SCHOOL OF ENGINEERING KMITL

FRELAB
FOOD REFRIGERATION
ENGINEERING LABORATORY

Cold Chain Management for Premium Fruits and Vegetables

รองศาสตราจารย์ ดร.ณัฐวุฒิ ชาวเมือง

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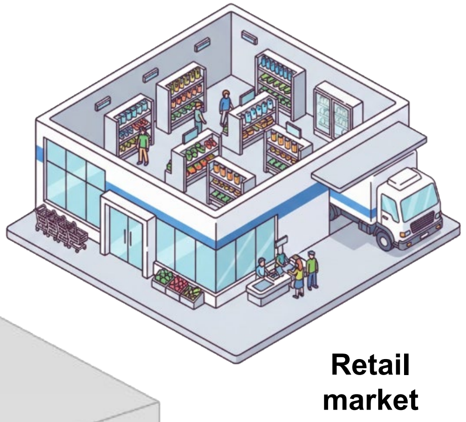
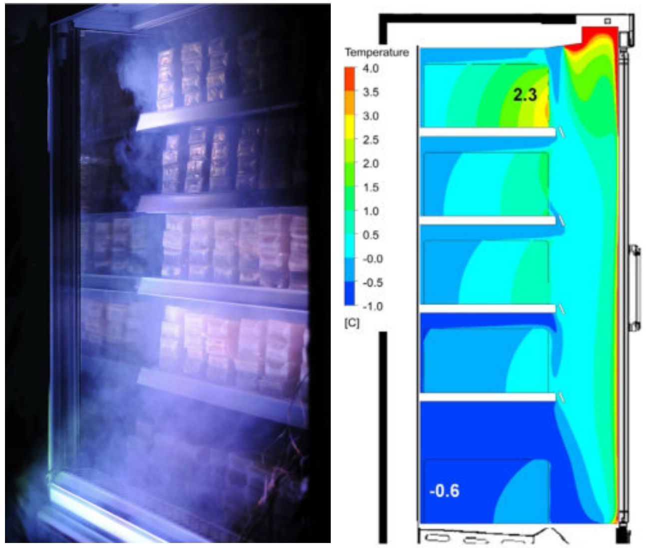
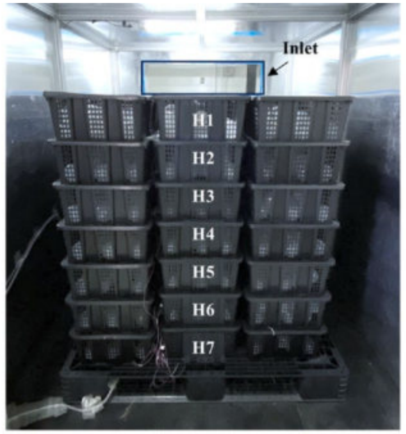
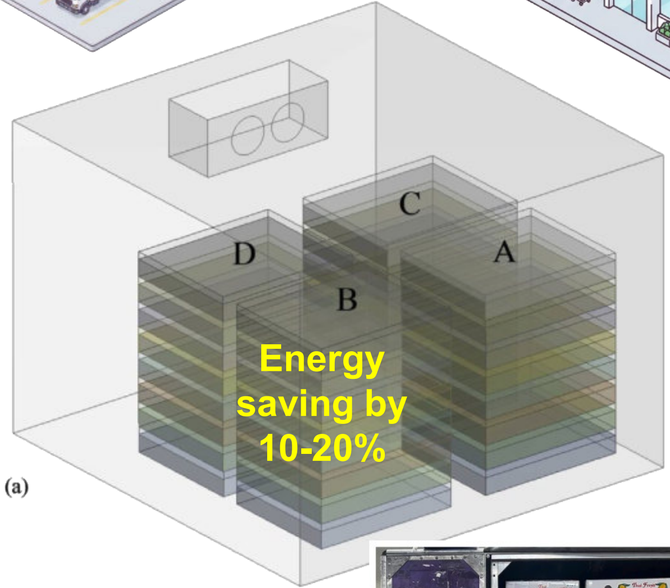
- Cold Chain
- Food Preservation

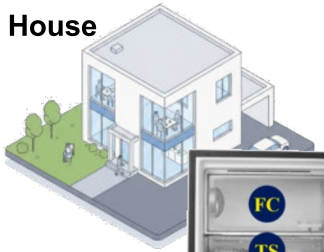
FRELAB | Food Refrigeration Engineering Laboratory

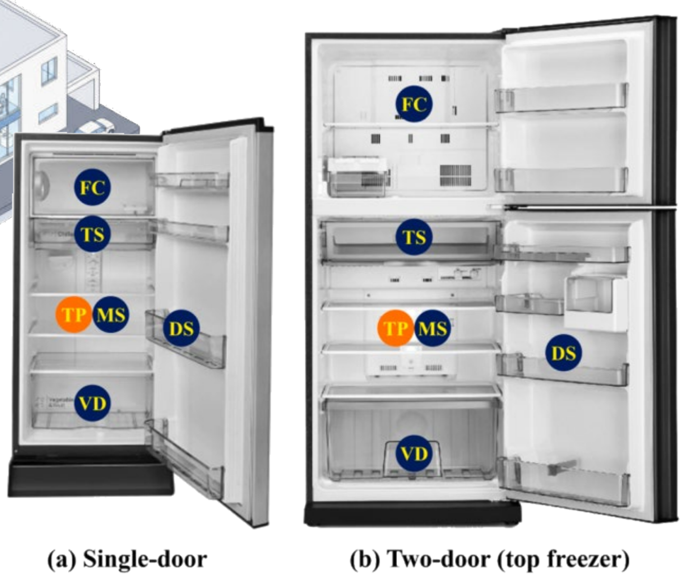






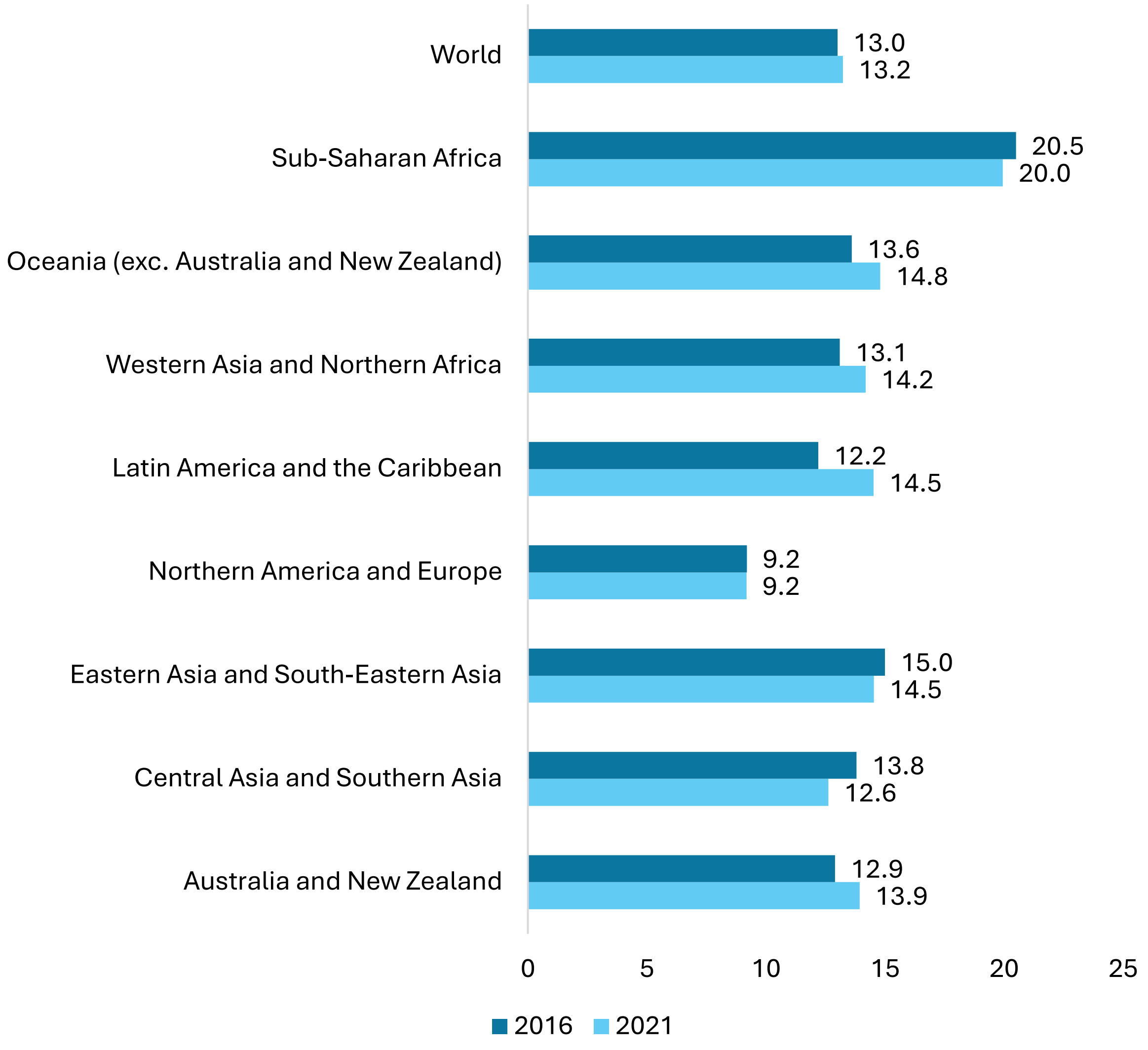






Importance of Refrigeration in Food Industry

Estimates of global food loss percentage (%) in 2021



Estimates of global food waste in 2022

SECTOR	GLOBAL AVERAGE (KG/CAPITA/YEAR)	2022 TOTAL (MILLION TONNES)
Household	79	631
Food service	36	290
Retail	17	131
Total	**132**	**1 052**

Food loss (การสูญเสียอาหาร) ~ 13.2% after harvest, transport, storage, wholesale and processing levels.

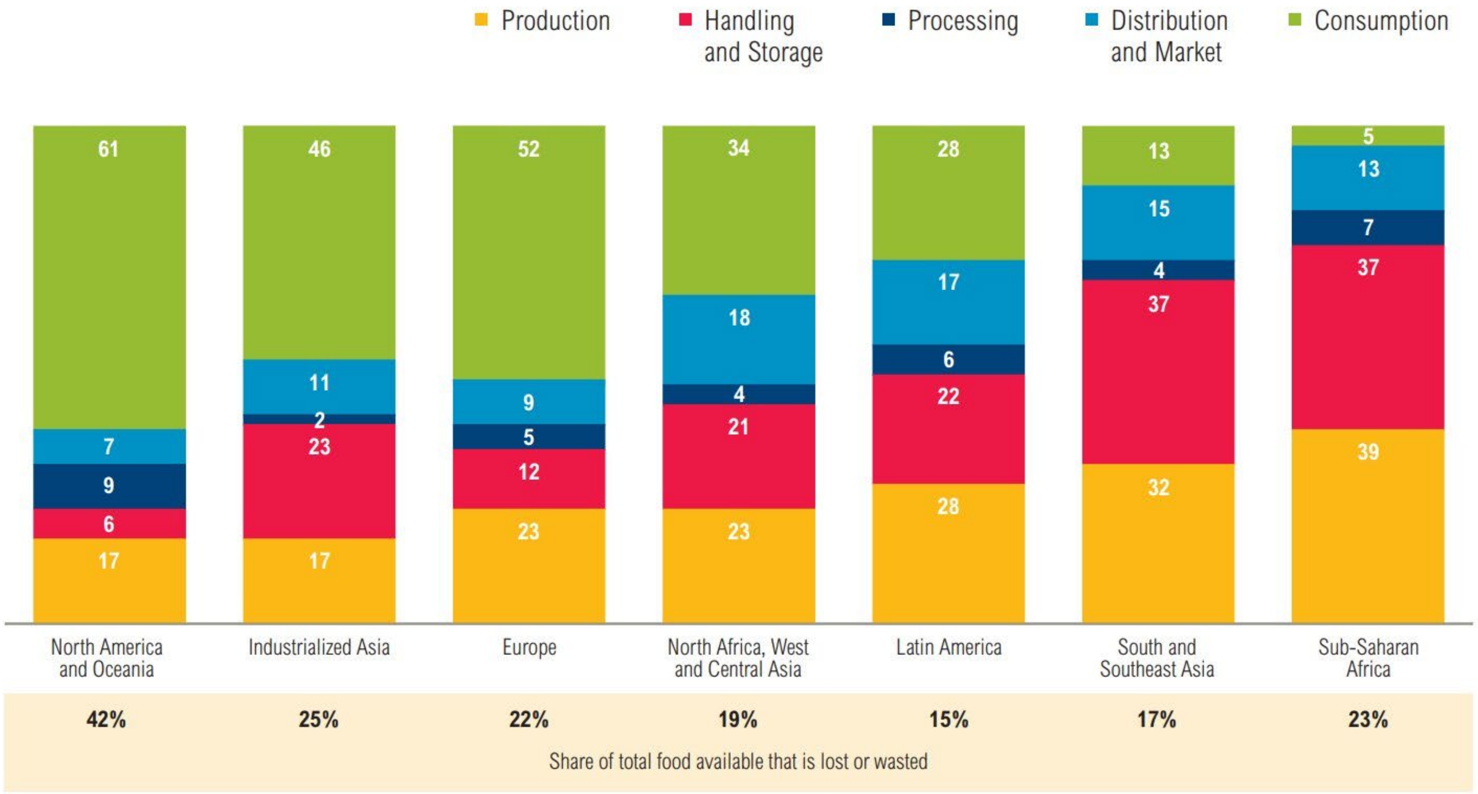
Food waste (ขยะอาหาร) ~19% at retail, food service and household levels.

1/3 is lost and wasted annually

(1.3 billion tons, 1 trillion USD, and 8-10% of GHG emissions)

Importance of Refrigeration in Food Industry

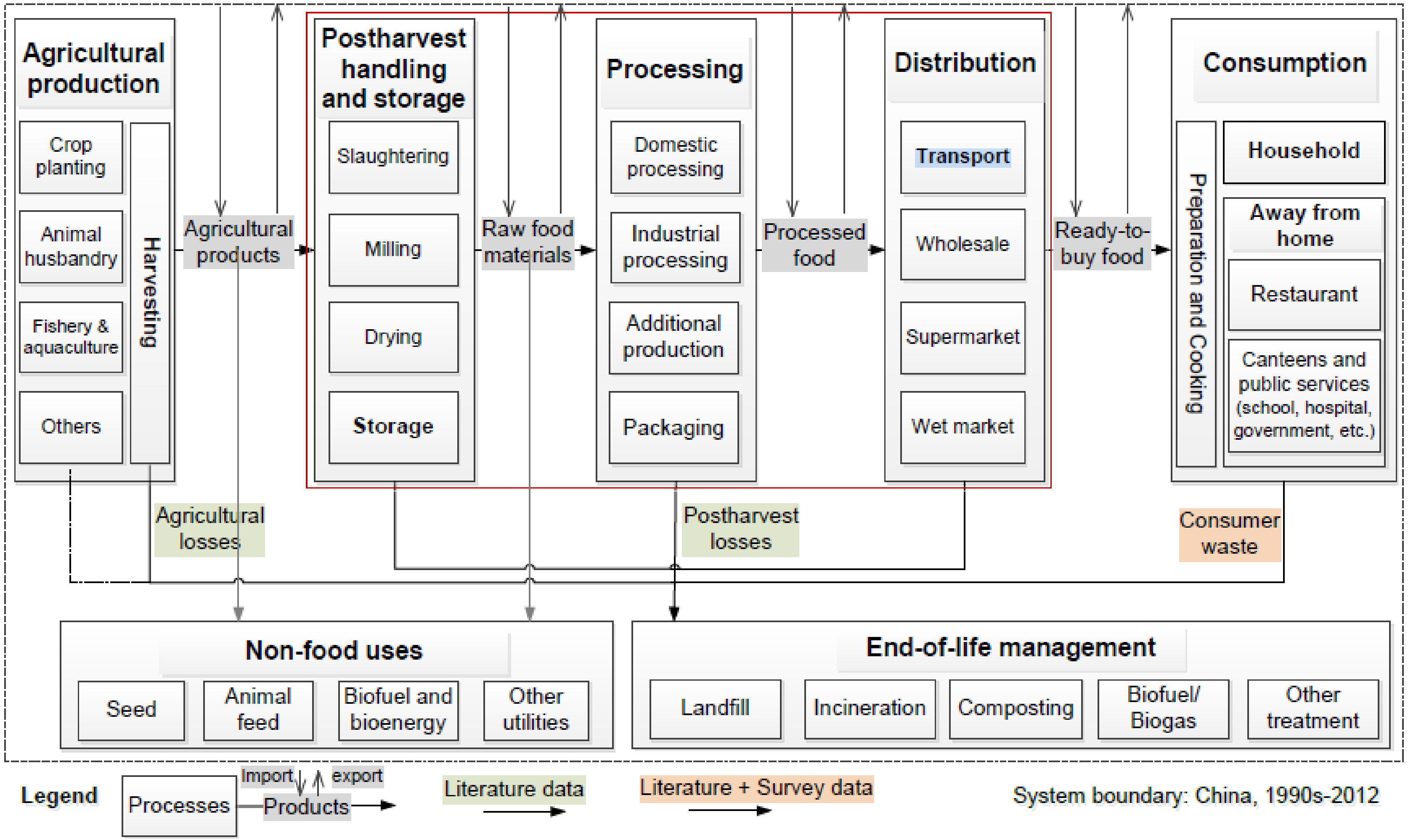
Global food loss and waste, percentage by regions and supply chain stages



- Food losses are equally high worldwide
- **Developing countries**: losses mainly at handling, storage & distribution
- **Developed countries**: losses mainly at retail & consumers (> Africa's total production)

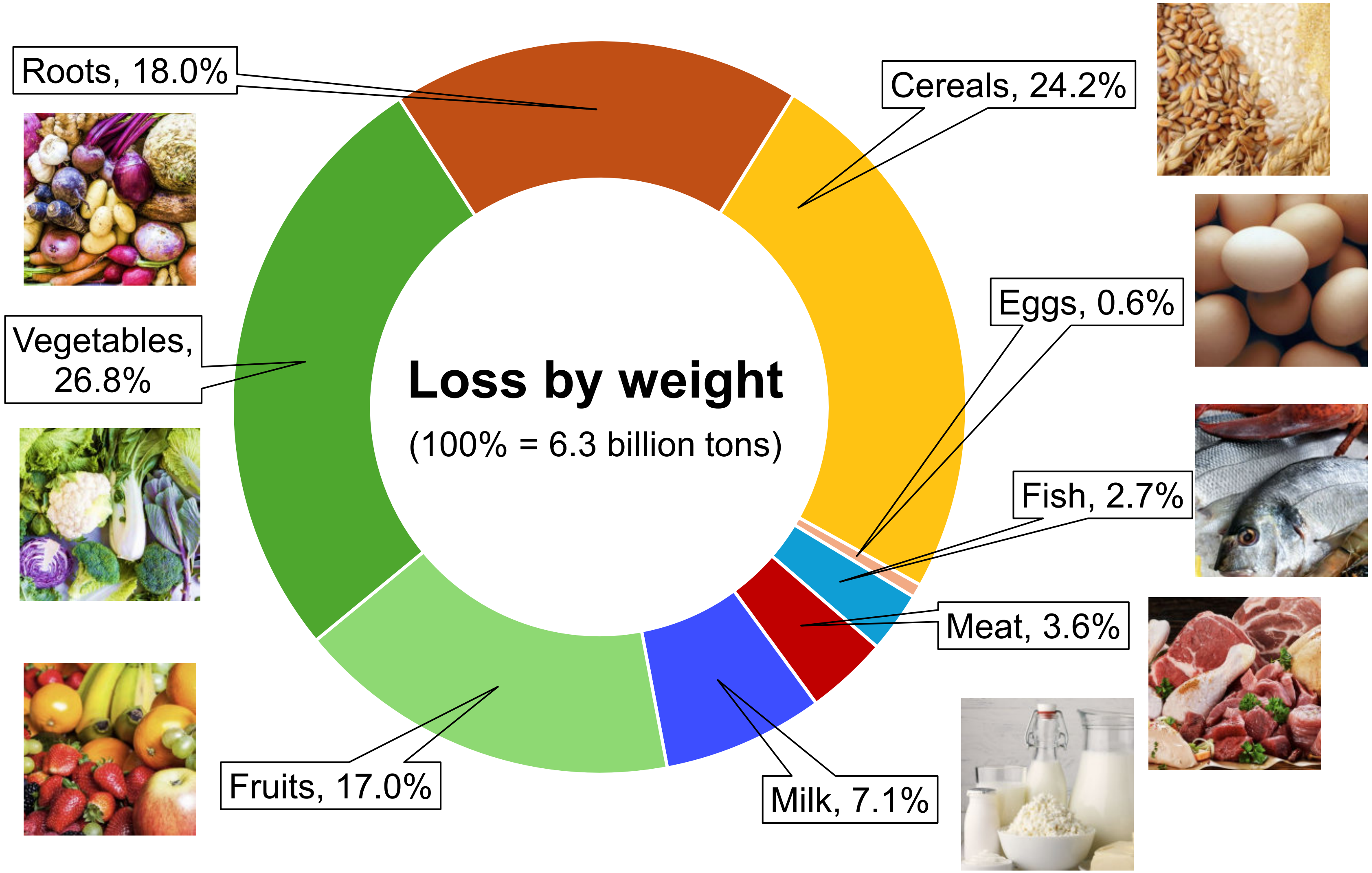
Importance of Refrigeration in Food Industry

Figure 3. Food losses and food waste along the different stages of the food value chain



Importance of Refrigeration in Food Industry

Food losses from agricultural production to consumption, percentages by commodity groups in 2013



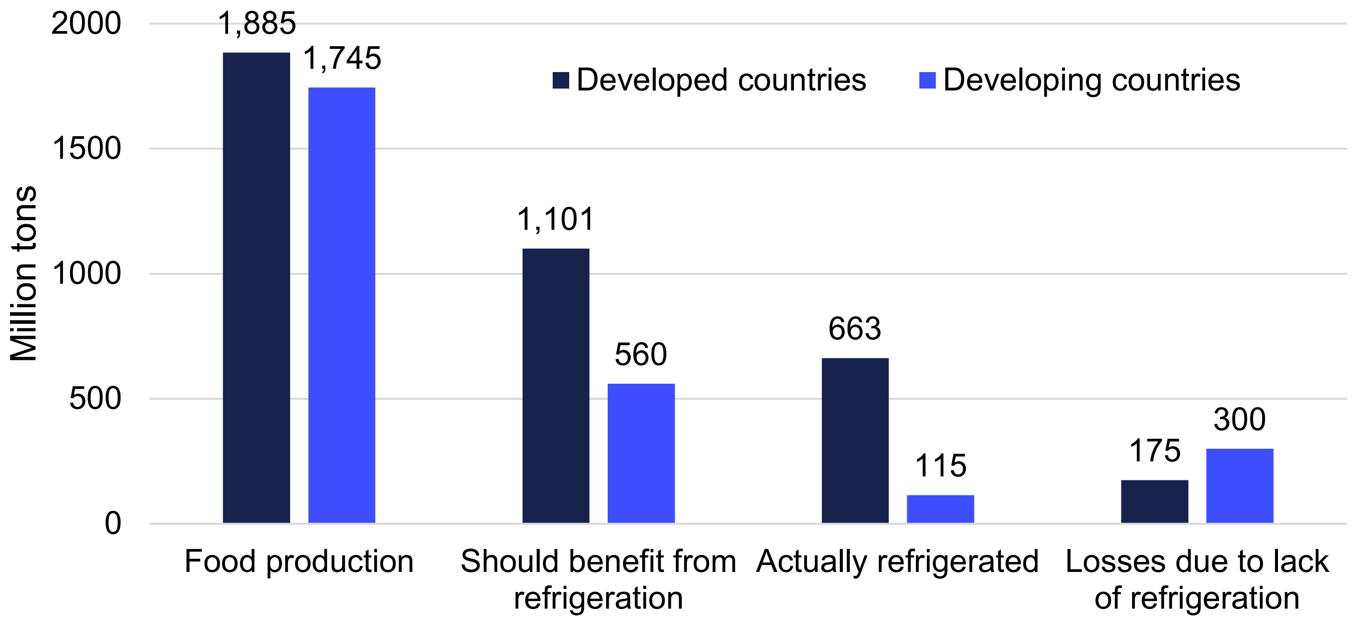
The highest share of food losses

~44%

Importance of Refrigeration in Food Industry

- About 46% of food should be refrigerated, but only 21% actually is.
- Large refrigeration gap:
  - ~60% coverage in developed vs. ~20% in developing countries.
- **About 13% of food lost annually due to lack of refrigeration** (≈ 475 million tons, 63% from developing countries).

