthodox seeds (FAO, 2014). Its use for intermediate taxa should be conditional on species-specific evidence, given the demonstrated possibility of freeze sensitivity that becomes evident only after multi-year storage (Chau *et al*., 2019).
- Cryogenic storage (≤ -130°C; LN_2 or vapour phase): Cryogenic storage is essential for many recalcitrant-seeded species through cryopreservation of embryos, embryonic axes, or tissues (FAO, 2014). It is also used for high-value security backups for selected orthodox taxa. However, cryogenic storage requires validation and monitoring because long-term performance is not uniformly static and may show species-specific changes (Walters *et al*., 2004).

13.5 MONITORING AND DECISION FRAMEWORKS

The primary operational requirement for a preservation programme is a monitoring strategy that reflects species- and condition-specific deterioration rates. FAO gene bank standards provide guidance on viability monitoring schedules and emphasise that monitoring intervals must be designed relative to expected decline rates and conservation objectives (FAO, 2014). Evidence from large-scale gene bank datasets further supports the need for stratified monitoring. Walters *et al*. (2005) analysed viability trajectories for approximately 42,000 accessions across 276 species, demonstrating systematic species and family effects. Such outcomes indicate that monitoring cannot be standardised to a single interval across diverse collections without risking either unnecessary retesting (inefficiency) or delayed detection of decline (loss of risk).

The Ellis-Roberts framework is well suited to setpoint comparisons and to time-to-threshold planning when species constants and initial seed quality are reasonably constrained (Ellis & Roberts, 1980). In practice, uncertainty in the seed quality term and condition-dependent kinetics described by Walters (1998) necessitate conservative application and iterative refinement based on observed performance. Where storage behaviour is uncertain, the evidence base supports a paired-storage approach (e.g., 5°C compared to -18°C) with multi-year monitoring to detect delayed freeze sensitivity (Chau *et al*., 2019).

13.6 CONDENSATION RISK IN REFRIGERATED SEED STORAGE

In cold environments, preservation outcomes are frequently constrained by transient increases in seed water activity during access and transfer events. Condensation is a thermodynamic phenomenon which occurs when a surface is below the dew-point temperature of adjacent air. ASHRAE guidance treats visible condensation as the direct result of dew-point relationships between surface temperature and air conditions (ASHRAE, n.d.). This issue is not a minor operational detail in seed conservation because seed stability is strongly dependent on water status (Vertucci & Roos, 1990). Condensation or frosting events can cause localised increases in water activity sufficient to shift seeds into condition ranges associated with increased metabolic activity and accelerated chemical deterioration, thereby undermining the benefits of low-temperature storage even if the long-term mean temperature remains controlled.

Accordingly, refrigeration-based seed preservation requires operating procedures that prevent dew-point crossings during exposure. This requirement is particularly stringent in refrigerated (5°C) and frozen (≤-18°C) storage, where typical ambient conditions readily exceed the dew point relative to cold surfaces. The scientific basis for this control derives from the water-activity thresholds associated with stability transitions (Vertucci & Roos, 1990) and from the broader mechanistic understanding that ageing kinetics vary across temperature and water status domains (Walters, 1998).

13.7 CRYOPRESERVATION APPROACHES FOR DESICCATION-SENSITIVE SPECIES

For recalcitrant seeds and other taxa unsuitable for conventional freezer storage, long-term preservation depends on cryopreservation of excised embryos, embryonic axes, or tissues (FAO, 2014). Cryopreservation success is governed by management of freezable water and intracellular ice formation, and outcomes are strongly influenced by dehydration heterogeneity and tissue-specific responses.

Wesley-Smith *et al*. (2014) provided ultrastructural evidence linking intracellular ice and survival outcomes in cryo-exposed embryonic axes of a recalcitrant-seeded species, emphasising that cellular and ice structures are determinants of viability. Ballesteros *et al*. (2014) demonstrated that uneven drying of embryos and embryonic axes contributes to variable post-cryo survival, reinforcing that cryopreservation requires careful control of dehydration state and uniformity. These findings support a refrigeration-relevant conclusion that cryogenic temperature alone is insufficient, and the preserved unit and its water distribution at cooling and warming stages are decisive.

13.8 USING COLD TO BRING SEEDS OUT OF DORMANCY

Because of dormancy, the seeds of numerous species do not germinate at the moment of their harvest or germinate slowly and at a low percentage. Refrigeration can be very useful in increasing the germination rate.