Year 2013	Million tons (%)
World food production	3,630 (100%)
Food that should benefit from refrigeration	1,661 (45.8%)
Food that is actually refrigerated	778 (21.4%)
Losses due to lack of refrigeration	475 (13.1%)



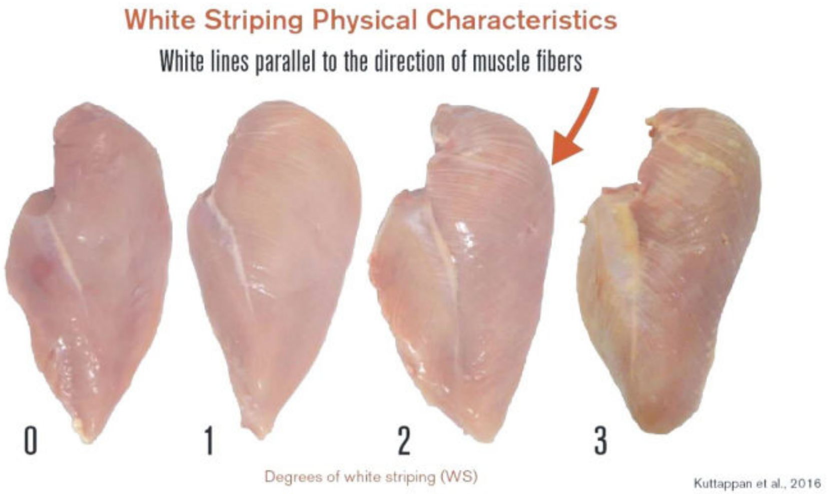
Quality and safety-related losses

Food loss and waste include:

- Over-preparation or excess food that is not consumed (depending on consumer behavior)
- Aesthetic trimming and rejection of edible food ("ugly" but safe), texture and functional defects, insect damage or pest infestation, physical or mechanical damage
  - **Quality-related losses:** food that is edible and safe but rejected due to quality standards or market (consumer perception)
- Spoiled or unsafe food that is inedible and must be discarded.
  - **Safety-related losses** are unavoidable, as they are necessary to prevent foodborne illness and protect public health.

Quality and safety-related losses

- **Quality issue at pre-harvest** (white striping and woody breast) due to rapid growth and high breast yield in broiler chickens.
- Poorer texture (hard/woody), lower tenderness, and reduced juiciness/water-holding capacity.



สังเกตเส้นสีขาวคล้ายไขมัน พาดขนานไปกับแนวเส้นใยกล้ามเนื้อ

Quality issue at post-harvest

Discoloration

- Poor temperature control → Higher reaction rates → accelerates pigment (myoglobin) oxidation → metmyoglobin → brown/gray discoloration

Drip loss (watering)

- pH decline → protein (myofibrillar) denaturation → reduced water-holding capacity → exudate / drip formation → Pale Soft Exudative (PSE)

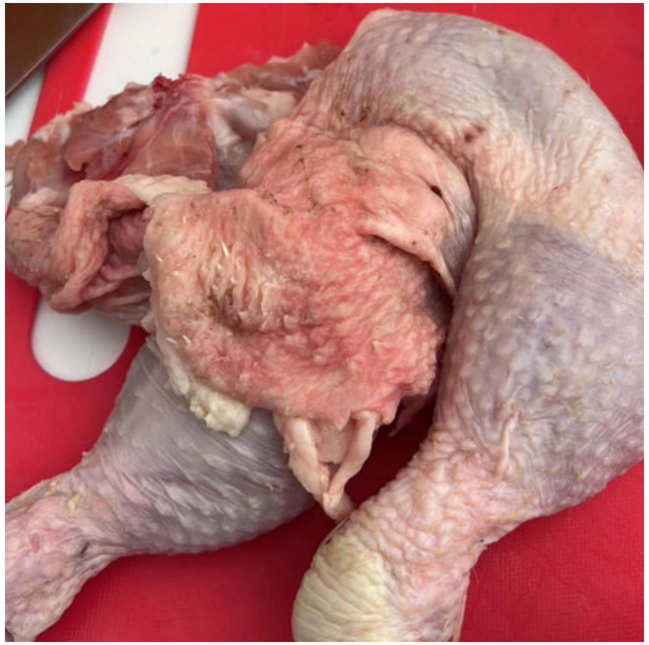
Poor temperature control
=
High or Fluctuating temperature

Quality and safety-related losses

Quality issue

Slime formation

- Poor temperature control → rapid growth of spoilage microorganisms (e.g., lactic acid bacteria, LAB) → production of extracellular polysaccharides → slimy surface → quality rejection



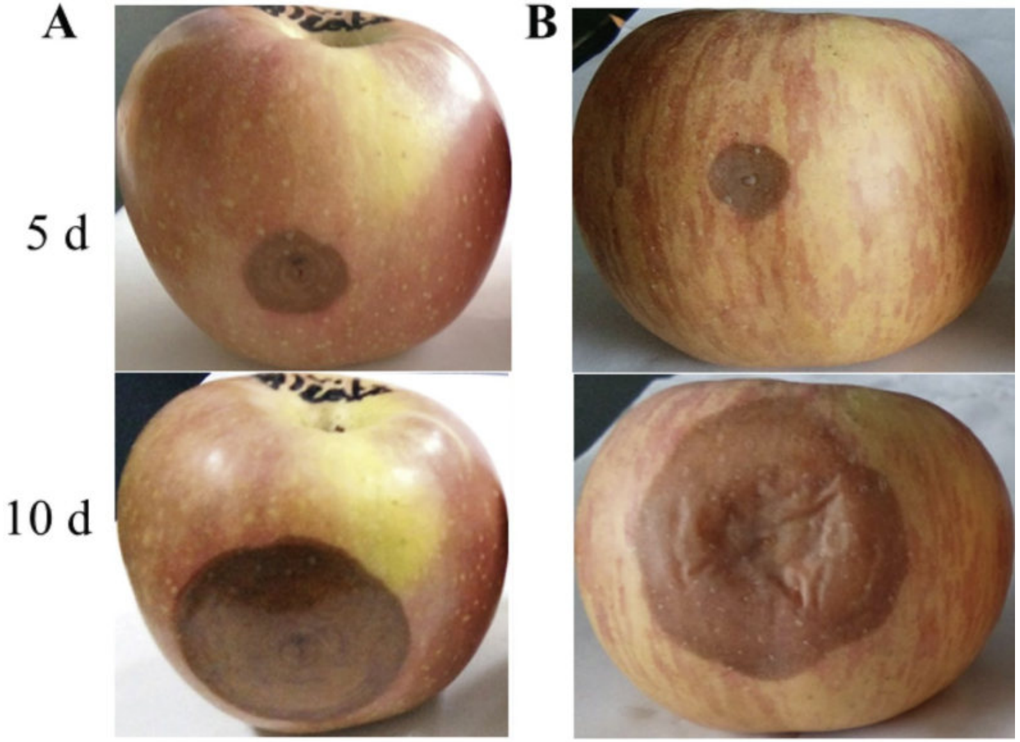
Safety issue

Rotten meat

- Poor temperature control or prolonged storage (even at low temperature)→ growth of spoilage and potential pathogenic bacteria (*Pseudomonas* spp., *Enterobacteriaceae*) → protein and lipid degradation, slime formation, off-odors, and discoloration

Microbial spoilage of fruits

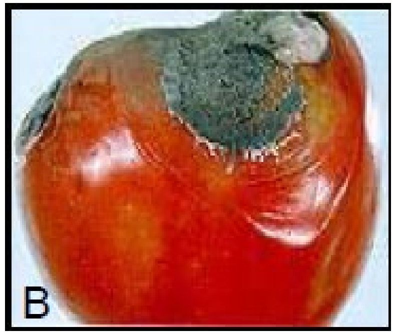
(a) **Anthracnose** and (b) **stem end rot** on mangoes cv. Nam Dok Mai obtained from Talaad Tai wholesale market and SCRI.



Apple ring rot (soft rot) on Fuji apple fruit (Malus) caused by (A) *B. dothidea* and (B) C. gloeosporioides after 5 d and 10 d at 25 °C

Microbial spoilage of fruits

Gray mold rot From left to right, in the first row: quince strawberry, kiwi, raspberry. Second row: baby kiwi, table grapes, pomegranate, blueberry. Third row: persimmon, peach (infection on the left), orange, sweet cherry.

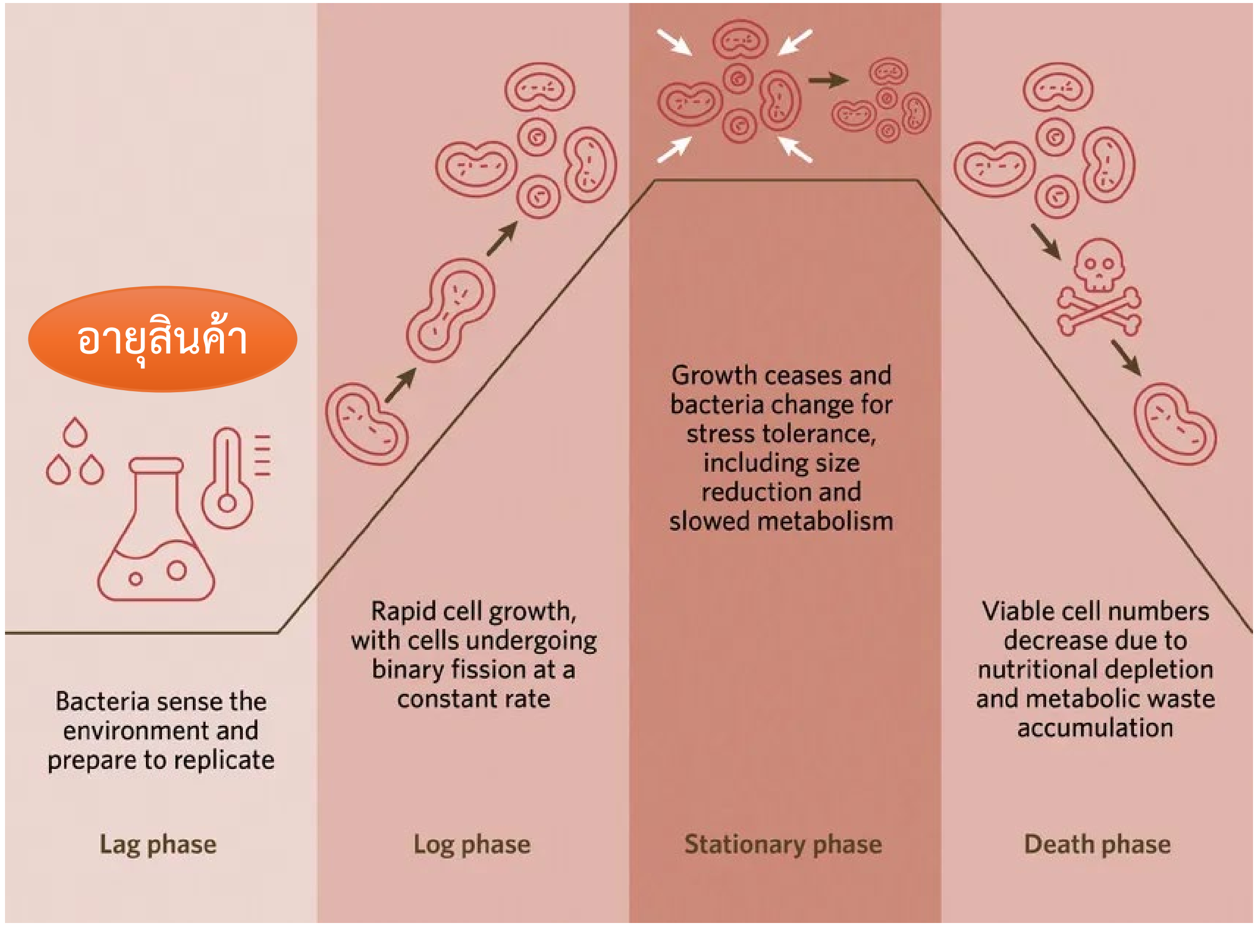


Fungal infection (mold rot) on tomato caused by *Penicilliumi* spp.

Common spoilage defects of fruits and vegetables

Defect	Casual organism
Bacterial soft rot	*Erwinia carotovora*
Gray mold rot	*Botrytis cinerea*
Rhizopus soft rot	*Rhizopus nigricans*
Blue mold rot	*Penicillium spp*
Alternaria rot	*Alternaria spp*
Pink mold rot	*Trichothecium roseum*
Green mold rots	*Cladosporium, Trichoderma*
Watery soft rot, Brown rot	*Sclerotinia sclerotiorum*
Downy mildew	*Phytophthora, Bremia*
Sliminess or souring	Saprophytic bacteria
Black rot/ smut/ Black mold	*Alternaria / Aspergillus niger*
Anthracnose	*Coletotrichum lindemuthianum*

Growth of microorganisms



Microbial (bacterial) growth over time under fixed environmental conditions, often follow an S-shaped curve with four distinct phases: lag, log, stationary, and death.

Microbial growth follows predictable phases, strongly influenced by **storage conditions** such as temperature.

- **Lag phase:** Bacteria sense and adapt to the environment (temperature, nutrients, pH). Cells are metabolically active but do not yet divide. **Shelf life is essentially the length of the lag phase.**
- **Log (exponential) phase:** Bacteria undergo rapid, constant cell division by binary fission. This is the phase of fastest growth and highest metabolic activity.
- **Stationary phase:** Growth stops as nutrients become limited and waste products accumulate. The number of new cells equals the number of dying cells. Bacteria adapt to stress by slowing metabolism and reducing cell size.
- **Death phase:** Viable cell numbers decline due to severe nutrient depletion and toxic waste buildup. Cell death exceeds cell division.

Factors affecting microbial growth

- Microbial growth is influenced by a combination of intrinsic and extrinsic factors.
- Intrinsic factors define how suitable the food is for growth; extrinsic factors control how fast microbes grow.
- **Intrinsic factors (food-related)**
  - pH (acidity)
  - Water activity (a_w / moisture)
  - Nutrient availability
  - Natural antimicrobial compounds

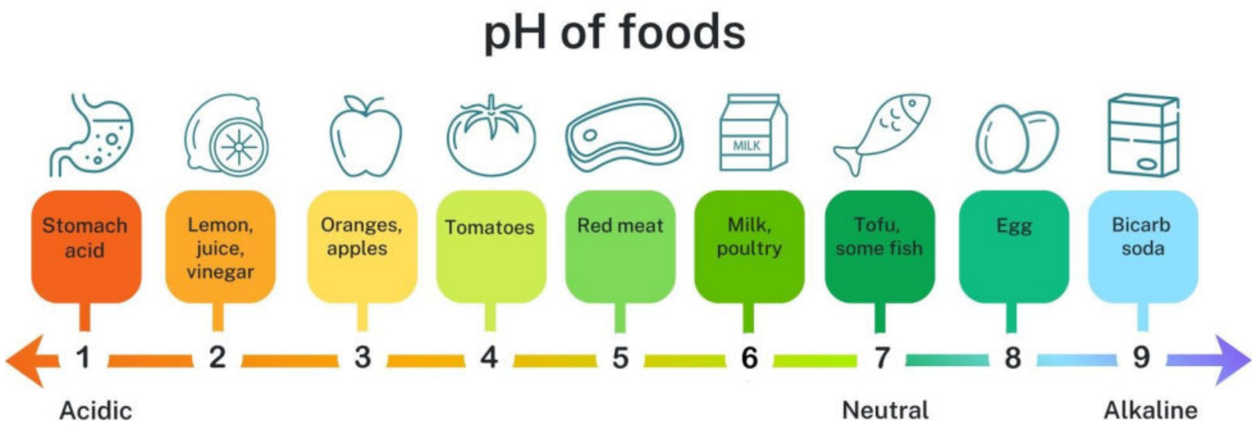
  Difficult to control
- **Extrinsic factors (environment-related)**
  - Temperature
  - Relative humidity
  - Storage time
  - Atmosphere / oxygen availability (air, vacuum, MAP)
  - Handling and sanitation conditions

  Controllable

pH (acidity) and water activity (a_w)

Approximate pH ranges of different microbial groups

	Min	Optimum	Max
Most bacteria	4.5	6.5-7.5	9.0
Yeasts	1.5-3.5	4.0-6.5	4.0-6.5
Molds	1.5-3.5	4.5-6.8	8.0-11.0



Minimum water activity values of spoilage microorganisms

	Min a_w	Examples
Most bacteria	0.91	*Salmonella spp., Clostridium botulinum*
Most yeasts	0.88	*Torulopsis spp.*
Most molds	0.80	*Aspergillus flavus*
Halophilic bacteria	0.75	*Wallemia sebi*
Xerophilic molds	0.65	*Aspergillus echinulatas*
Osmophilic yeasts	0.60	*Saccharomyces bisporus*

$a_w > 0.95$

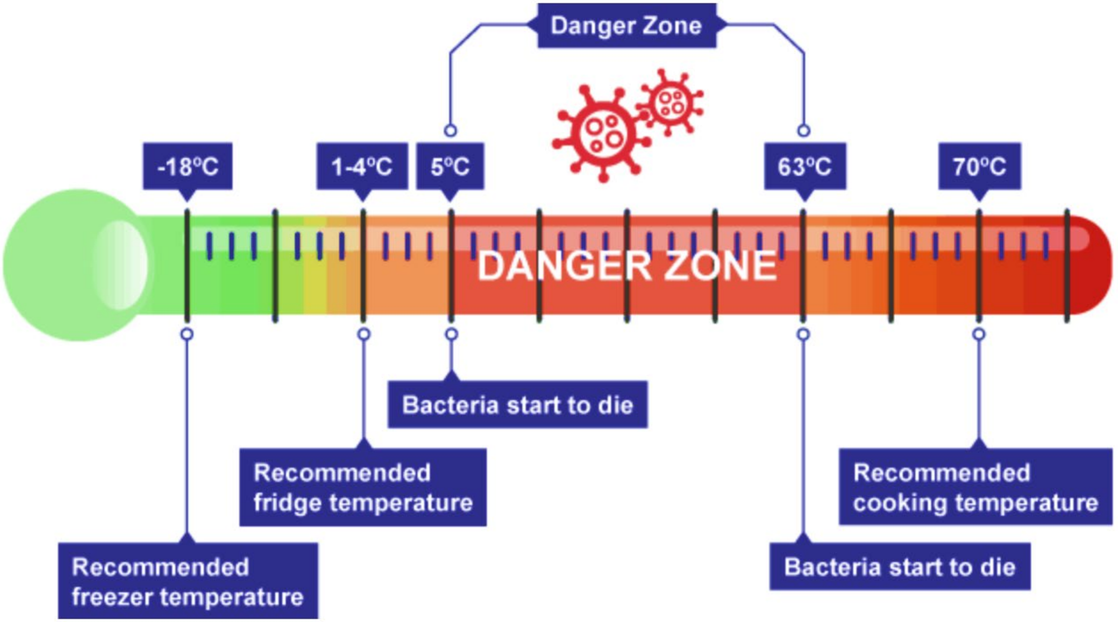
$a_w < 0.8$

Water activity (a_w)

Water activity of some foods and susceptibility to spoilage by microorganisms

Water activity	Microorganisms grow at this a_w and above	Examples
1.00-0.95	*Pseudomonas, E.coli, Proteus, Shigella, Klebsiella, Bacillus, Clostridium perfringens* & some yeasts	Highly perishable fresh foods & canned fruits, vegetables, meat, fish, milk, eggs; foods containing up to 40% (w/w) sucrose or 7% NaCl.
0.95-0.91	*Salmonella, Vibrio parahemolyticus, Clostridium botulinum, Serratia, Lactobacillus, Pediococcus;* some molds and yeasts	Some cheeses (cheddar, Swiss), Cured meats; some fruit juice concentrates; bread; high moisture prunes; foods containing 55%(w/w) sucrose or 12% NaCl
0.91-0.87	Many yeasts like *Candida, Torulopsis, Hansenula; Micrococcus*	Fermented sausages; sponge cakes; dry cheese; margarine; foods containing 65%(w/w) sucrose (saturated) or 15% NaCl
0.87-0.80	Most molds, *Staphylococcus aureus,* most *Saccharomyces* spp., *Debaromyces*	Most fruit juice concentrates, sweetened condensed milk, flour, rice, pulses containing 15-17% moisture, salami
0.80-0.75	Most halophilic bacteria*, Mycotoxigenic Aspergilli*	Jam, Marmalade, Glace fruits, Soy sauce
0.75-0.65	Xerophilic molds*, Saccharomyces bisporus*	Rolled oats containing 10% moisture; Fudge; Marshmallows; Jelly; Some dried fruits; Nuts, Peanut Butter
0.65-0.60	Osmophilic yeasts, Few molds	Dried fruits containing 15-20% moisture; Honey
0.50	No microbial proliferation	Pasta containing 12% moisture; Spices containing 10% moisture
0.40	No microbial proliferation	Whole egg powder containing 5% moisture
0.30	No microbial proliferation	Cookies, biscuits crackers, bread crusts etc. containing 3-5% moisture
0.20	No microbial proliferation	Whole milk powder containing 2-3% moisture, Dried vegetables containing 5% moisture, Corn flakes containing 5% moisture, Instant coffee

Storage temperature and time



Growth response of microorganisms

Chilling ⟹ Slow down ≠ Death

Freezing ⟹ Stop ≠ Death

*Pseudomonas**: Spoilage of milk and many dairy products

*Listeria monocytogenes**: Key pathogenic concern for chilled and ready-to-eat foods

Bacillus cereus: Spoilage of cooked rice (heat-resistant spores)

Psychrotrophs

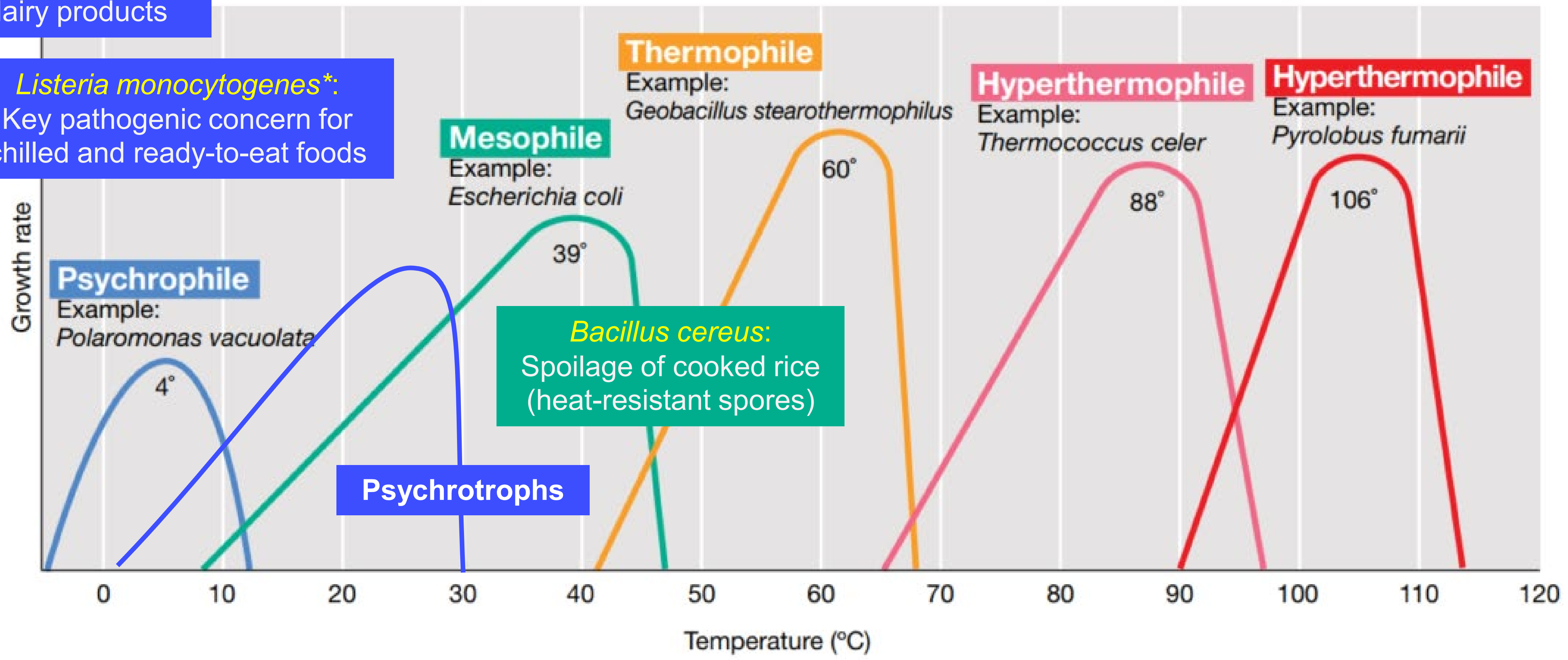
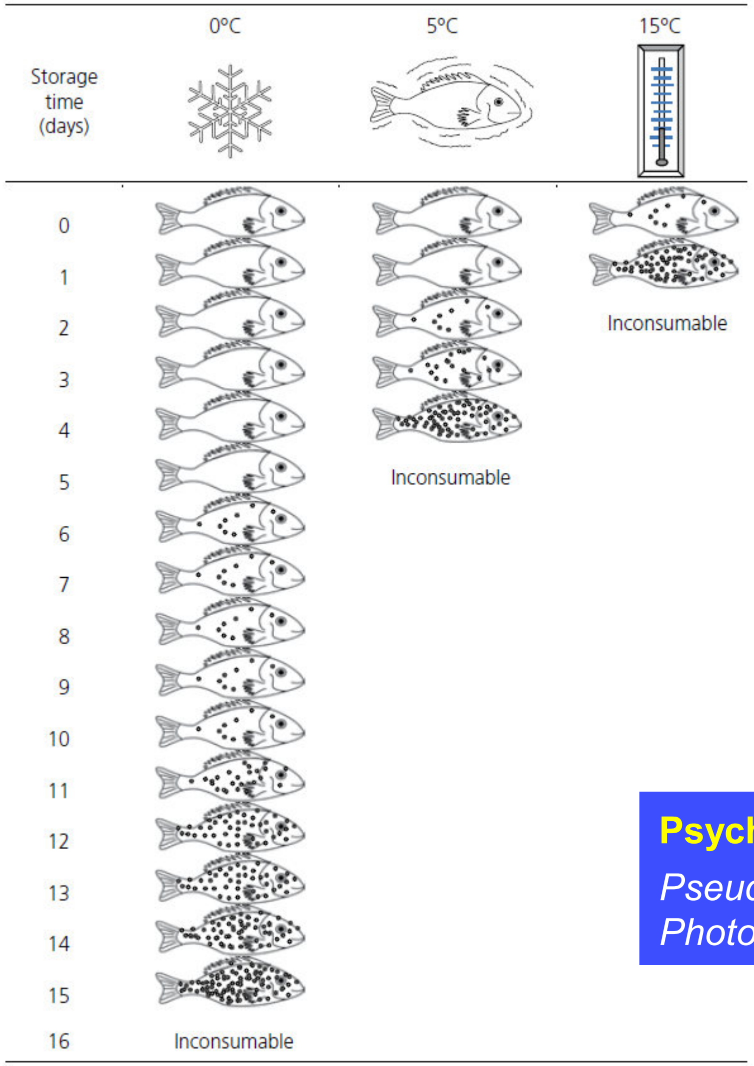


Figure 5.18 Temperature and growth response in different temperature classes of microorganisms. The temperature optimum of each example organism is shown on the graph.

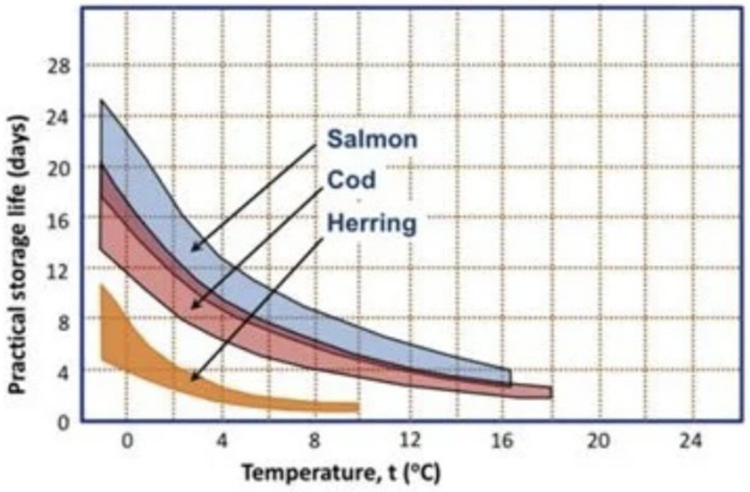
*Psychrotrophs (จุลินทรีย์ทนหนาว) ≠ Psychrophiles (จุลินทรีย์ชอบความเย็น)

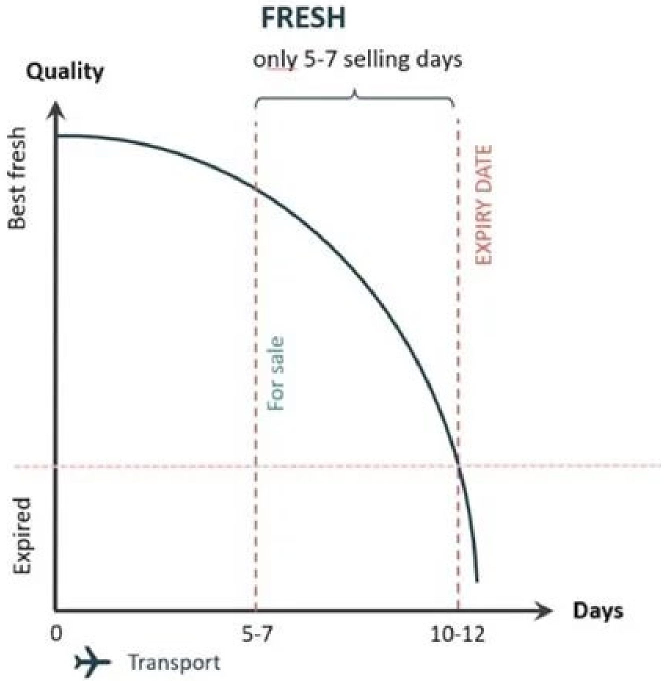
Recommended storage temperature of Potentially Hazardous Foods (PHF)

Change in fish freshness with temperature



The number of days a fish fillet stays fresh in the chiller cabinet





Psychrotrophs (จุลินทรีย์ทนหนาว):

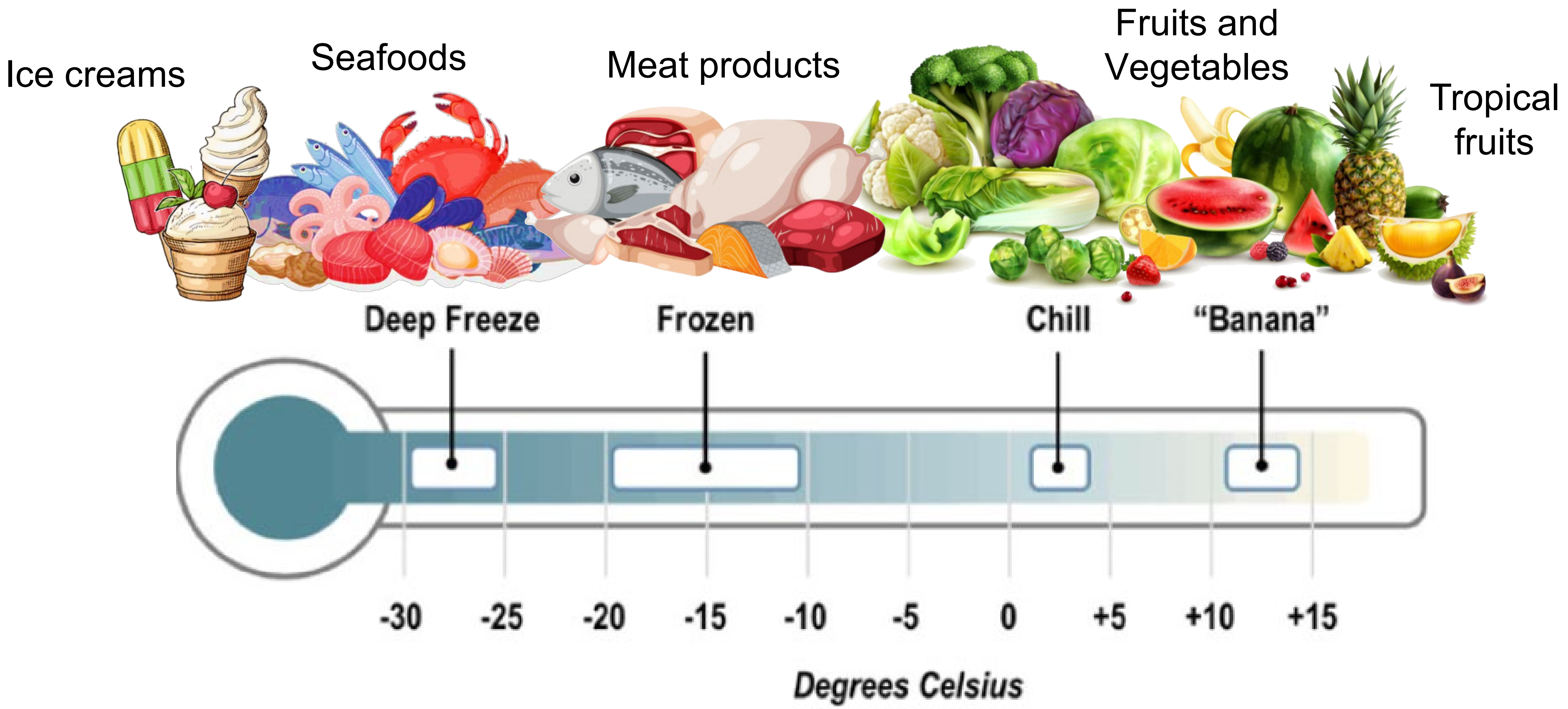
Pseudomonas spp., *Shewanella putrefaciens*, *Photobacterium phosphoreum*, *Aeromonas* spp.

More than half of the time is often lost in transport. You can keep it in the fridge for a few days before it starts smelling “fishy” as it spoils.

Recommended storage temperature of Potentially Hazardous Foods (PHF)

Country	References	Year	Enforcement Status	Type of Food Covered	Cold Holding	Hot Holding
Australia	FSANZ Standard 3.2.2	2025	Food Standards Code / Legally enforceable	Retail, food service	≤ 4°C	≥ 60°C
Canada	Health Canada	2024	Food safety tips / Legally enforceable (provincial)	Retail, food service, processing	≤ 4°C	≥ 60°C
Europe	Regulation (EC) 852	2004	Legally enforceable	All foods	≤ 4°C (France) ≤ 5°C	≥ 63°C
Europe	Regulation (EC) 853	2004	Legally enforceable	Foods of animal origin	≤ 4°C (France) ≤ 5°C	≥ 63°C
Japan	Food Sanitation Act	2018	Food Hygiene Control File / Legally enforceable	Restaurant	≤ 10°C	≥ 60°C
New Zealand	MPI National Programme 2	2025	Guidance / Legally enforceable	All food businesses	≤ 4°C	≥ 60°C
Singapore	Environmental Public Health (Food Hygiene) Regulations	2026	Legally enforceable	Retail & food service	≤ 5°C	≥ 60°C
South Korea	Korean Food Code	2019	Legally enforceable	Retail & processing	0-10°C	≥ 60°C
Thailand	MOPH Notification	2018	Legally enforceable	Retail & food service	< 5-7°C	≥ 60°C
USA	FDA Food Code	2022	Model code / Voluntary	Retail & food service (TCS foods)	≤ 5°C (41°F)	≥ 57°C (135°F)
UK	Food Safety & Hygiene (England) Regulations (Regulation 32/Schedule 4)	2013	Legally enforceable	Retail & catering	≤ 8°C	≥ 63°C

Recommended storage temperature of different foods



FUN FACT: *Why is −18 °C as the standard freezer temperature?*

-18°C ?

Early freezer design, standards, and household guidance in the U.S. used 0 °F as a clear target, once refrigeration spread −18 °C became the freezer standard because it equals 0 °F (historical convenience) and is cold enough to ensure food safety and quality.

Appropriate low temperature for fruits and vegetables

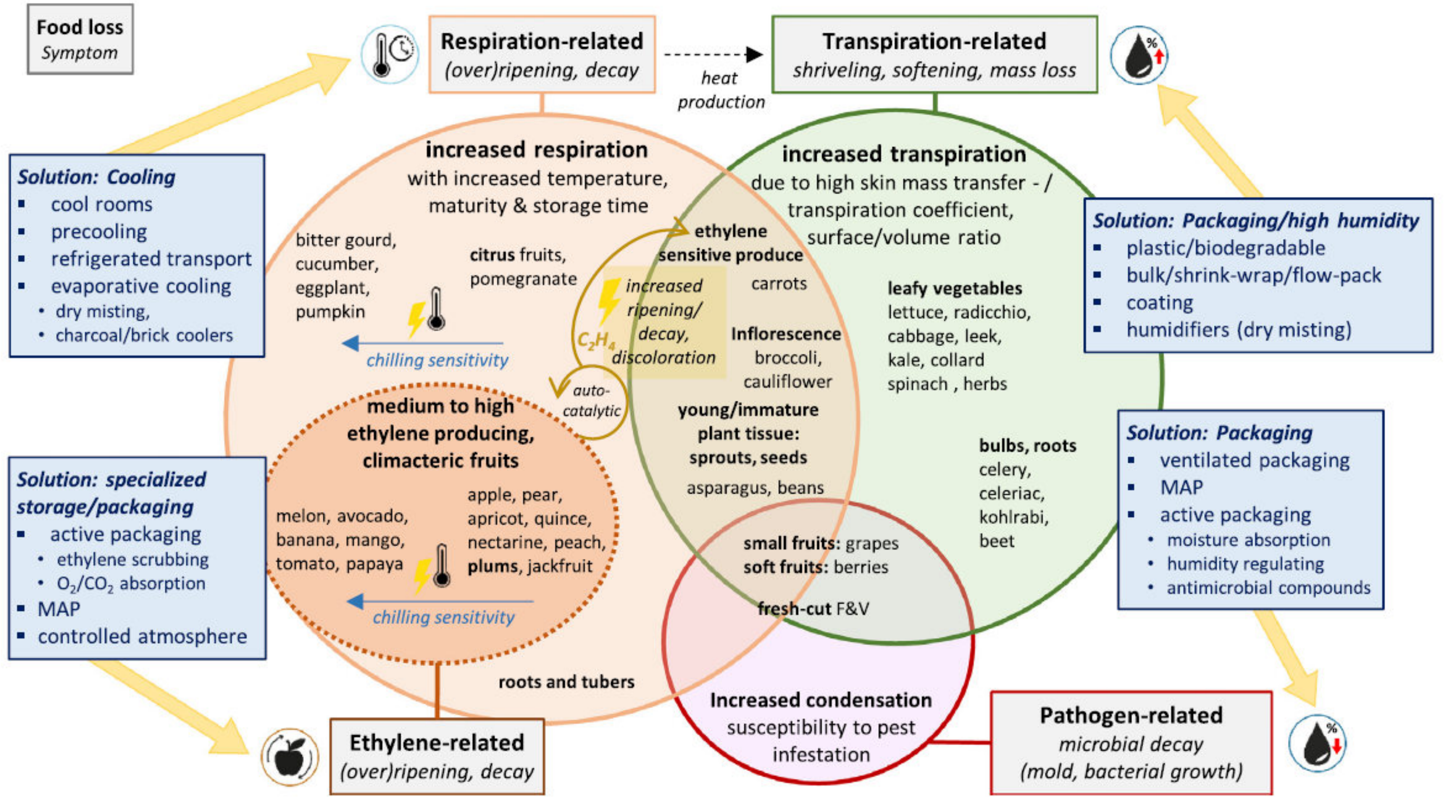
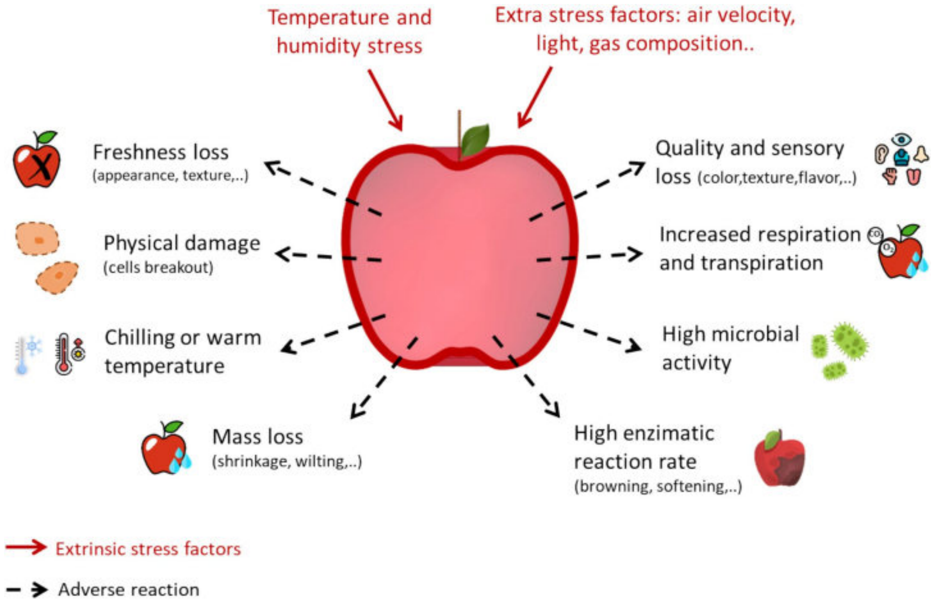


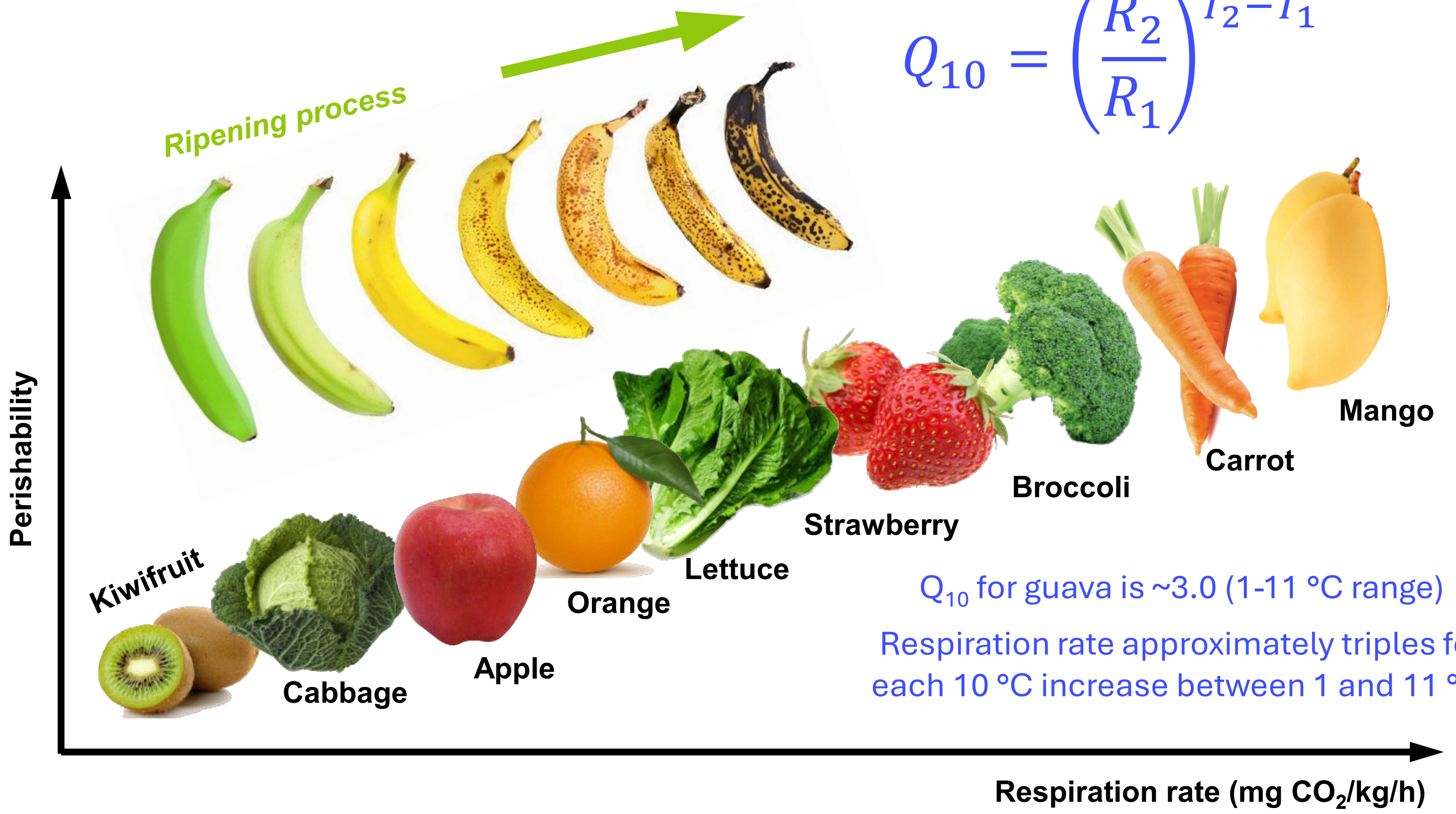
Fig. 2. Plant product groups mapped to different physiological (respiration-, transpiration-, ethylene-related) or pathological food loss categories and related symptoms (grey shaded) plus antagonizing postharvest solutions (blue shaded). Abbreviations: F&V, fruits and vegetables; MAP, modified atmosphere packaging.

1. Why does *fruits and vegetables* get lost?
2. Which products are affected most?
3. What intervention works best?



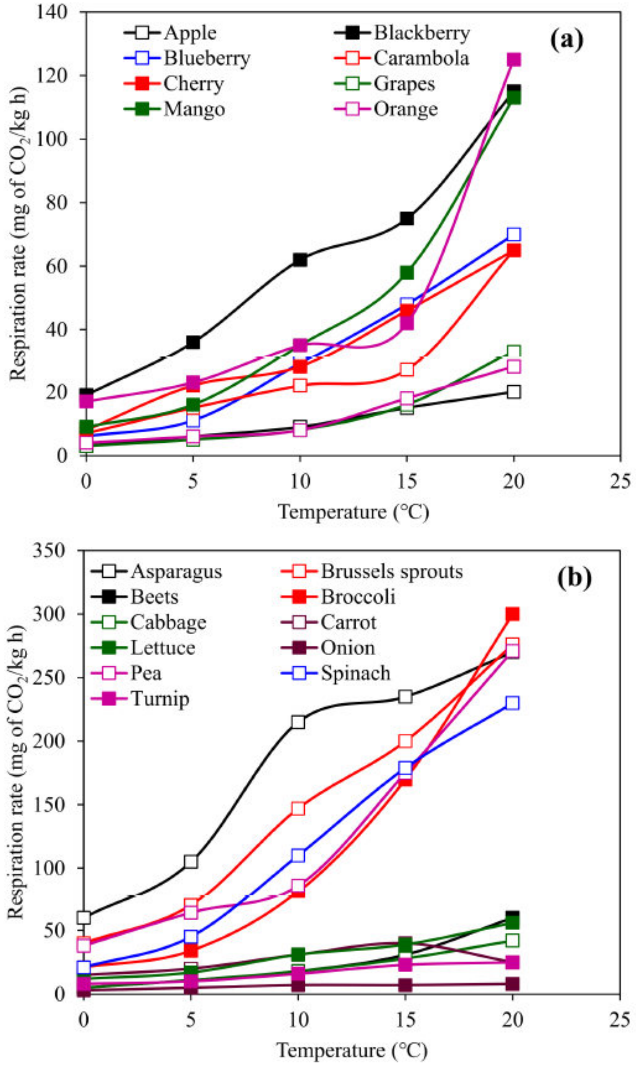
Respiration rate (R) of fruits and vegetables

$$Q_{10} = \left(\frac{R_2}{R_1}\right)^{\frac{10}{T_2 - T_1}}$$



Q_{10} for guava is ~3.0 (1-11 °C range)

Respiration rate approximately triples for each 10 °C increase between 1 and 11 °C.

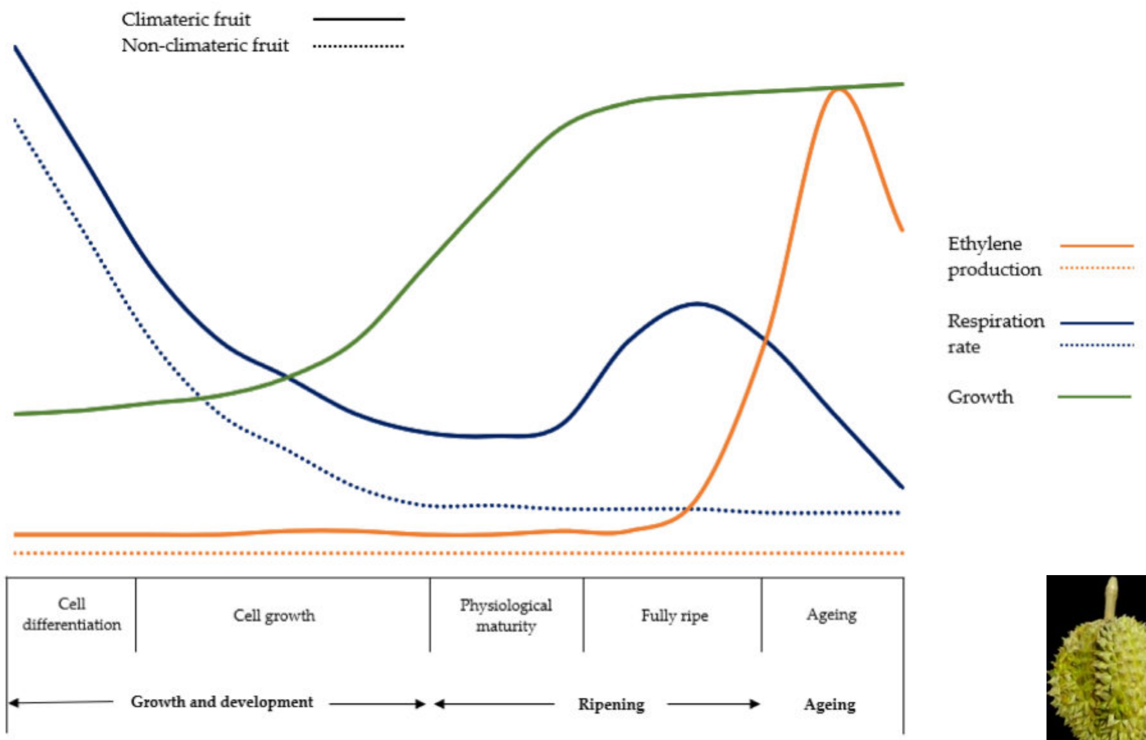


Effect of temperature on respiration rate of some (**a**) fruits, and (**b**) vegetables

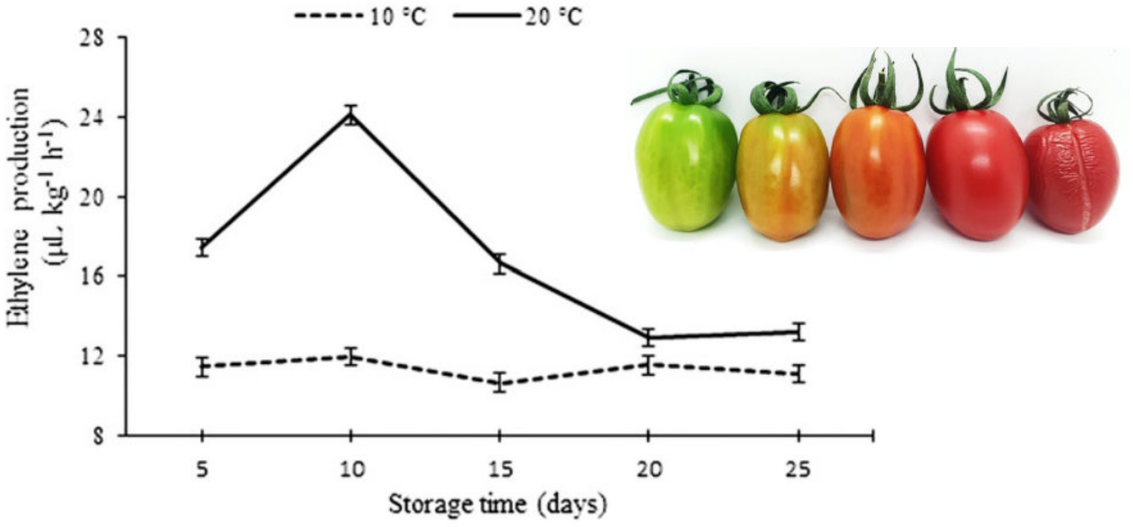
- High respiration rate rapidly depletes energy reserves (sugars and vitamins), leading to faster quality loss and shorter shelf life.
- Q_{10} describes how respiration rate increases with temperature, indicating how much the rate rises for every 10 °C increase (typically ~2–3× in fruits and vegetables).