13.8.1 Stratification

Refrigerated humid-atmosphere treatment, called “stratification”, brings many types of seeds out of dormancy. The most effective temperatures are often around 5°C, and the duration of treatment to be applied is generally from 1 to 3 or 4 months (see ► **Table 13.3**). Refrigeration can only be used to bring seeds out of dormancy if the seeds are moistened. When they are dry and cold, dormancy is maintained.

13.8.2 Hard seeds

So-called “hard” seeds do not germinate since their seed coats are impermeable to water. Dipping such seeds into liquid nitrogen for a few minutes is often very effective, since this causes tiny cracks in the seed coats, making the seeds permeable.

13.9 CONCLUSIONS

Refrigeration is an effective preservation tool only when implemented within a category-appropriate strategy. Orthodox seeds generally benefit from frozen storage near -18°C, consistent with international standards, but longevity remains species dependent even under standardised conditions (FAO, 2014; Walters *et al*., 2005). Intermediate behaviour and freeze sensitivity constitute a substantive risk in mixed collections; long-term evidence demonstrates that 5°C storage can outperform -18°C for some taxa and that sensitivity may be delayed for several years (Chau *et al*., 2019). Recalcitrant seeds cannot

be preserved long-term by conventional dry-cold storage and require cryopreservation of embryos or tissues, with success governed by dehydration and ice-management constraints (FAO, 2014; Wesley-Smith *et al*., 2014; Ballesteros *et al*., 2014).
Finally, condensation control must be treated as a first-order thermodynamic requirement for refrigeration-based programmes. Dew-point crossings during access can induce rapid shifts in water activity that move seeds into accelerated deterioration condition ranges, undermining the benefits of cold storage (ASHRAE, n.d.; Vertucci & Roos, 1990). A scientifically defensible refrigeration chapter, therefore, emphasises behaviour classification, setpoint selection based on evidence and standards, monitoring stratified by species risk, and operating rules grounded in dew-point thermodynamics.

Table 13.3 Temperatures and treatment durations necessary for bringing seeds of some species out of dormancy (the seeds should be moistened)

Species	Temperature (°C)		Duration of treatment at optimal temperature (months)
	Effective	Optimal	
Abies sp. (firs)	1 to 5	4	1 to 2
Acer platanoides (Norway maple)	1 to 5	5	1 to 3
Acer pseudoplatanus (sycomore maple)	1 to 5	5	1.5 to 3
Betula verrucosa (Europ. white birch)	1 to 10	5	1
Chamaecyparis sp. (false cypress)	1 to 5	4	2 to 4
Corylus avellana (hazel tree)	1 to 5	5	1 to 3
Cotoneaster sp. (cotoneaster)	5	5	4 to 5
Crataegus monogyna (hawthorn)	5	5	4 to 5
Crataegus oxyacantha (may tree)	5	5	6
Cupressus sp. (cypress)	1 to 5	4	1 to 2
Fagus silvatica (beech)	5	5	1.5 to 3
Fraxinus sp. (ash)	5	5	4 to 5
Juglans nigra (American black walnut)	1 to 10	3	2 to 4

Species	Temperature (°C)		Duration of treatment at optimal temperature (months)
	Effective	Optimal	
Juniperus communis (juniper)	1 to 5	5	2 to 3.5
Juniperus virginiana (common red cedar)	1 to 5	5	3 to 4
Malus domestica (apple tree)	0 to 8	4	3 to 4
Picea abies (common spruce)	4 to 5	5	1 to 2
Prunus armeniaca (apricot tree)	1 to 10	7	2 to 2.5
Prunus avium (sweet cherry tree)	4 to 10	5	4 to 4.5
Prunus cerasifera (cherry plum tree)	5 to 10	5	3.5 to 4
Prunus persica (peach tree)	1 to 10	5	2 to 4.5
Pseudosuga menzeisii (Douglas fir)	1 to 5	4	1 to 2
Pyrus communis (pear tree)	1 to 5	5	2 to 3
Rosa canica (dogrose)	5	5	5 to 6
Rosa multiflora (multiflower rose)	5 to 8	5	1.5 to 3
Sorbus aucuparia (mountain ash)	1 to 5	1	2 to 4
Taxus cuspidata (Japanese yew)	1 to 5	5	9

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