Ethylene C_2H_4 production rate of climacteric fruits and vegetables

- Climacteric fruits and vegetables show a sharp increase in ethylene (C_2H_4) production during ripening, which triggers and accelerates respiration, ripening, and senescence.
- Low temperature reduces ethylene production, thereby slowing ripening and reducing the rate of quality deterioration.



Respiration rate and ethylene production during postharvest



- Natural splitting (dehiscence) increases with ripening and is a practical visual indicator of maturity and eating quality
- Advanced splitting (stage 4) signals over-ripening and shorter shelf life

Ethylene C_2H_4 production rate of climacteric fruits and vegetables

Table 1. The quality of softened kiwi fruit according to storage temperature and ethylene concentration.

Ethylene	Sourness[x]			Sweetness[y]			Overal taste[z]		
($\mu L \cdot L^{-1}$)	10℃	15℃	20℃	10℃	15℃	20℃	10℃	15℃	20℃
10	++++	++++	+++	++	++	++	++	++	++
50	++++	+++	++	++	+++	+++	++	++	+++
100	++++	++	+	++	++++	++++	++	+++	++++

[x]Sourness: +++++ very strong, + very low.
[y]Sweetness: +++++ very strong, + very low.
[z]Overal taste: +++++ very good, + very bad.

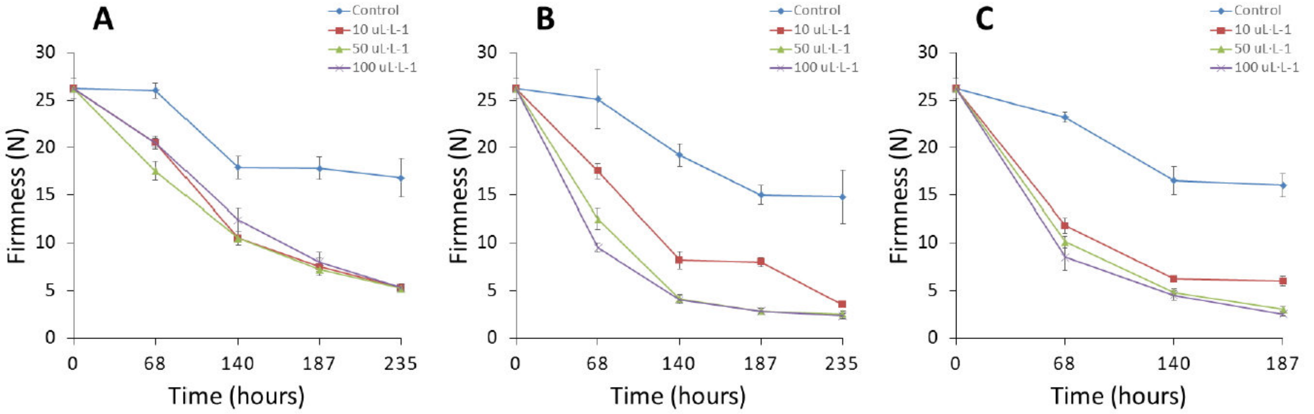


Fig. 2. Changes in firmness of kiwi fruit according to different storage temperatures and ethylene concentrations (A, 10℃; B, 15℃; C, 20℃). Vertical error bars represent the standard errors (n = 3).

- Higher storage temperatures and ethylene concentrations softened the kiwi fruit quickly.
- Quality characteristics of kiwi fruits stored at 15°C and 20°C were better than those of fruits at 10°C.
- Fruits stored at lower temperatures took a longer time to ripen and retained their quality longer.
- Correct temperatures and ethylene concentrations are required.

Chilling injury (CI) *caused by low temperature*

- CI is a group of physiological disorders caused by storage at low but non-freezing temperatures.
- Approximately 50% of globally traded postharvest commodities are chilling-sensitive, and CI contributes to losses of up to 33% of these products annually.

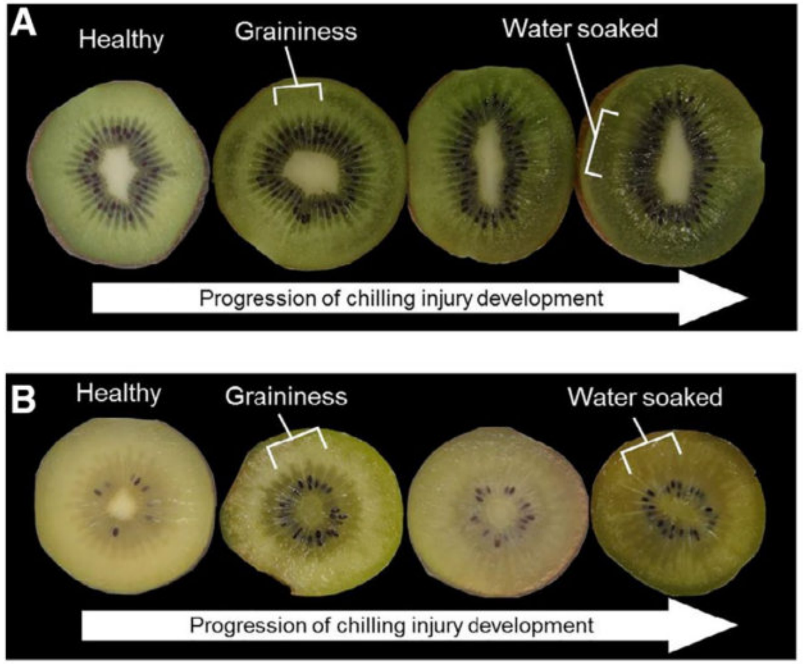
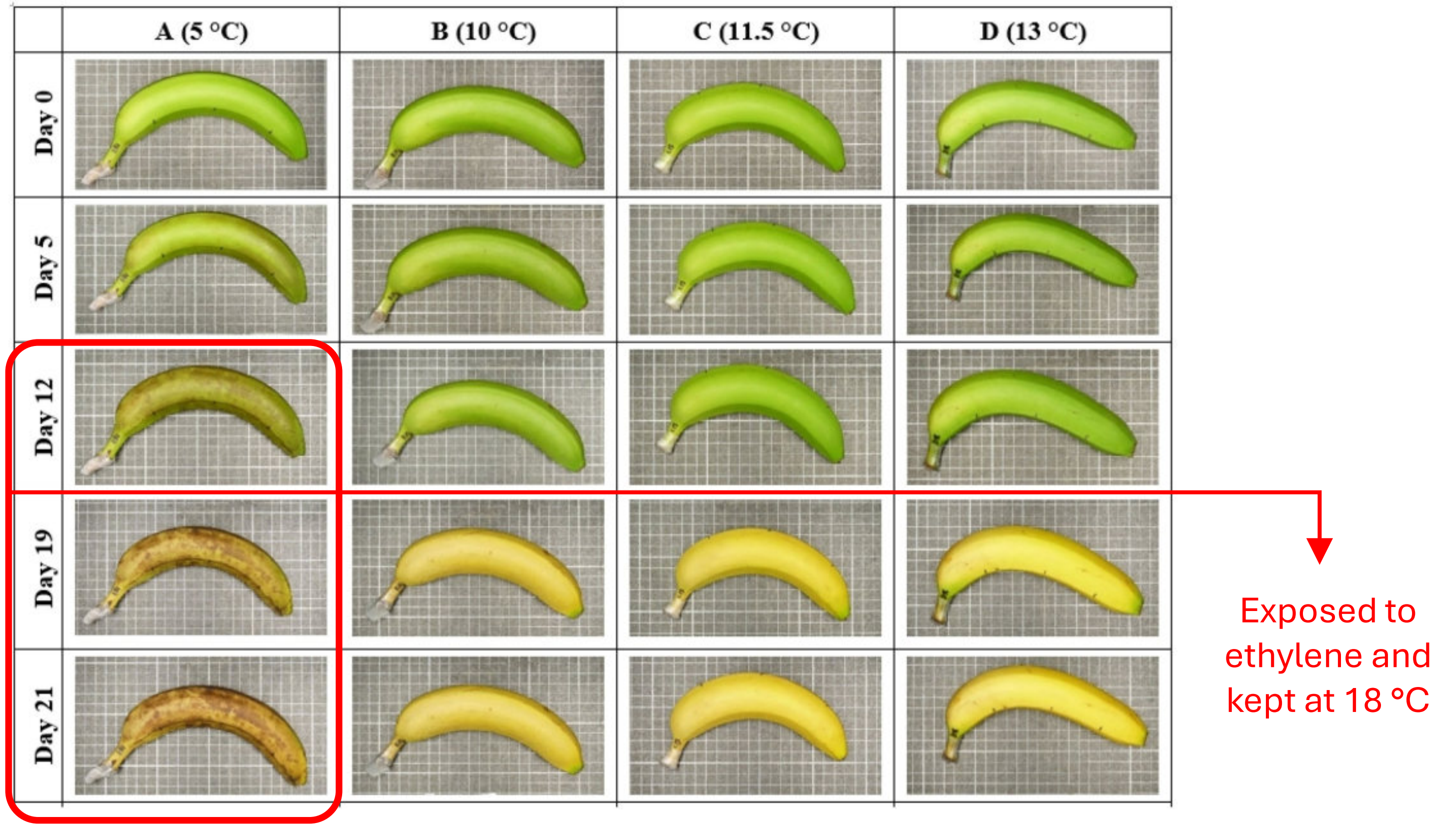


Fig. 1. Progression of chilling injury in 'Hayward' (A), and 'Zesy002' (B) kiwifruit.



- Peel browning, discoloration, uneven ripening.
- Poor response to ethylene
  (Ripening processes irreversibly disrupted)

Chilling injury (CI) *caused by low temperature*

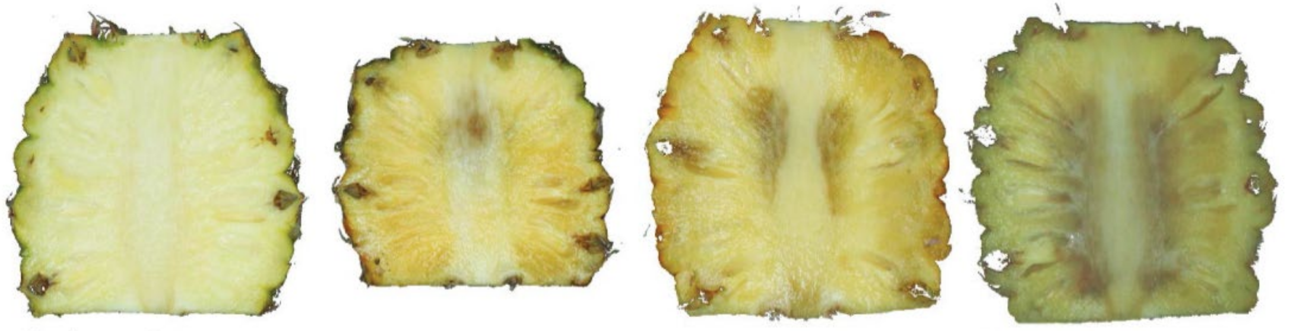


Fig. 3 Chilling injury (CI) incidence of green-yellow pineapple corresponding with visual rating scale, percentage of CI area form image analysis (IA) and fractal dimension (FD) values

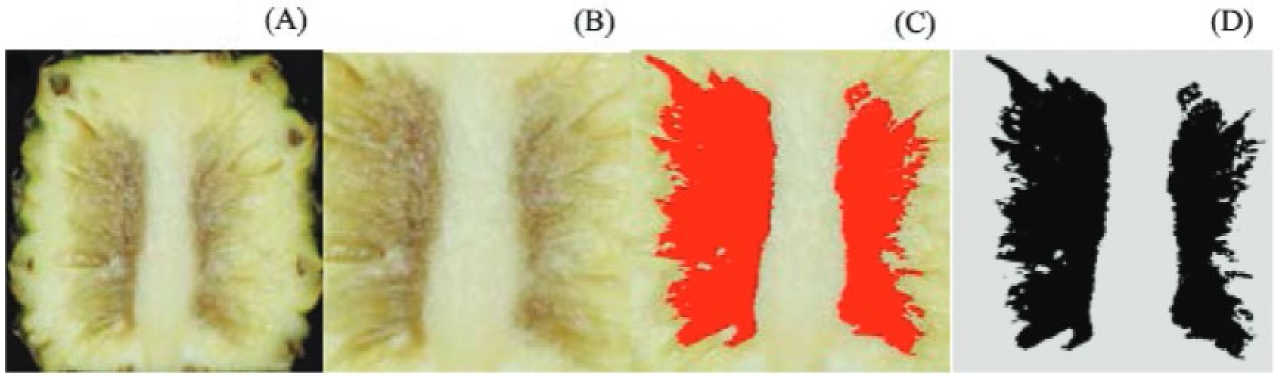
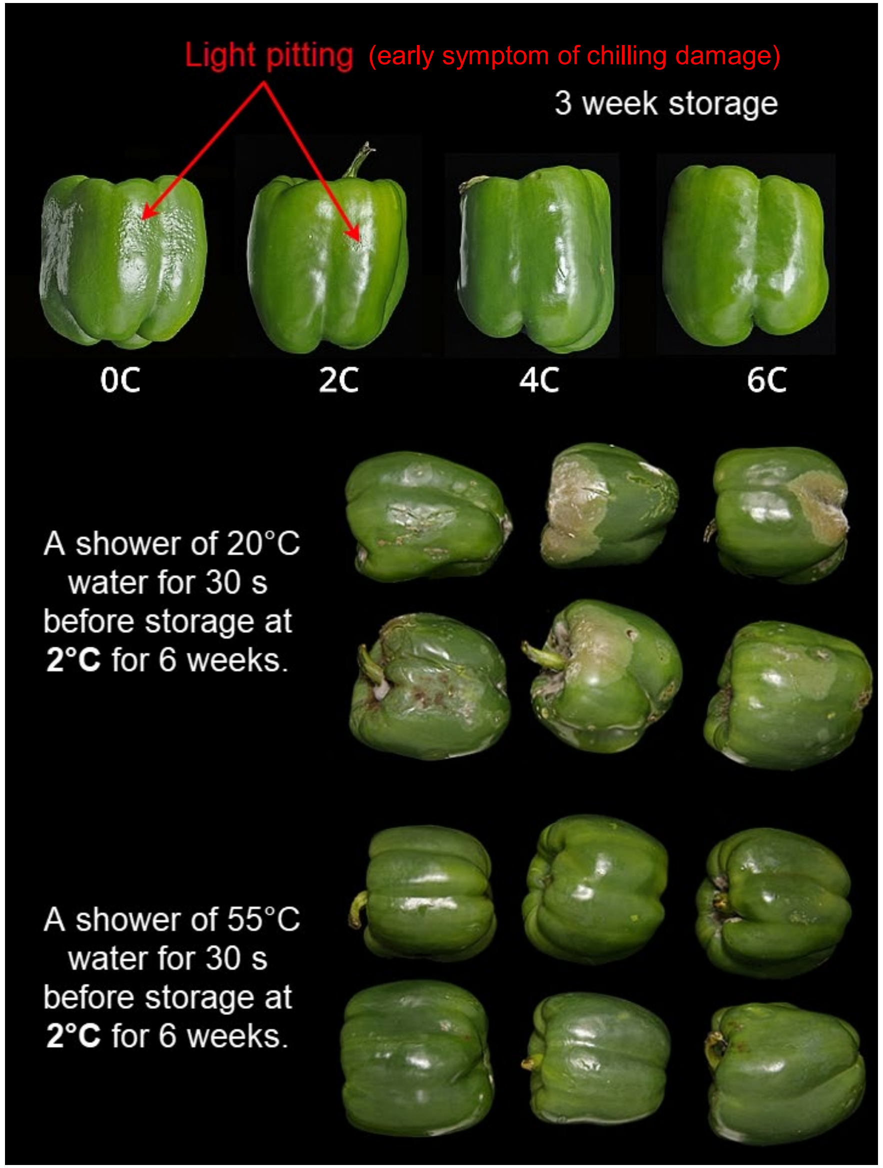


Fig. 1 Image analysis procedure: (A) original image; (B) cropped image; (C) thresholding; (D) Chilling injury selection

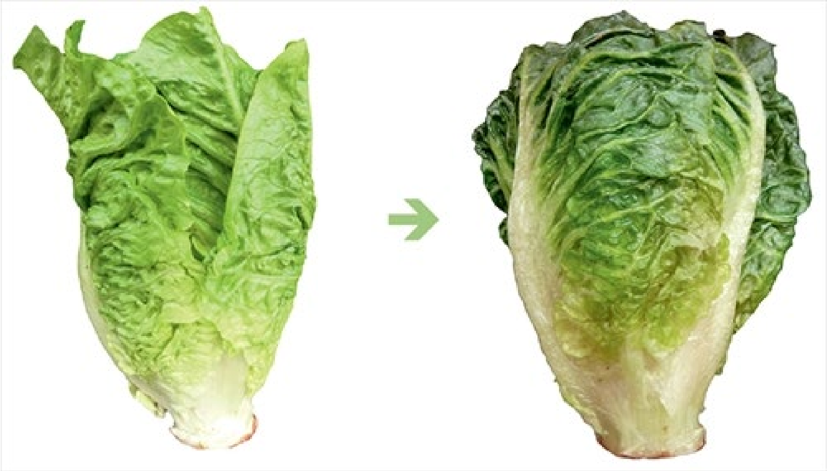


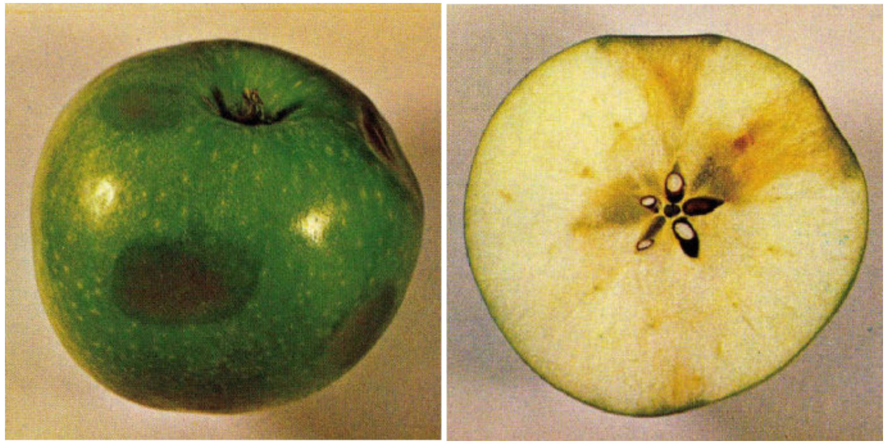
Heat treatments induce stress tolerance mechanisms (e.g., heat-shock proteins, HSPs) that protect tissues from chilling injury during low-temperature storage.

Freezing injury (FI)

- **Freezing injury (FI)** refers to a range of physiological disorders that occur when horticultural commodities are stored at **freezing temperatures**.

  Because freezing point depends on tissue composition:
  - **Lettuce**, with very high water content, freezes at approximately **−0.2 °C**.
  - **Carrots and sweet potato**, which contain higher levels of soluble sugars (up to ~10% at harvest), freeze at **lower temperatures (below −1.8 °C)**.
- Frozen tissues often show a **water-soaked or dehydrated appearance** due to ice crystal formation and cell rupture.
- Additional damage may occur during **rapid thawing**, which can exacerbate membrane disruption and moisture loss.





Bruises in frozen Granny Smith apple-external and internal after thawing.

Safe temperatures for fruits and vegetables

Table 1. Fresh produce susceptible to chilling injury when stored at low but nonfreezing temperatures

Commodity	Lowest Safe Temperature °C	°F	Symptoms of injury when stored between 0 °C and safe temperature*
Apples—certain cultivars	2-3†	36-38	Internal browning, brown core, soggy breakdown, soft scald
Asparagus	0-2	32-36	Dull, gray-green, limp tips
Atemoya	4	39	Skin darkening, failure to ripen, pulp discoloration
Avocados	4.5-13†	40-55	Grayish-brown discoloration of flesh
Bael	3	38	Brown spots on skin
Bananas	11.5-13†	53-56	Dull color when ripened
Bean (lima)	1-4.5	34-40	Rusty brown specks, spots or areas
Bean (snap)	7†	45	Pitting and russeting
Breadfruit	7-12	45-53	Abnormal ripening, dull brown discoloration
Choyote	5-10	41-50	Dull brown discoloration, pitting, flesh darkening
Cranberries	2	36	Rubbery texture, red flesh
Cucumbers	7	45	Pitting, water-soaked spots, decay
Eggplants	7	45	Surface scald, alternaria rot, blackening of seeds
Ginger	7	45	Softening, tissue breakdown, decay
Guavas	4.5†	40	Pulp injury, decay
Grapefruit	10†	50	Scald, pitting, watery breakdown
Jicama	13-18	55-65	Surface decay, discoloration
Lemons	11-13†	52-55	Pitting, membranous staining, red blotch
Limes	7-9	45-48	Pitting, turning tan with time
Lychee	3	38	Skin browning
Mangos	10-13†	50-55	Grayish scald-like discoloration of skin, uneven ripening
Mangosteen	4-8	39-47	Hardening and browning of the cortex
Melons			
Cantaloupe	2-5†	36-41	Pitting, surface decay
Honeydew	7-10	45-50	Reddish-tan discoloration, pitting, surface decay, failure to ripen
Casaba	7-10	45-50	Pitting, surface decay, failure to ripen
Crenshaw and Persian	7-10	45-50	Pitting, surface decay, failure to ripen
Okra	7	45	Discoloration, water-soaked areas, pitting, decay
Olive, fresh	7	45	Internal browning
Oranges	3†	38	Pitting, brown stain
Papayas	7	45	Pitting, failure to ripen, off flavors, decay
Passion fruit	10	50	Dark red discoloration on skin, loss of flavor, decay
Peppers, sweet	7	45	Sheet pitting, alternaria rot on pods and calyxes, darkening of seeds
Pineapples	7-10†	45-50	Dull green when ripe, internal browning
Pomegranates	4.5	40	Pitting, external and internal browning
Potatoes	3†	38	Mahogany browning, sweetening
Pumpkins and hardshell squash	10	50	Decay, especially alternaria rot
Rambutan	10	50	Darkening of exocarp
Sweet potatoes	13	55	Decay, pitting, internal discoloration, hardcore when cooked
Tamarillos	3-4	37-40	Surface pitting, discoloration
Taro	10	50	Internal browning, decay
Tomatoes			
Ripe	7-10†	45-50	Water soaking and softening, decay
Mature-green	13	55	Poor color when ripe, alternaria rot
Water convolvulus	10	50	Darkening of leaves and stems
Watermelons	4.5	40	Pitting, objectionable flavor

*Symptoms often become apparent only after removal to warm temperatures, as in marketing
†See individual commodity sections in this Handbook.

Air humidity effect: moisture loss

Table 2. Water loss at which commodities become unsalable, in order of increasing maximum weight loss

Commodity	Maximum weight loss (% fresh weight)	Reason for loss
Spinach	3	wilting
Broccoli	4	taste, wilting
Turnip with leaves	4	wilting
Tomato	4	shrivel
Leaf lettuce	3–5	wilting, decay
Grapes	5	berry shrivel
Pear	6	shrivel
Cabbage	6	shrivel
Apple	7	shrivel
Watercress	7	wilting
Persimmon	7	shrivel
Carrot	8	wilting
Brussels sprouts	8	wilting, rot, yellowing
Green pepper	8	shrivel
Peach	11	shrivel
Winter squash	15	hollow neck

Sources: Hardenburg et al. 1986; Hruschka 1977; Nelson 1985; Robinson et al. 1975.

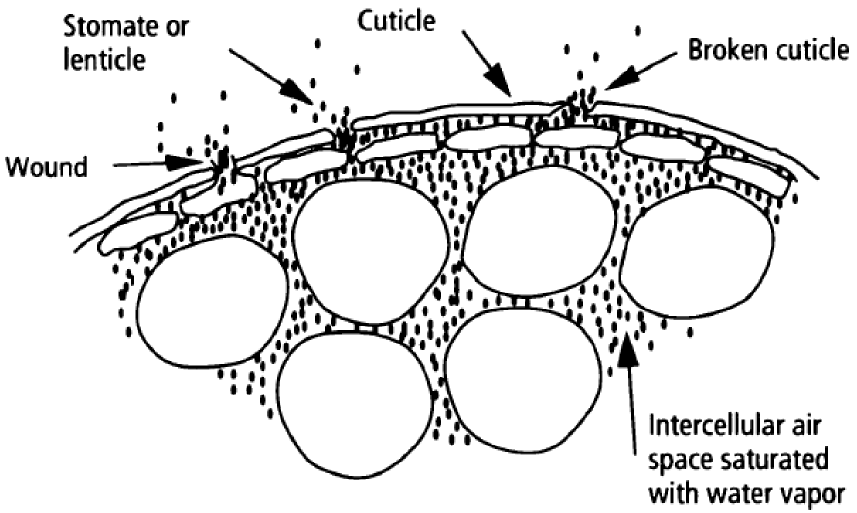


Figure 4. Primary routes of water loss in fresh produce.

- **Transpiration coefficient** used to describe total effect of the physiological mechanisms of water loss and the surface-to-volume ratio of produce
- **Vapor-pressure difference (VPD)** relates to the temperature and relative humidity of the surrounding air.
- A 5 percent weight loss causes 0.5 kg less salable product in each 10-kg package, or 50 kg less for each ton of produce handled.

Air humidity effect: moisture loss

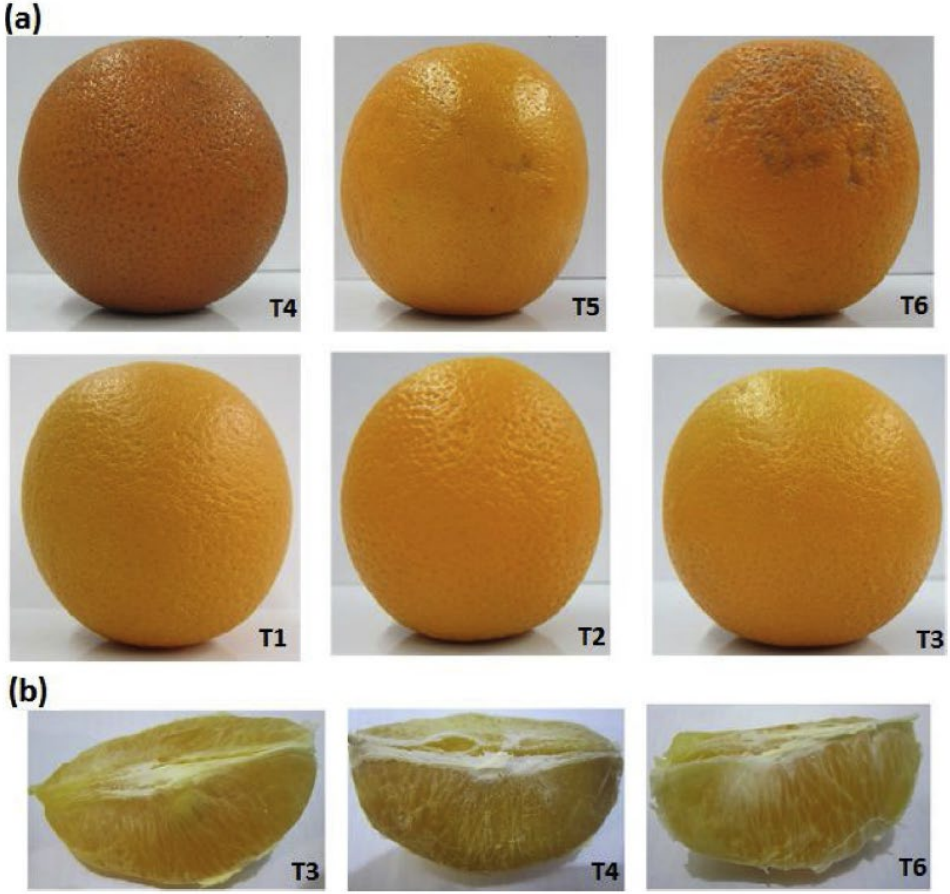


Fig. 2. Effects of wax coating on the outer (a) and inner (b) visual appearance of 'Valencia' orange fruit after 56 d of cold storage at 4 °C with additional 7 d storage at 20 °C (Motamedi et al., 2018). Synthesized carnauba wax with 0.0 % (T1), 0.5 (T2) and 1.0 % (T3) organoclay, commercial wax 1 (T4) and wax 2 (T5) and no wax control fruit (T6).

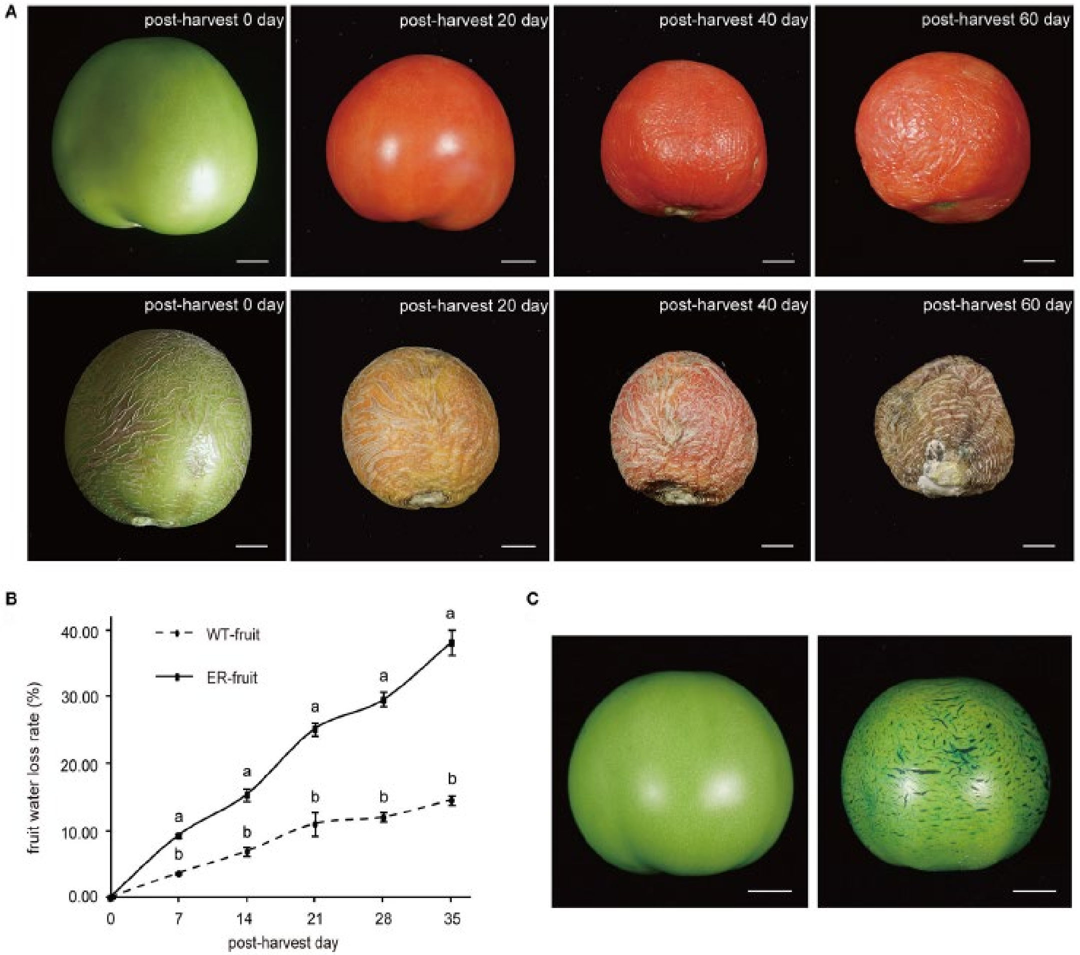


FIGURE 2 | Analysis of transpirational water loss from mature wild type (WT) and epidermal reticulation (ER) fruit. **(A)** Comparison of the phenotypes of normal and ER fruits during postharvest storage. The upper row of fruit are WT and the lower row are ER. **(B)** Postharvest fruit water loss from WT and ER fruits over a 5-week period. The data are presented as the mean ± *SD*, and the different letters in the same days indicated significant difference between two samples at 0.05 level **(C)** Toluidine blue (TB, 0.5% solution) staining of WT (left) and ER (right) fruit 40 days after pollination (DAP). Scale bar = 1 cm.

Air humidity effect: moisture loss

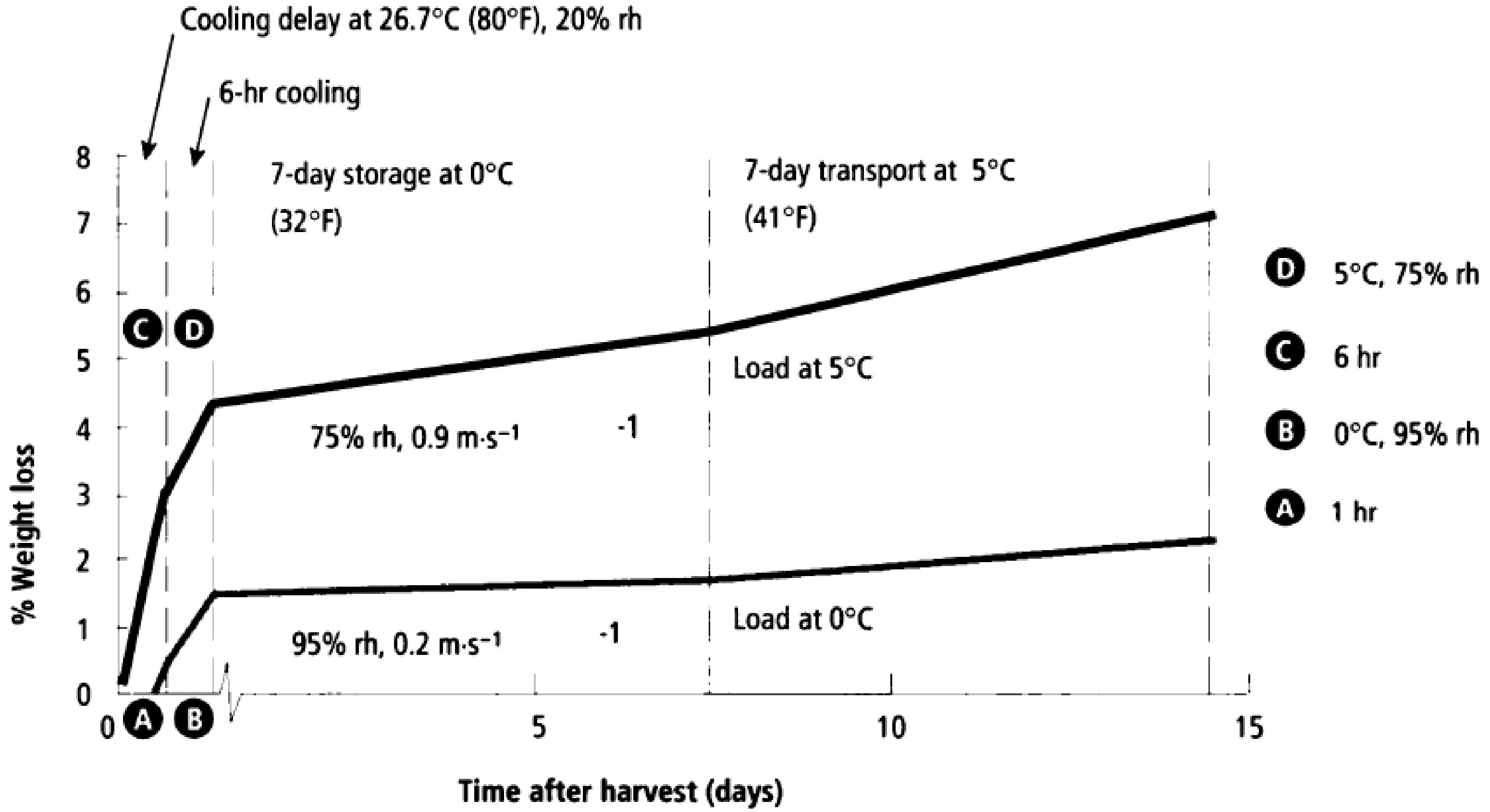


Figure 5. Table grape weight loss resulting from two different cooling and handling regimes. Lower line represents nearly ideal conditions; upper line represents the effect of poor handling.

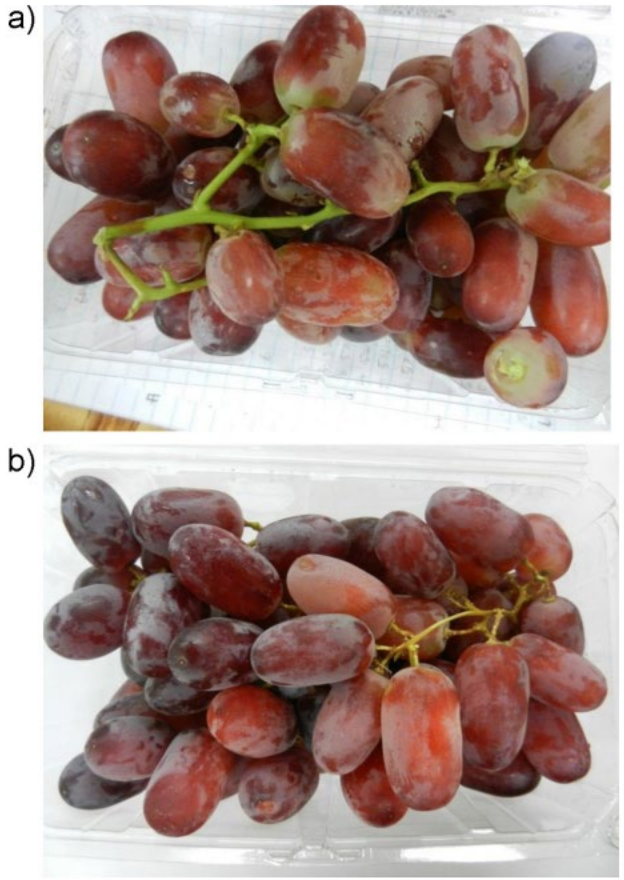


Fig. 7. Visual appearance of grape bunches packed in clamshell punnet multi-packaging after 28 days of cold storage under (a) humidified and (b) non-humidified rooms.

Calculation of moisture loss

Table 3. Transpiration coefficients for selected fruits and vegetables, in order of increasing maximum transpiration coefficient

Commodity	Transpiration coefficient ($mg \cdot kg^{-1} \cdot sec^{-1} \cdot MPa^{-1}$)	Range of coefficients reported in literature
Apple	42	16–100
Potato	44	2–171
Onion	60	13–123
Pear	69	10–144
Grapefruit	81	29–167
Orange	117	25–227
Grapes	123	21–254
Plum	136	110–221
Tomato	140	71–365
Lemon	186	139–229
Cabbage	223	40–667
Rutabaga	469	—
Peach	572	142–2,089
Leek	790	530–1,042
Carrot	1,207	106–3,250
Celery	1,760	104–3,313
Parsnip	1,939	1,094–2,771
Brussels sprouts	6,150	3,250–9,770
Lettuce	7,400	680–8,750

Source: Adapted from Sastry et al. 1978.

I. Estimate the vapor pressures at the produce surface (V_{pp}) and in the surrounding air (V_{pa}) from

$$V_{pp} = \frac{\omega(T,\varphi) \times P_{atm}}{0.622}$$

$$V_{pa} = \frac{\omega(T,\varphi) \times P_{atm}}{0.622}$$

$\boldsymbol{P_{atm}}$ is atmospheric pressure in Mpa

$\boldsymbol{\omega(T,\varphi)}$ is humidity ratio (kg of water vapor/kg of dry air) that can be obtained from a psychrometric chart by knowing temperature (T) and relative humidity (φ) of the air.

II. Calculate the moisture loss from

$$ML = K\left(V_{pp} - V_{pa}\right)$$

$\boldsymbol{K}$ is transpiration coefficient [mg/(kg·s·MPa)]

1 atm = 1.01325×10^5 Pa = 1.01325 bar = 760 torr

1 torr = 1 mmHg

Calculation of moisture loss (Example)

Determine the moisture loss from tomato at 7°C were exposed to the air at 4°C and 80%RH.

$$V_{pa} = \frac{\omega(4°\text{C}, 80\%\text{RH}) \times P_{atm}}{0.622} = \frac{0.00402\ kg/kg \times 0.101325\ MPa}{0.622} = 6.549 \times 10^{-4}\ \text{MPa}$$

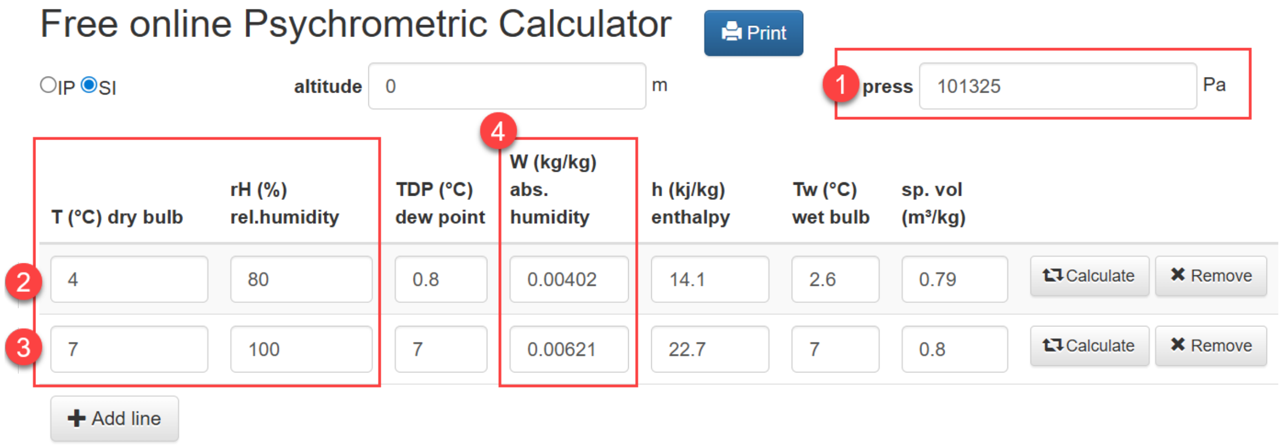
$$V_{pp} = \frac{\omega(7°\text{C}, 100\%\text{RH}) \times P_{atm}}{0.622} = \frac{0.00621\ kg/kg \times 0.101325\ MPa}{0.622} = 10.116 \times 10^{-4}\ \text{MPa}$$

$K = 140$ mg/(kg·s·Mpa) (Page 32, Table 3)

$$ML = 140(10.116 - 6.549) \times 10^{-4}$$

$$= 499.4 \times 10^{-4}\ \text{mg/(kg·s)}$$

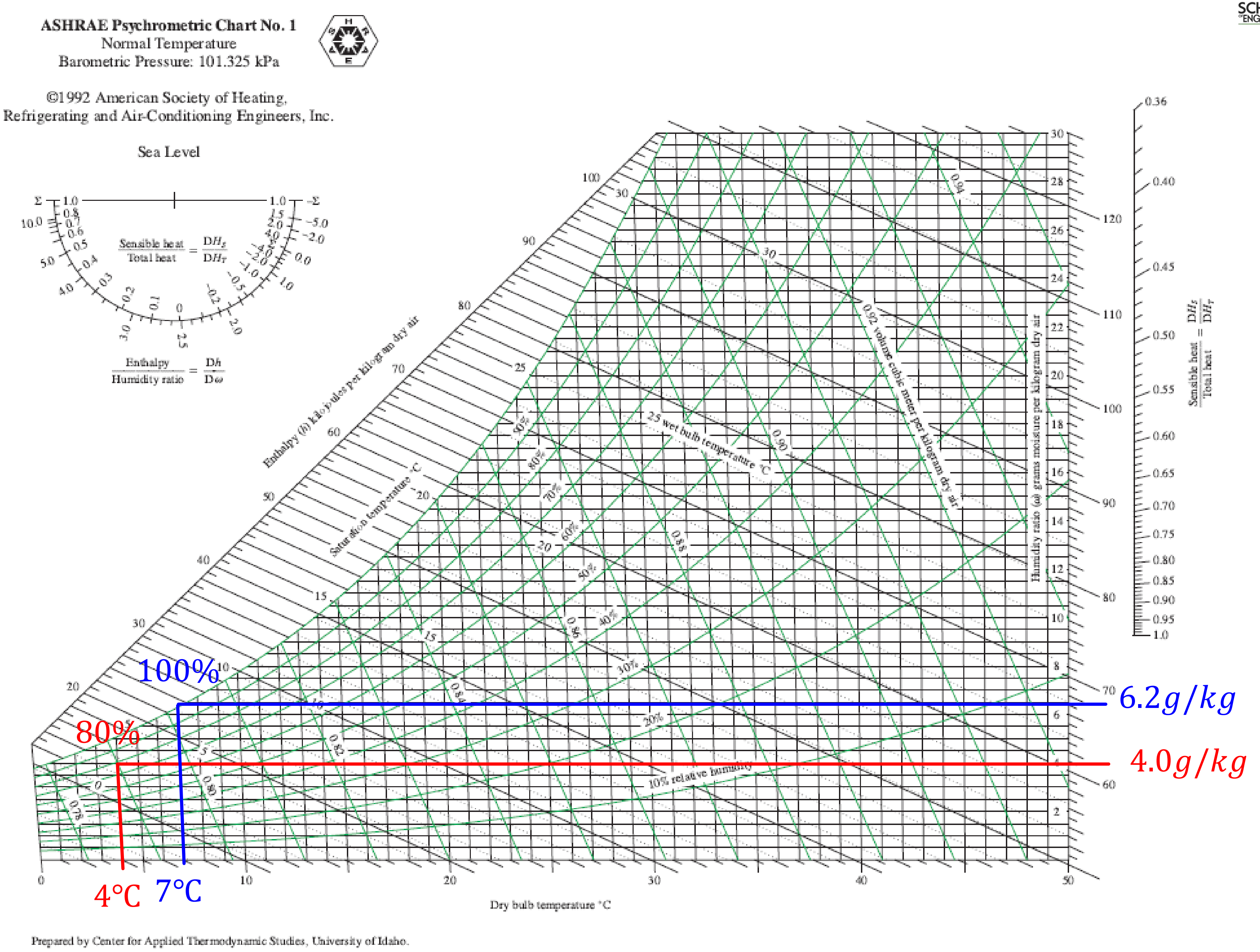
$$= 49.94\ \mu\text{g/(kg·s)}$$



Tomato 1 kg losses its mass ~50 μg/s ~4.32 g/day (0.43% per day → 4% in 9 days)

What if it exposed to air at 4°C and 45%RH?

Ex.


ASHRAE Psychrometric Chart No. 1
Normal Temperature
Barometric Pressure: 101.325 kPa
©1992 American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
Sea Level
Sensible heat / Total heat = DH_S / DH_T
Enthalpy / Humidity ratio = $Dh / D\omega$
Enthalpy (h) kilojoules per kilogram dry air
Saturation temperature °C
wet bulb temperature °C
volume cubic meter per kilogram dry air
Humidity ratio (ω) grams moisture per kilogram dry air
10% relative humidity
Dry bulb temperature °C
Prepared by Center for Applied Thermodynamic Studies, University of Idaho.
100%
80%
$6.2 g/kg$
$4.0 g/kg$
4°C
7°C

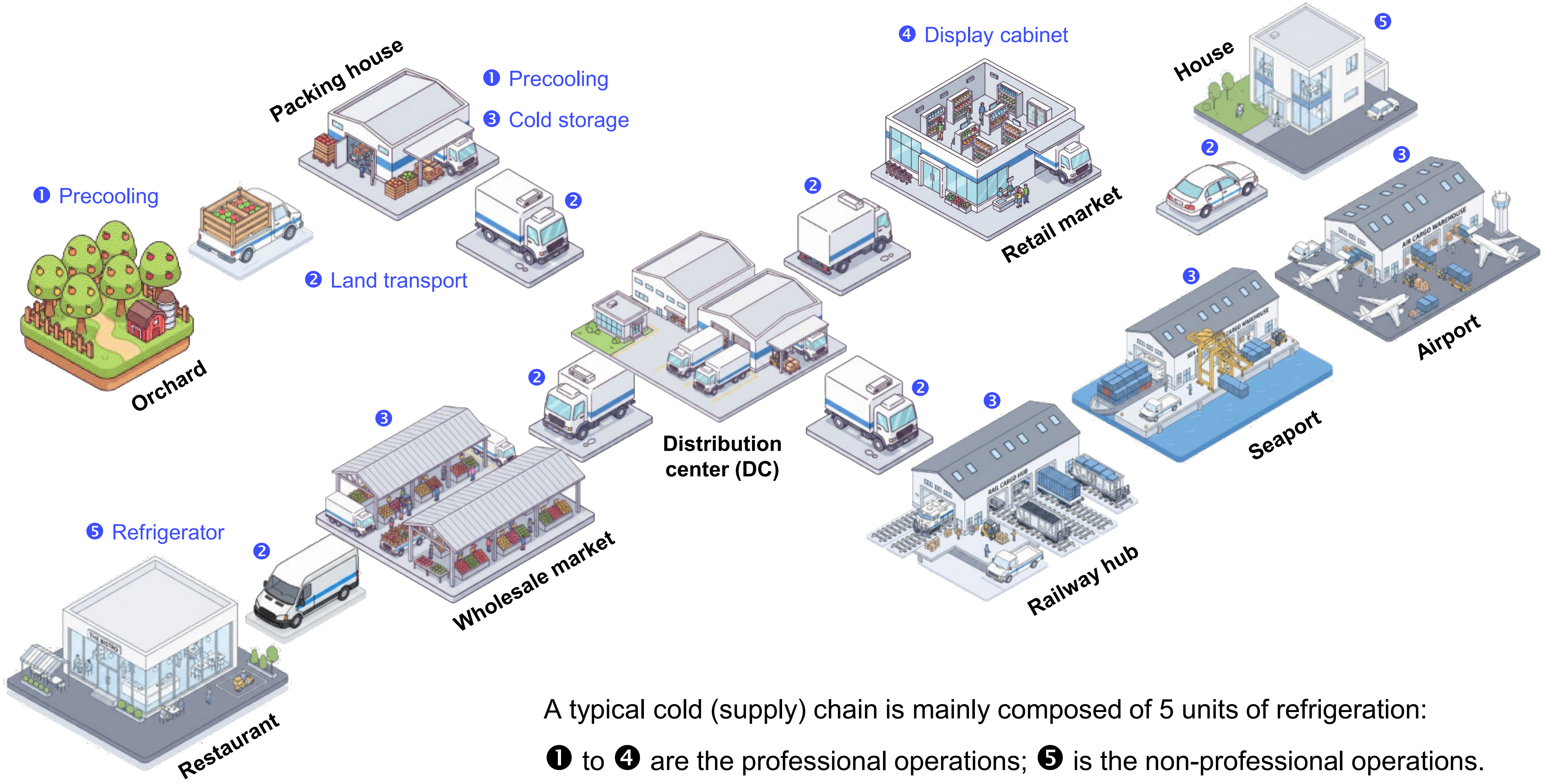
Part 2

Cold Chain

Cold Chain: Definitions

- 1998 | The part of the Food Industry which deals with the transport, storage, distribution and selling of frozen food. It includes **equipment** and the **operation** of that equipment to maintain **frozen food** in a fully frozen condition at the correct temperature.
- 2006 | A term applied to food handling and distribution where the product is maintained at suitable conditions all the way from the **cooling or freezing** process to the point of sale.
- 2019 | Series of actions and equipment applied to maintain a product within a **specified low-temperature range** from harvest / production to consumption.
- 2020 | A supply-chain that incorporates temperature control and consists of a series of unbroken storage and transportation stages maintaining the same low temperature conditions.
- 2020 | A temperature-controlled supply chain linked to the material, equipment and procedures used to maintain specific shipments within the **appropriate temperature range**.
- 2022 | The cold chain is the management of temperature for **perishable products** in order to maintain quality and safety from the point of origin through the distribution chain to the final consumer.

Refrigeration units in a typical cold chain



A typical cold (supply) chain is mainly composed of 5 units of refrigeration:

❶ to ❹ are the professional operations; ❺ is the non-professional operations.

Refrigeration units in a typical cold chain

❶ Precooling

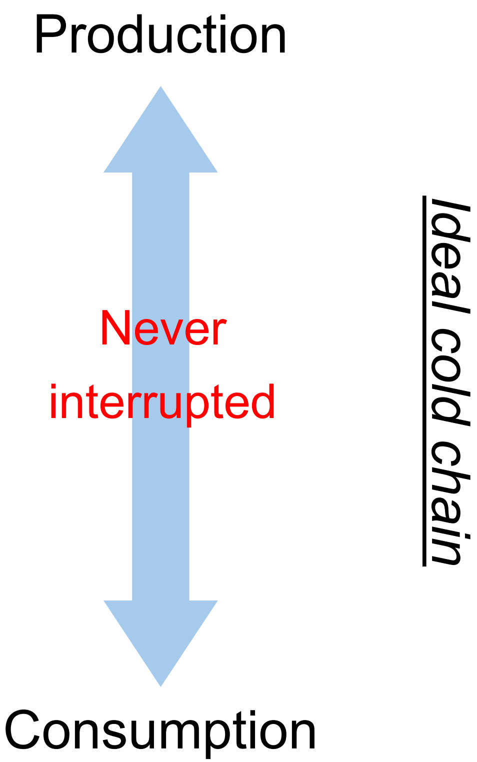
❷ Transportation (Air, Land, Rail, and Sea)

❸ Cold storage

❹ Display cabinet

❺ Refrigerator

❻ **Insulated containers with PCMs**



Real situation

Temperature abuses **above or below the optimal product-specific temperature range** *frequently* occur in the cold chain.

Temperature abuses

- Inappropriate precooling
- Poor temperature control
- Temperature fluctuations due to on/off refrigeration cycles
- Loading/unloaded in summer

- Overloading of display cabinets
- Transportation by consumers without thermal protection
- High temperature in refrigerators

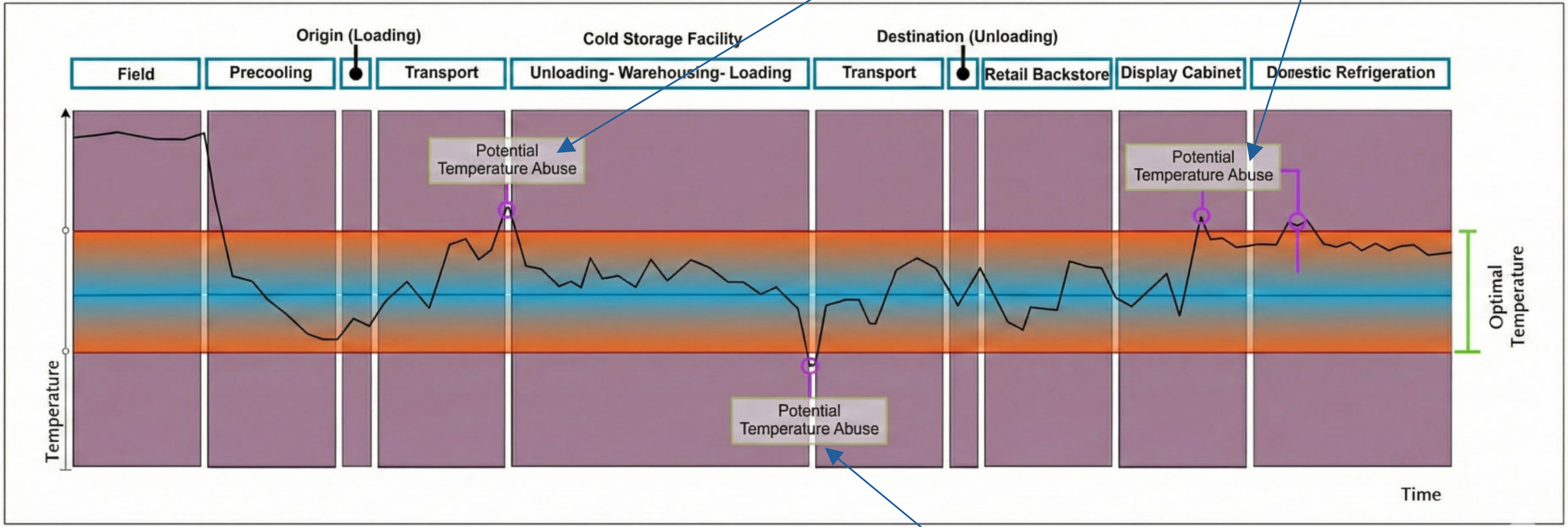


Figure 1—Typical temperature profile of perishable food along the cold chain.

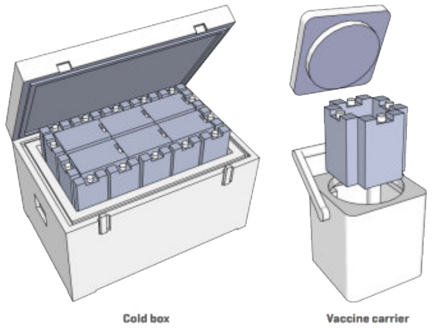
- Inappropriate temperature control
- Loading/unloading in winter

Insulation Box with Phase Change Materials (PCM)

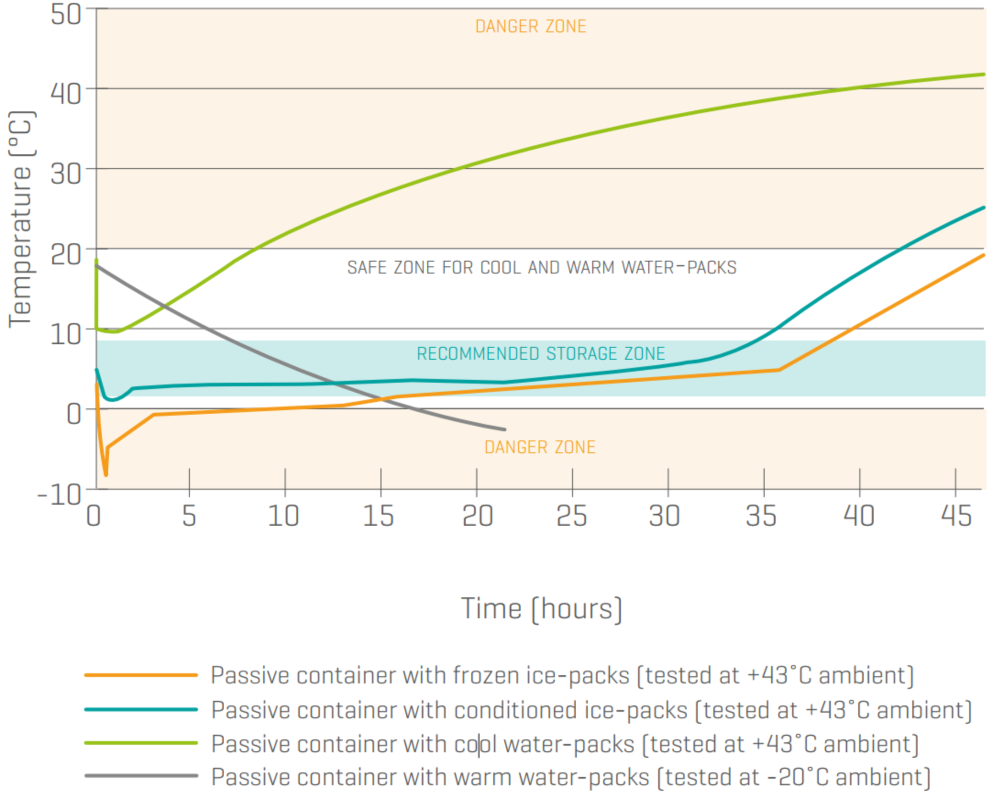
Vaccine cold chain

The temperature in the vaccine storage compartment must remain above 0°C and below +10°C with an accuracy of ±0.5°C in ambient temperatures of +15°C to +43°C for a minimum of 48 h for a short-range cold box and 96 h for a long-range cold box.

Figure 1. Cold box and vaccine carrier with **coolant-packs**

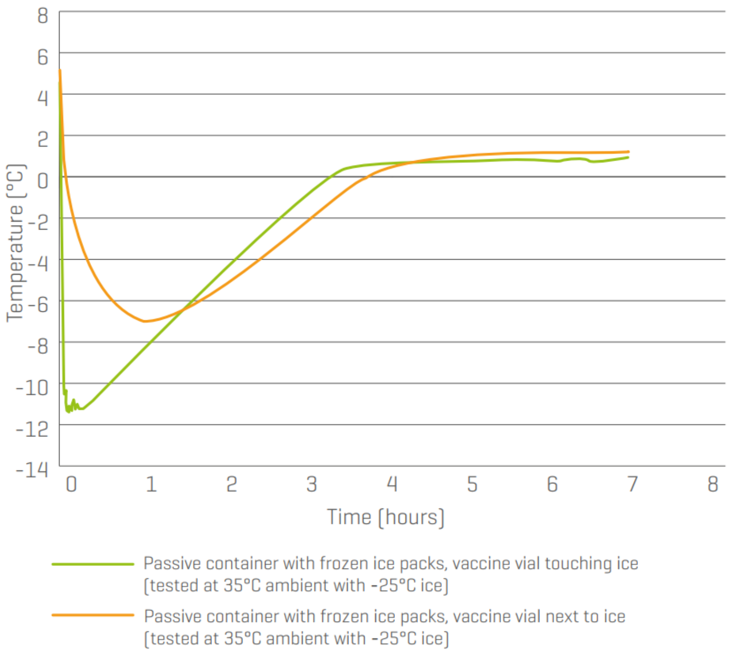


Temperatures inside vaccine vials placed in the center of a vaccine carrier packed with four types of water-packs



- Ice-pack: A water-pack that has been frozen to a temperature of between -5°C and -25°C before use.
- Conditioned ice-pack: An ice-pack that has been allowed to warm at ambient temperature until some water is present inside the pack. The pack is correctly conditioned as soon as the ice core is able to move inside the pack when it is shaken. The effective temperature of a conditioned ice-pack in this state is 0°C.
- Cool water-pack: A water-pack cooled to a temperature between +2°C and +8°C before use.
- Warm water-pack: A water-pack typically stabilized at room temperature, up to a recommended maximum of +24°C. Warm water-packs are used for the transport of freeze-sensitive vaccines when the ambient temperature is below 0°C

Temperatures inside vaccine vials adjacent to and in contact with frozen ice-packs inside a vaccine carrier



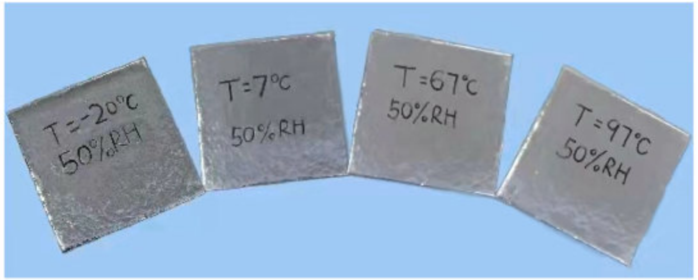
Performance of prequalified passive containers

Product type		Cold life (hours)	Cool life (hours)	Warm life (hours)
Minimum PQS standard for cold boxes	*Long range*	*96.0*	*No standard set*	*No standard set*
	Short range	*48.0*	*No standard set*	*No standard set*
Large cold box (≥15 litres)	MAX	156.0	51.3	53.1
	MIN	53.6	18.7	16.4
Small cold box (<15 litres)	MAX	132.3	30.0	48.7
	MIN	57.9	12.0	21.6
Minimum PQS standard for vaccine carriers	*Long range*	*30.0*	*No standard set*	*No standard set*
	Short range	*15.0*	*No standard set*	*No standard set*
Large vaccine carrier (≥1 litre)	MAX	50.2	18.0	19.0
	MIN	30.3	6.0	7.0
Small vaccine carrier (<1 litre)	MAX	21.5	4.5	8.0
	MIN	17.8	3.0	4.4

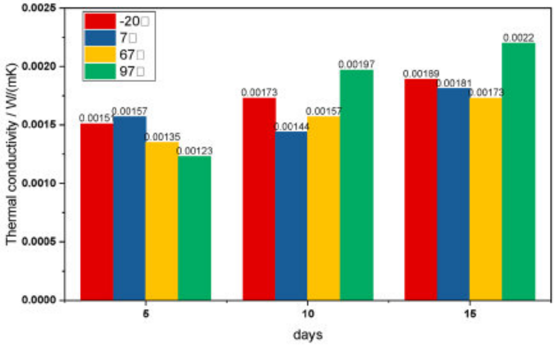
More detail: WHO Catalogue of Prequalified Immunization Devices

- **Cold Life**: The empty passive container is stabilized at +43°C and loaded with icepacks frozen at -25°C. Cold life is measured from the moment when the container lid is closed until the temperature of the warmest point in the vaccine storage compartment first reaches +10°C, at a constant ambient temperature of +43°C.
- **Cool Life**: The empty passive container is stabilized at +43°C and loaded with cool water-packs that have been stabilized at + 5°C for a minimum of 24 hours. Cool life is measured from the moment when the container is closed until the temperature of the warmest point inside the vaccine storage compartment first reaches +20°C, at a constant ambient temperature of +43°C.
- **Warm life**: The empty passive container is stabilized at +18°C and loaded with warm water-packs that have been stabilized at the same temperature for a minimum of 24 hours. Warm life is measured from the moment when the container is closed until the temperature of the coldest point inside the vaccine storage compartment first reaches 0°C at a constant ambient temperature of -20°C.

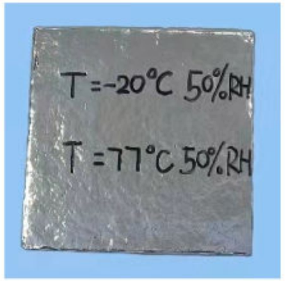
Vacuum Insulation Pane (VIP)



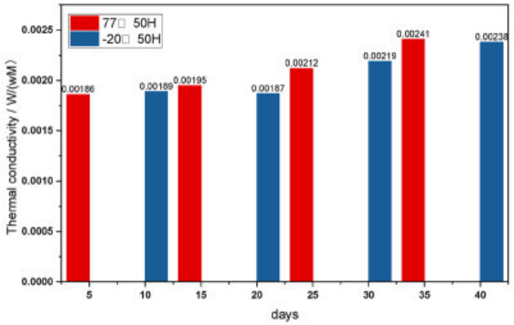
(a) Temperature variable samples



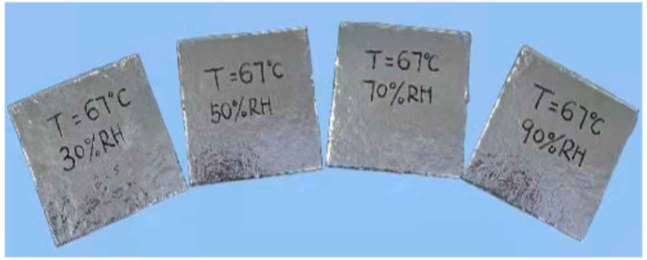
(b) Thermal conductivity measured at four different temperatures (-20°C, 7°C, 67°C and 97°C)



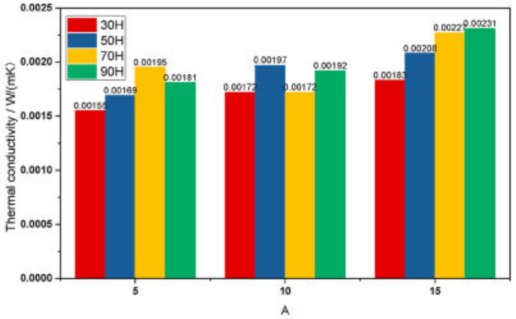
(c) Alternating temperature sample



(d) 50%RH, 77°C and 50%RH, -20°C



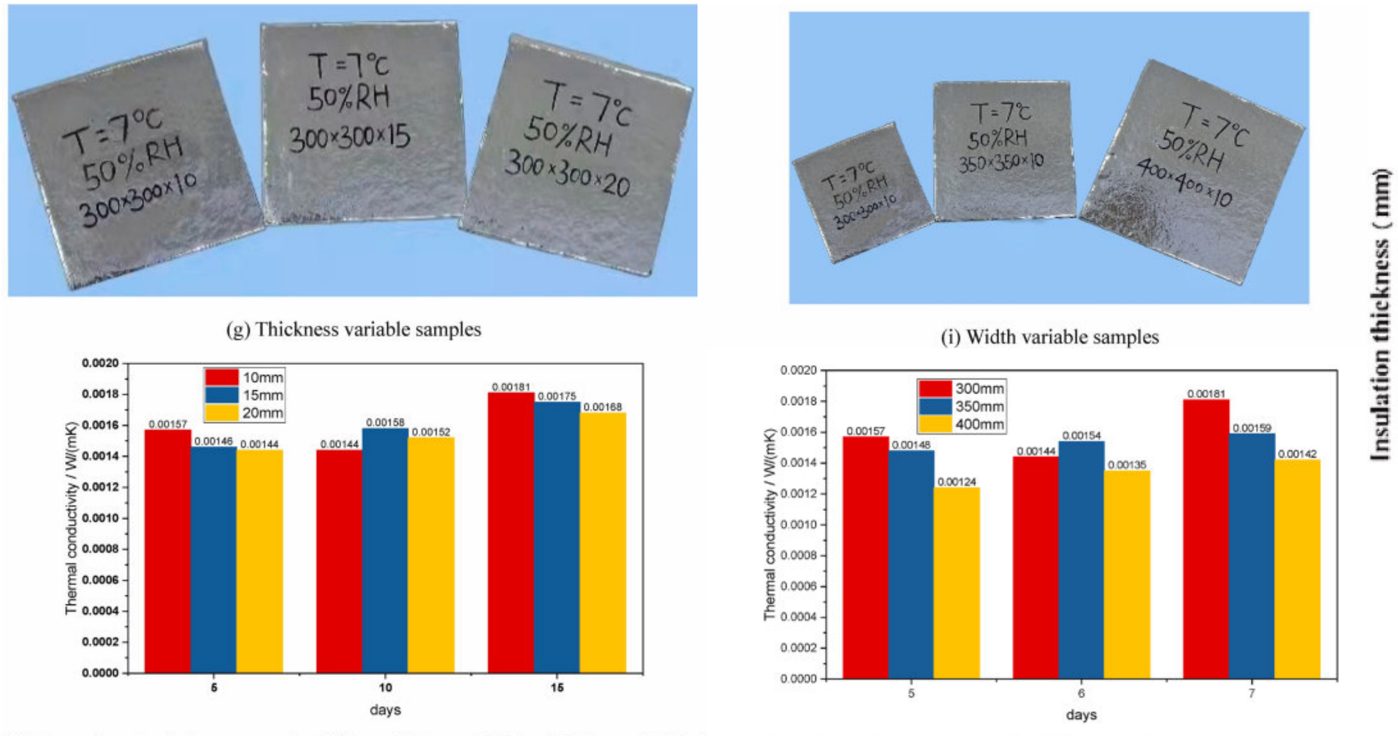
(e) Humidity variable samples



(f) Thermal conductivity measured at four different humidity (30%RH, 50%RH, 70%RH and 90%RH)

- k varies from 0.0015 to 0.0025 W/(m·K).
- k increases with time.
- k is high at high temperature and/or high humidity (> 50%rh).

Vacuum Insulation Panel (VIP)

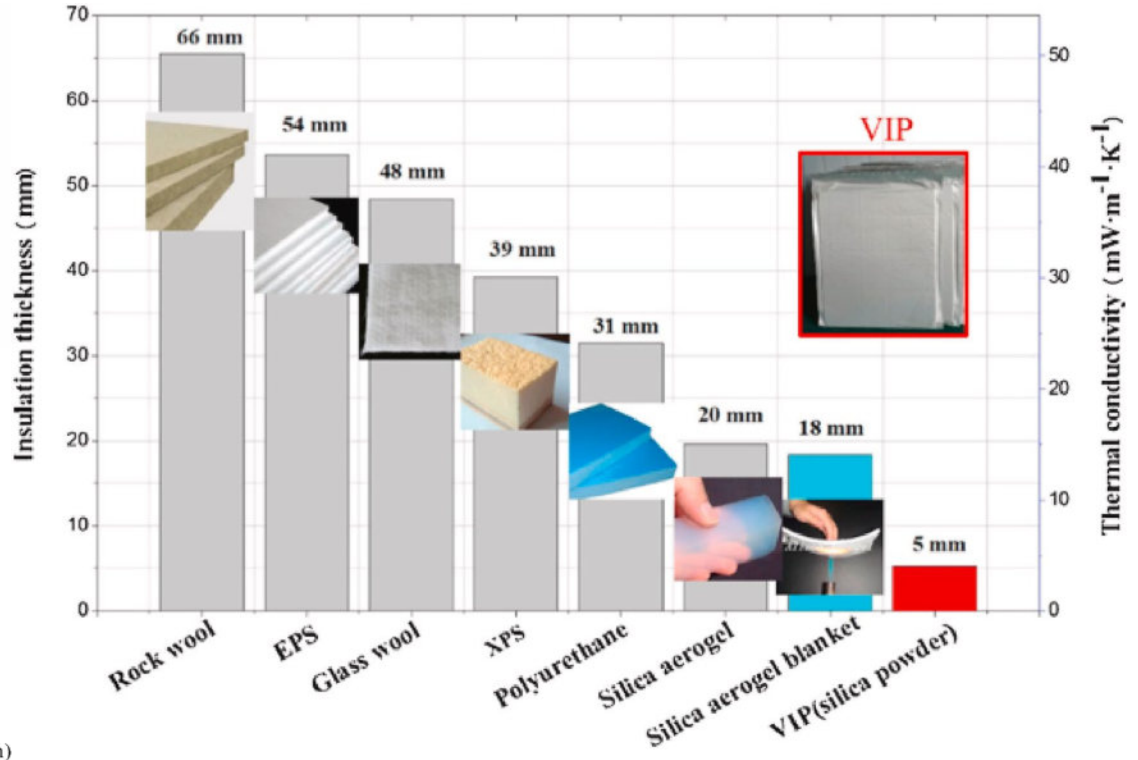


(g) Thickness variable samples

(i) Width variable samples

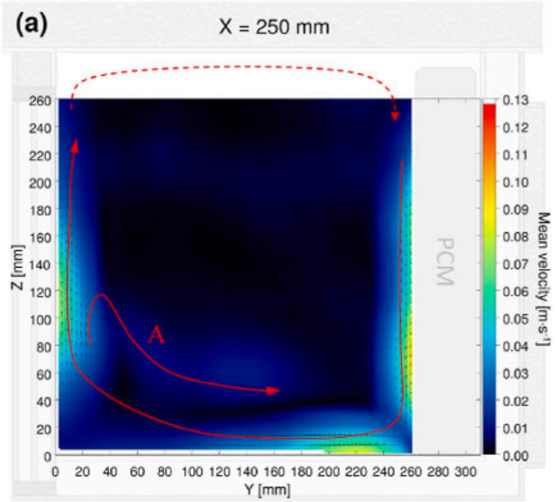
(h) Thermal conductivity measured at different thickness (0.01m, 0.015m and 0.02m)

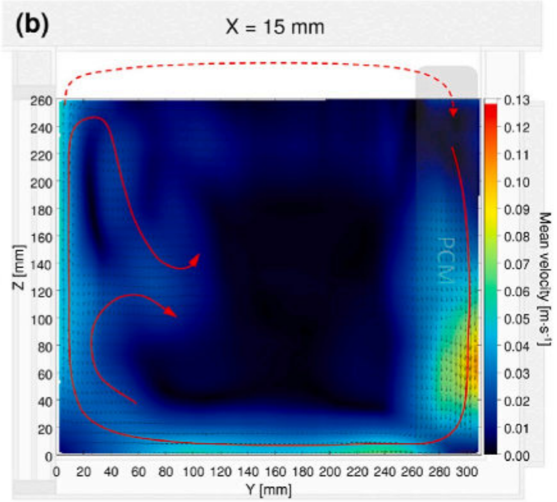
(j) Thermal conductivity measured at different width (0.3m, 0.35m and 0.4m)

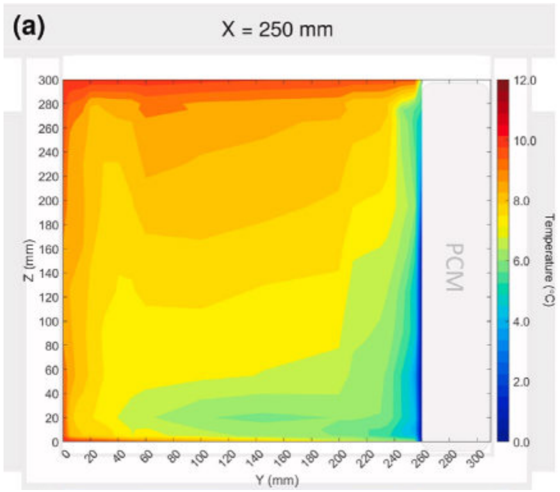


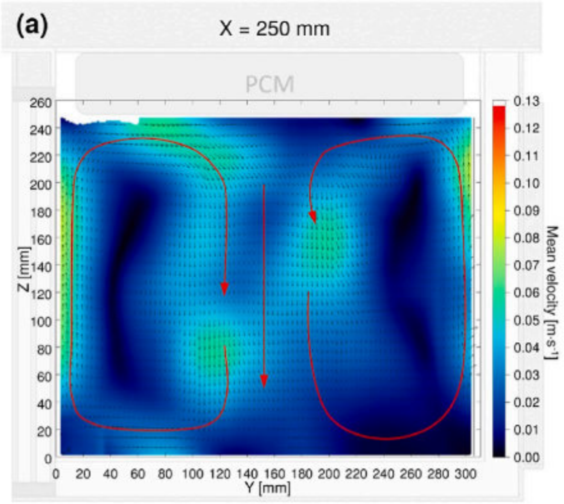
- k varies from 0.0014 to 0.0018 W/(m·K) under 7°C and 50%rh.
- k decreases with thickness and sizes.
- The required thickness of various insulation materials when the thermal resistance is the same.

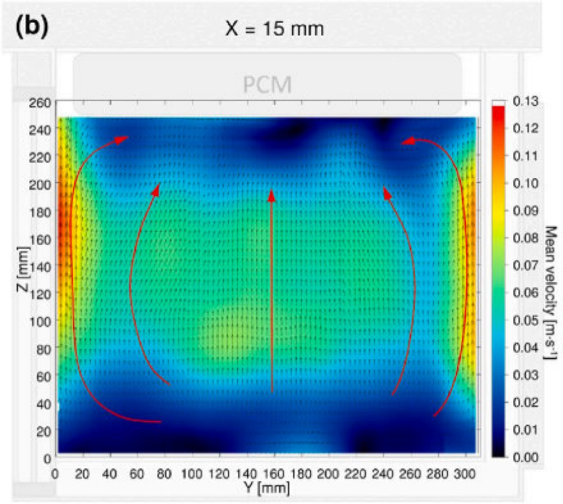
Free convection in cold chain applications

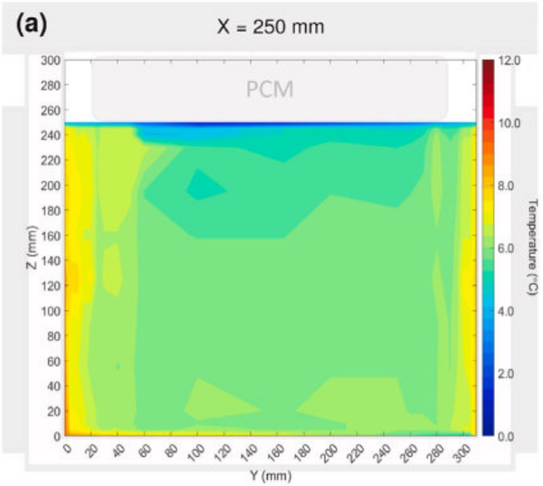




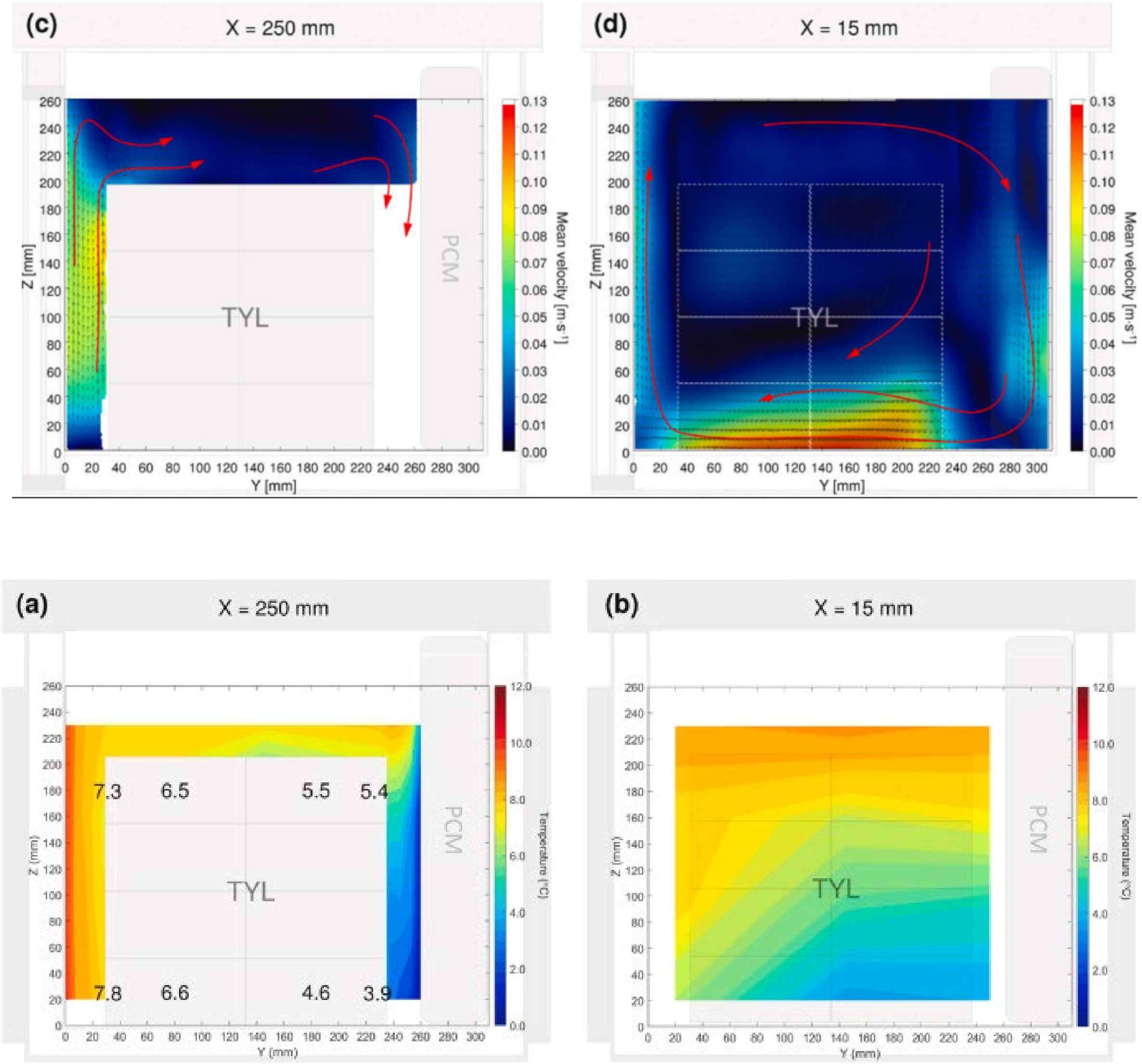


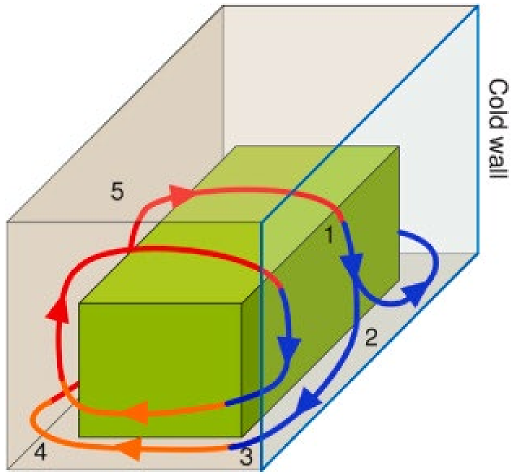






Free convection in cold chain applications





Free convection in cold chain applications

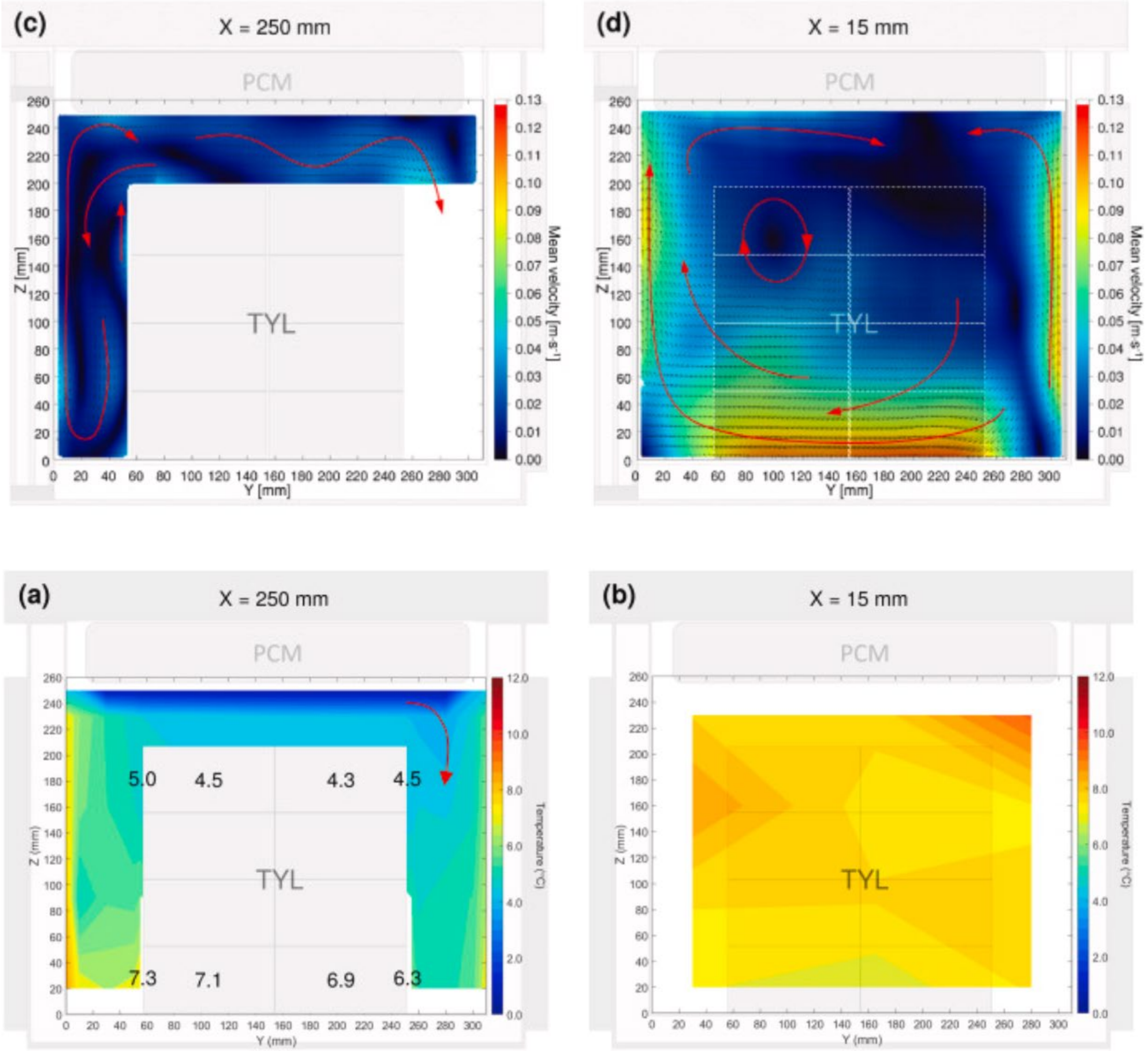


Table 1
Distribution of PCM mass in insulative container for evaluated layouts.

Layout	Bottom face (g)	Top face (g)	Long sides (each) (g)	Short sides (each) (g)
Layout 1	1000	1000	0	0
Layout 2	0	0	750	250
Layout 3	500	500	500	0

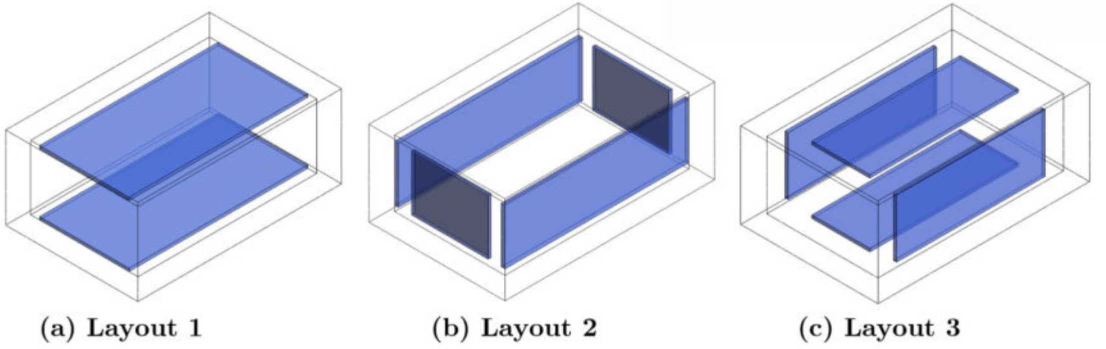


Fig. 4. Positioning of PCM in the insulative container for evaluated layouts.

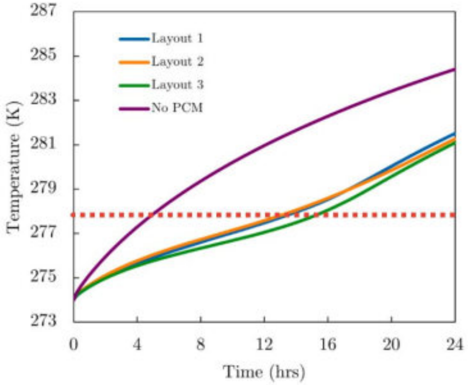


Fig. 7. Average content temperature over time.

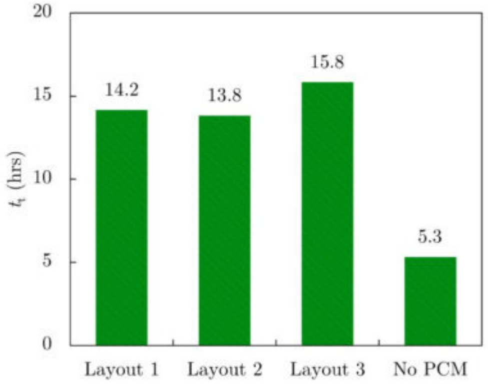
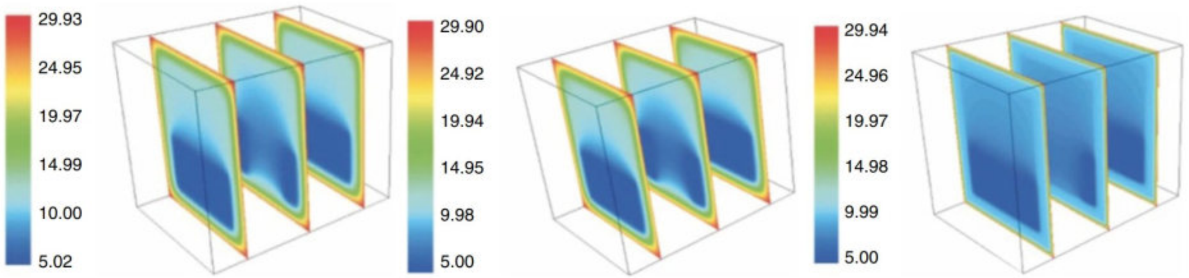
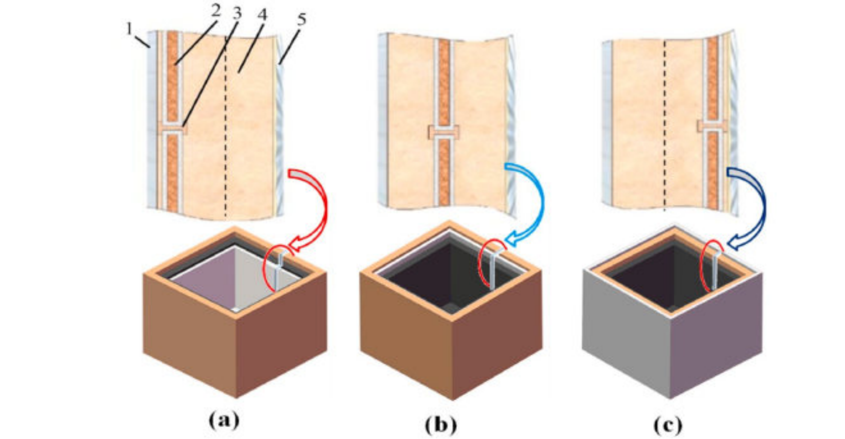


Fig. 8. Duration of average temperature below 5 °C threshold.

Free convection in cold chain applications



(a) XPS **(b)** EPU **(c)** VIP



(a) Internal insulation (b) Sandwich insulation (c) External insulation

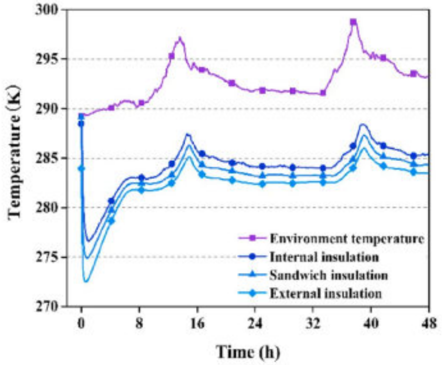
1-Inner surface decoration layer; 2-VIP; 3-Fastener; 4-PU; 5- Outer surface decoration layer

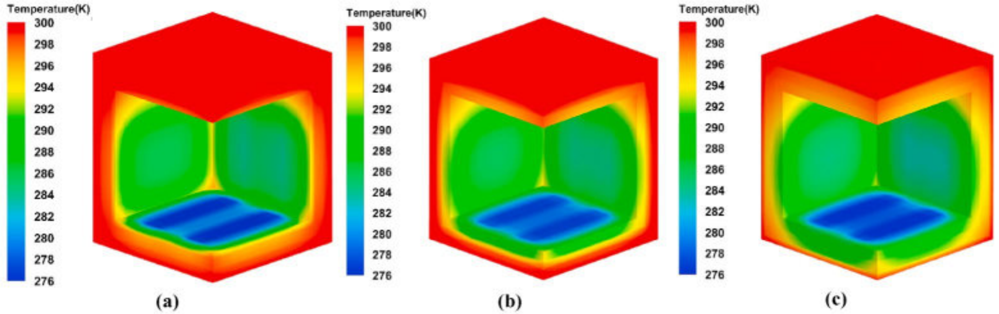
Fig. 1. Three samples of VIP + PU multi-layer insulation composite structures.

Table 2

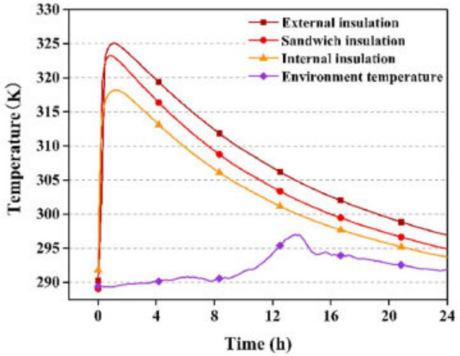
Arrangement order of insulation layers in different chambers.

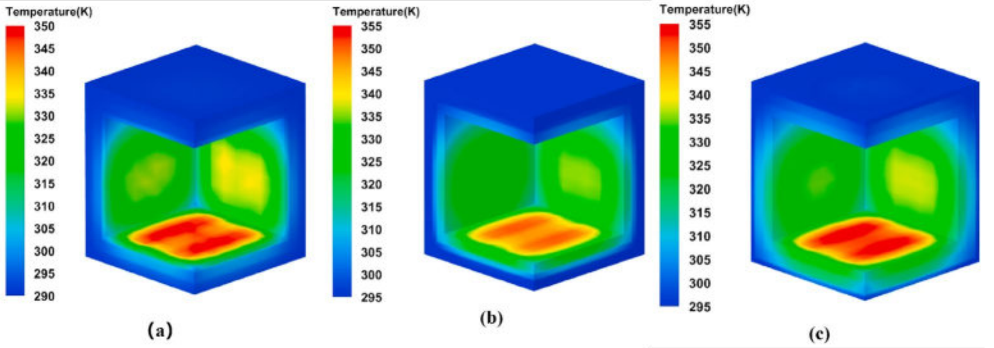
Chamber No.	Insulation structure	Layout order (from outside to inside)
a	Internal	δ_{PU}10mm +δ_{PU}10mm +δ_{VIP}10 mm
b	Sandwich	δ_{PU}10mm +δ_{VIP}10 mm +δ_{PU}10mm
c	External	δ_{VIP}10 mm +δ_{PU}10mm +δ_{PU}10mm



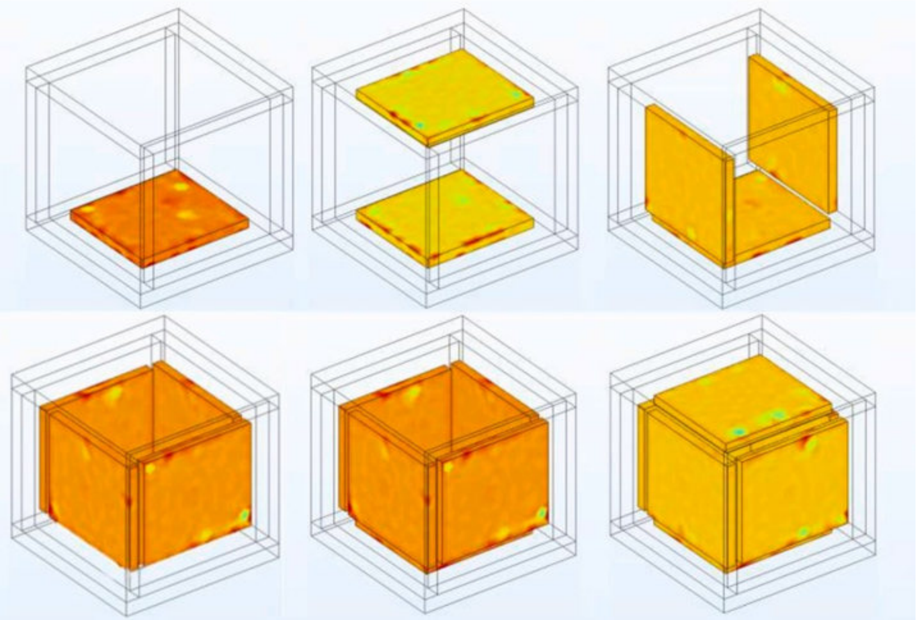


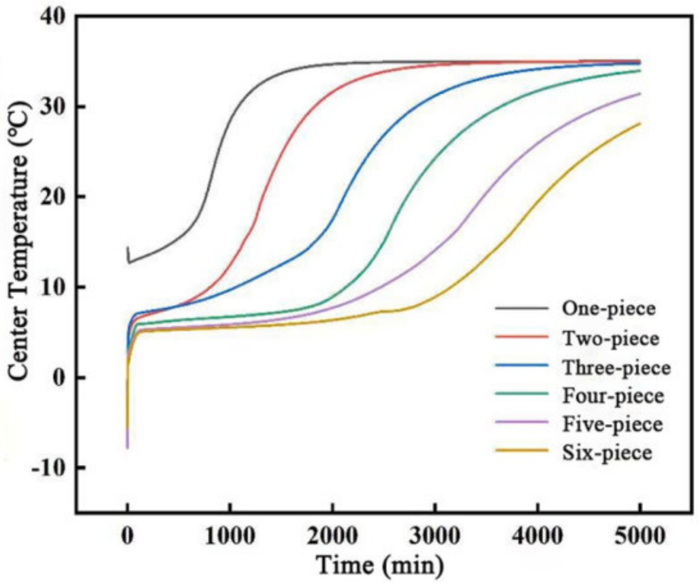
- Cold Chamber (PCM 4°C)
  Hot Chamber (Hot water 95°C)
- Regardless of whether the chamber, the vacuum insulation panel (VIP) should be placed on the outer side of the envelope.
- Positioning the VIP at the ambient side effectively reduces the amplitude of the external temperature wave before it penetrates into the chamber.





Free convection in cold chain applications



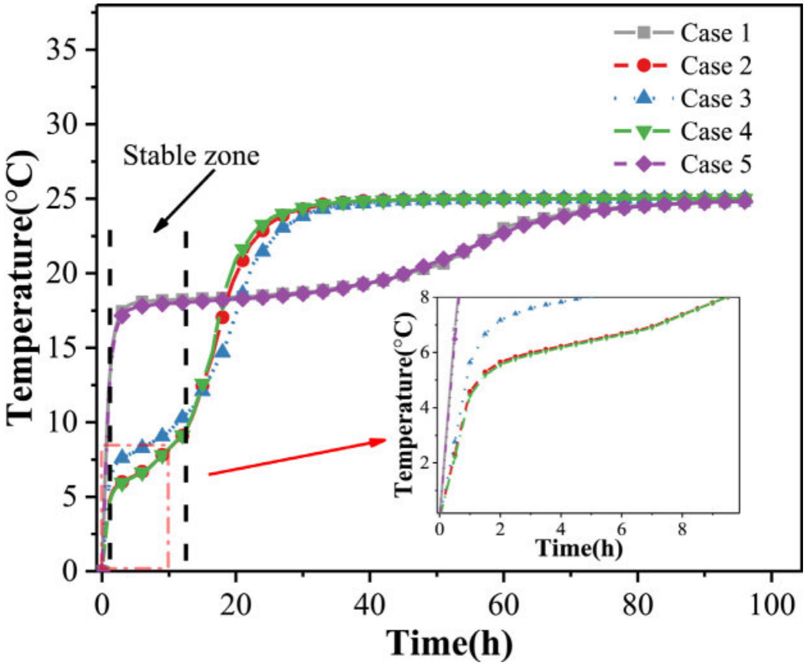


- Cooling duration of the box shortens with decreases in the number of PCMs.
- The top PCM has a greater impact on the effective cooling, reduced from 5 to 4, the effective cooling duration is decreased by 4.7h.

Table 7
Effective cooling duration of VIP refrigeration boxes with different numbers of PCM ice boxes.

Number of PCM ice box	Time as the center temperature reaches 2 °C (h)	Time as the center temperature reaches 8 °C (h)	Effective cooling duration (h)
6	0.30	50.40	50.10
5	0.05	37.02	36.97
4	0.15	32.37	32.22
3	0.03	9.70	9.67
2	0.03	9.01	8.98
1	0	0	0

Free convection in cold chain applications



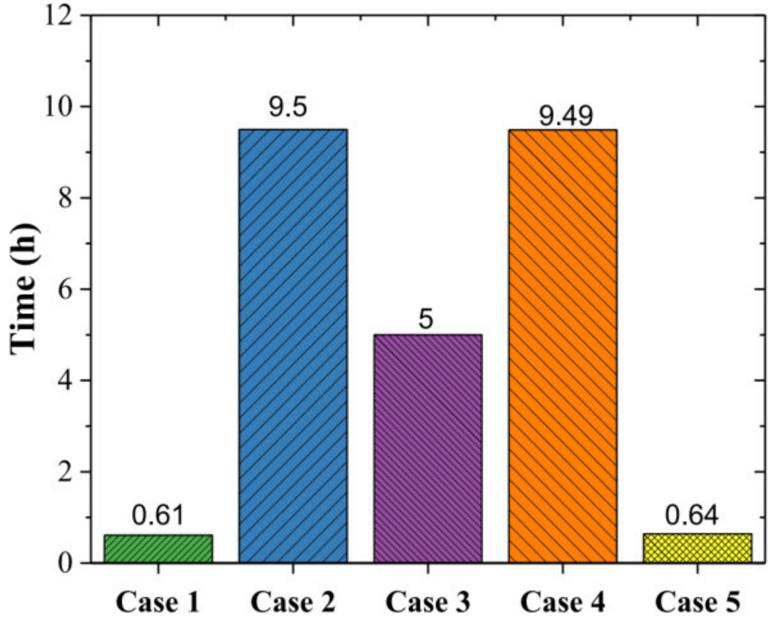


Fig. 6. Cooling duration of box with different locations of the plates.

- PU box
- Distributing PCM at the top and along the side walls (20% top + 20% each side) produced the longest cooling time, whereas placing PCM entirely at the top or bottom resulted in very short cooling durations (also no melting).
- The location with 20 % of the PCMs at the top of the box and 20 % of the PCMs on each side wall was an optimal arrangement.

Table 2.
Various distributions of the PCMs inside the box (mass fraction).

Configurations	Top	Side walls	Bottom
Case 1	100 %	0	0
Case 2	20 %	20 % × 4	0
Case 3	0	25 % × 4	0
Case 4	0	20 % × 4	20%
Case 5	0	0	100%

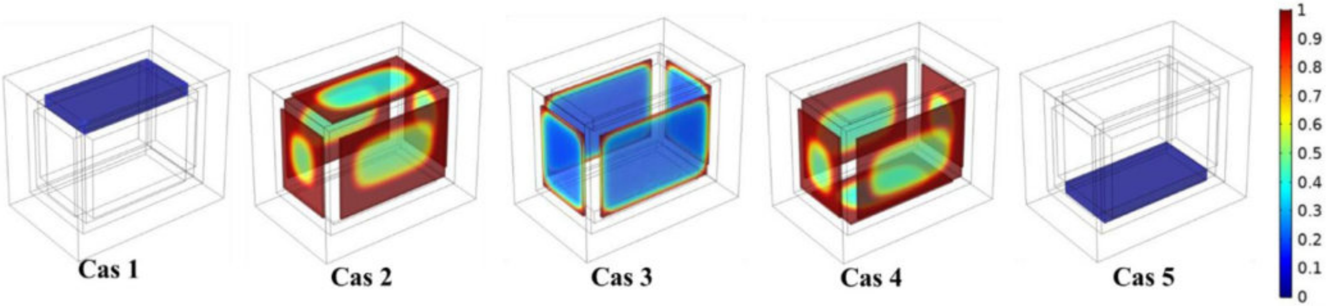


Fig. 9. Liquid fraction contours of the PCMs with different PCM arrangements when the central temperature reaches 8 °C.

Free convection in cold chain applications

Table 9
Time for the center temperature in refrigeration boxes with different materials to reach 2–8 °C.

Data Type	Materials	Rise to 4 °C time (h)	Rise to 6 °C time (h)	Rise to 8 °C time (h)	Effective duration (h)
Simulation	PU	2.2	13.55	18.55	17.19
	OCMPU VIPs	4.6	41.5	53.2	50
	FS VIPs	5.45	49.5	61.6	57.8
Experimental Testing	PU	1.83	11.28	15.15	14.12
	OCMPU VIPs	3.7	34.58	43.25	40.87
	FS VIPs	4.35	39.6	48.92	46.14

- The cooling efficiency of the OCMPU VIP box is 88 % of that of the FS (fumed silica) VIP box.
- The cooling duration of the PU box is only 14.12h, and the performance of the OCMPU VIP box is nearly 3 times that of the PU box.

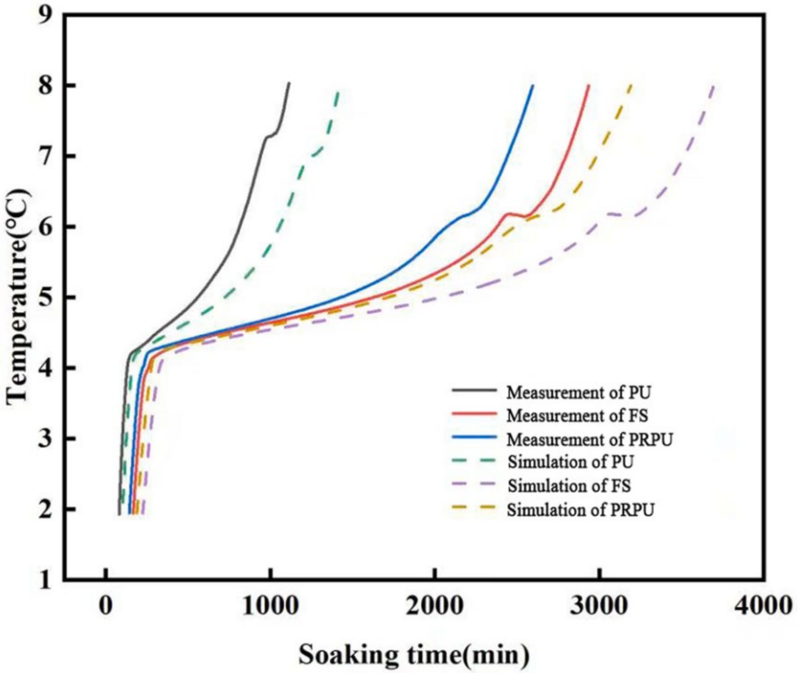
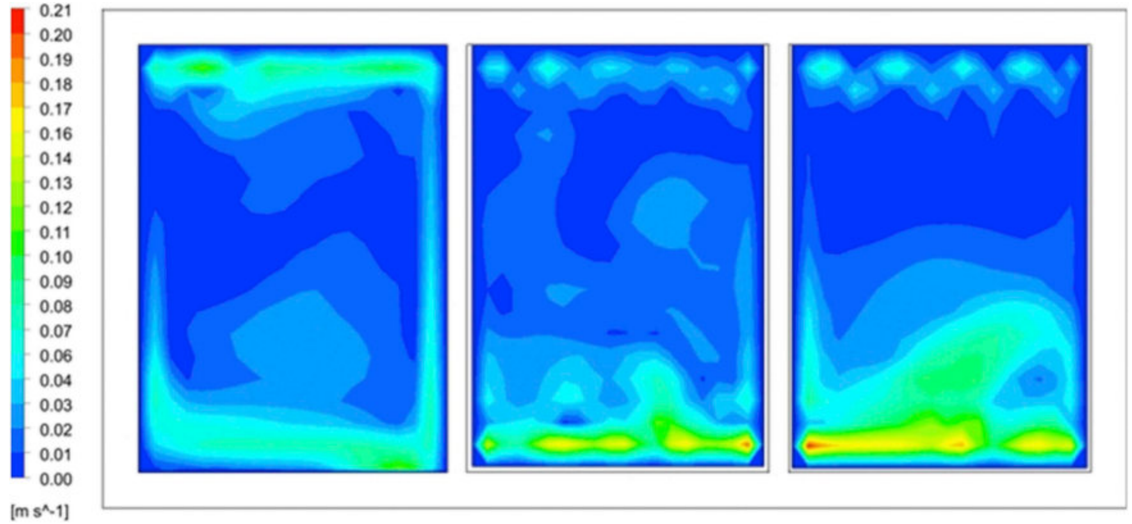
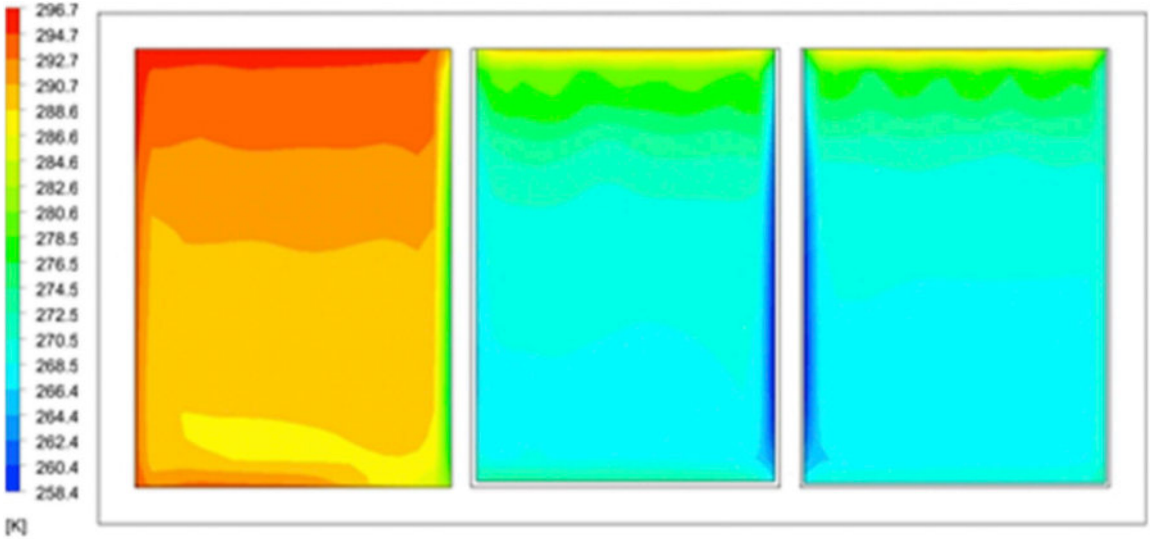
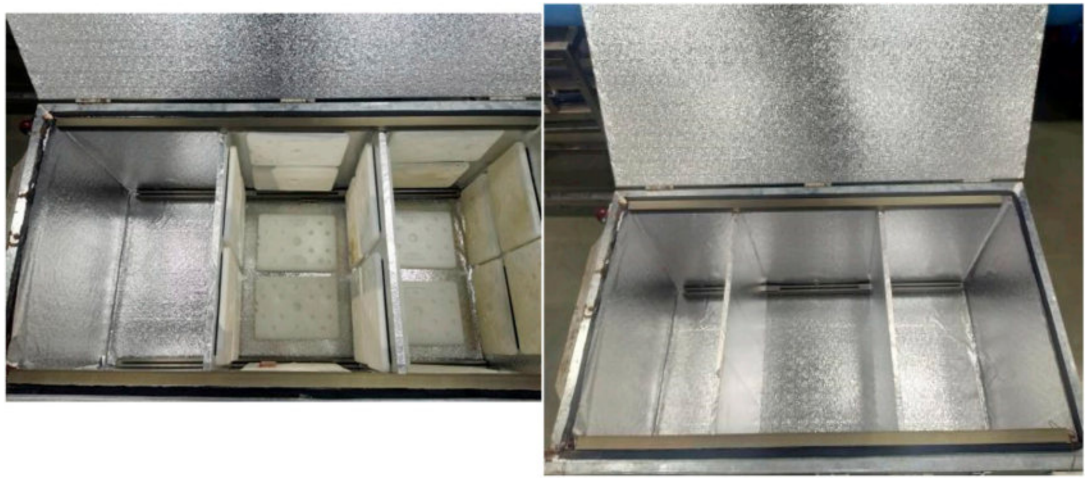


Fig. 26. Photographs of the three refrigeration boxes.
(a) PU refrigeration box (b) OCMPU VIP refrigeration box (c) FS VIP refrigeration box.

Free convection in cold chain applications







- The box was tested at an initial ambient temperature of about 25 °C with PCM plates pre-cooled to −20 °C and placed on the sidewalls and bottom of the refrigerated zones
- T2 (medium zone) was maintained at 7–9 °C for about 13 h during PCM1 phase change
- T3 (low zone) was maintained at −2 to 0 °C for about 14 h during PCM2 melting
- T1 (no PCM) stabilized at approximately 19 °C, slightly below ambient due to heat transfer from adjacent cooled zones

Thermal radiation

Linearized form of the rate equation

$$Q_{rad} = h_r A(T_s - T_{surr})$$

where

$$h_r = \varepsilon\sigma A(T_s - T_{surr})(T_s^2 - T_{surr}^2)$$

is radiation heat transfer coefficient, which is a linearization and useful when T_s and T_{surr} are not very different (ΔT~ 20-30 K).

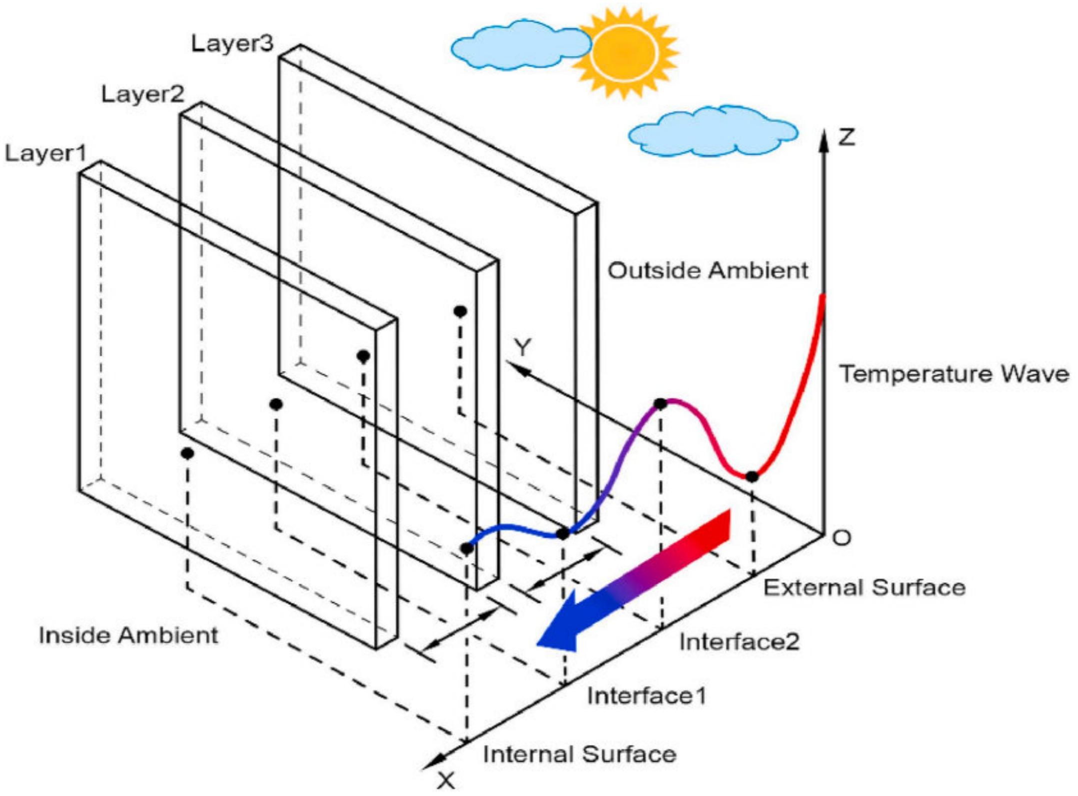
Emissivity (ε) is a surface property that measures how effectively a material emits (and absorbs) thermal radiation compared to a perfect blackbody.

$\varepsilon = 1$ perfect emitter (blackbody)

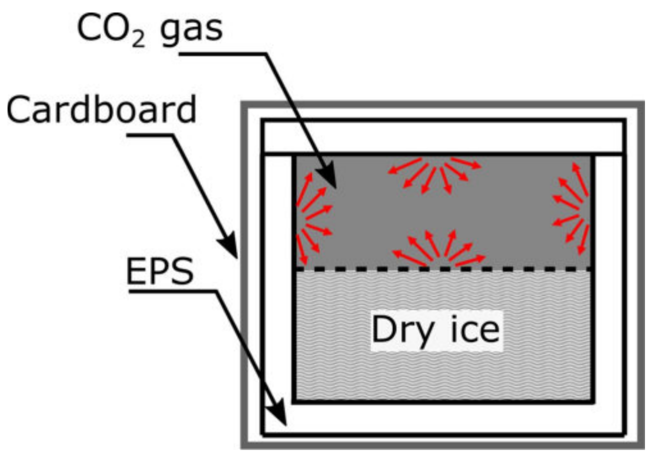
$\varepsilon = 0$ very poor emitter (highly reflective surface)

Note.

- Color relates to solar radiation absorption (shortwave, visible).
- Emissivity relates to thermal radiation emission (longwave, infrared).
- A white wall (ε = 0.85-0.95) and black (ε = 0.90-0.95) wall at the same temperature emit almost the same longwave radiation.



The role of aluminum foil in insulated boxes



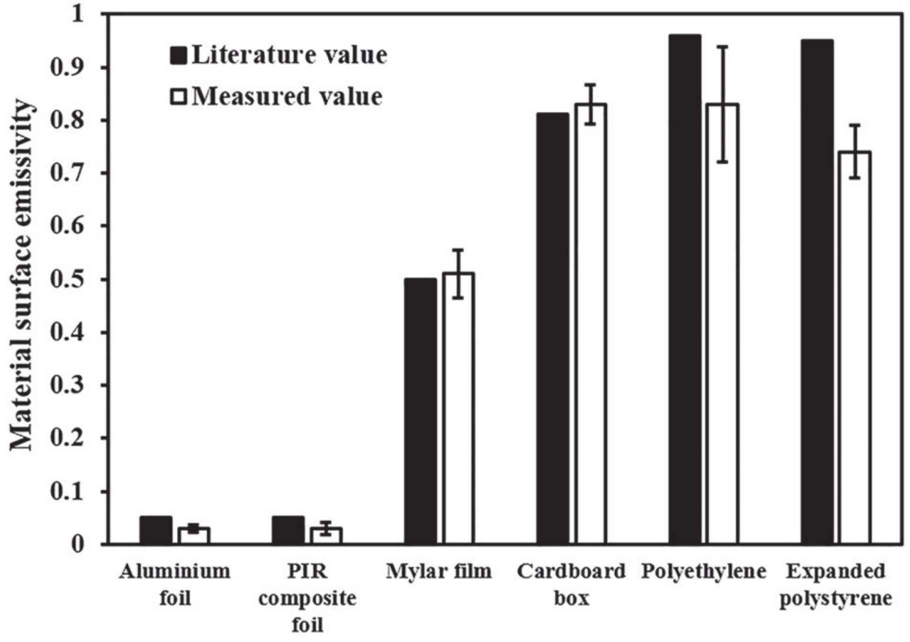


Table 1.8. Emissivity of Some Technical Materials at Low Temperature

	Radiation From 290K Surface at 77K	Radiation From 77K Surface at 4.2K
Stainless steel, as found	0.34	0.12
Stainless steel, mesh polished	01.2	0.07
Stainless, electropolished	0.10	0.07
Stainless steelplusaluminum foil	0.05	0.01
Aluminum, black anodized	0.95	0.75
Aluminum, as found	0.12	0.07
Aluminum, mesh polished	0.10	0.06
Aluminum, electropolished	0.08	0.04
Copper, as found	0.12	0.06
Copper, mesh polished	0.06	0.02

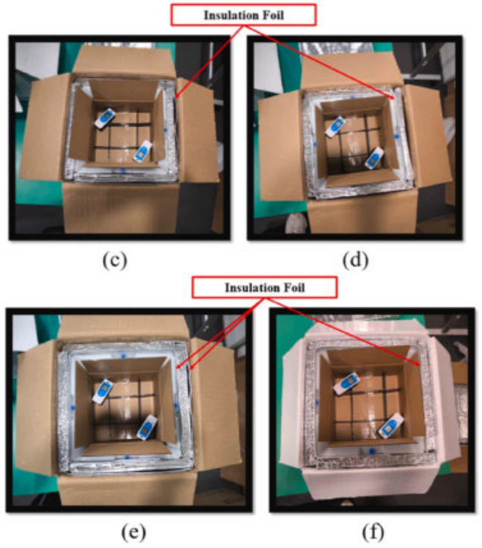
Table 4. Emissivity values in the literature for various materials.

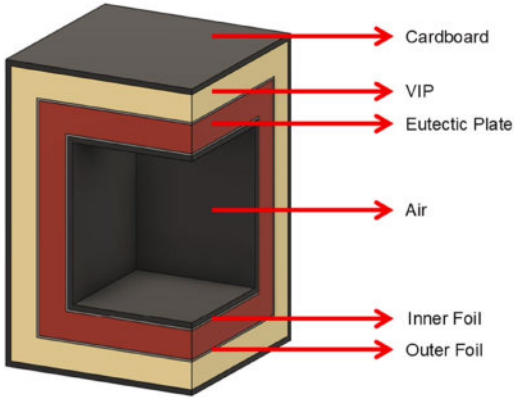
Items	This study	OMEGA [23]	MIKRON [24]	Engineering toolbook [25]	Thermoworks [26]
Source					
Black plastics	0.93646	0.93	0.95	0.90–0.97	0.94
Polyethylene plate	0.94164		0.95	0.92–0.98	0.97
Red brick	0.94408	0.93	0.93	0.93	0.90
Paper	0.80363	0.93	0.94	0.55 (any color)	0.68–0.93
Cotton cloth	0.80237	0.77–0.78		0.77	
Wood	0.90227	0.8–0.9	0.89	0.885–0.935	0.90
Glass	0.91129	0.91–0.93	0.95	0.92–0.94	0.92

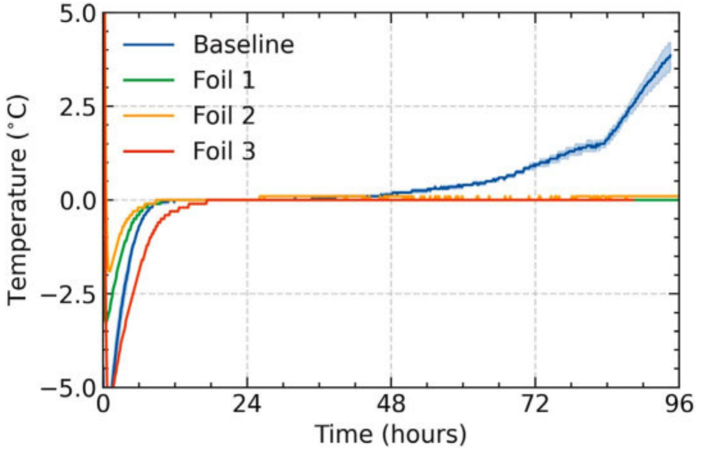
Table 3. Surface emissivities

Material	Emissivity (ε)
Aluminum	0.05
Copper	0.03
EPS foam	0.95
Ice	0.96
Paper	0.95
Plastic	0.95
Wood	0.65–0.95

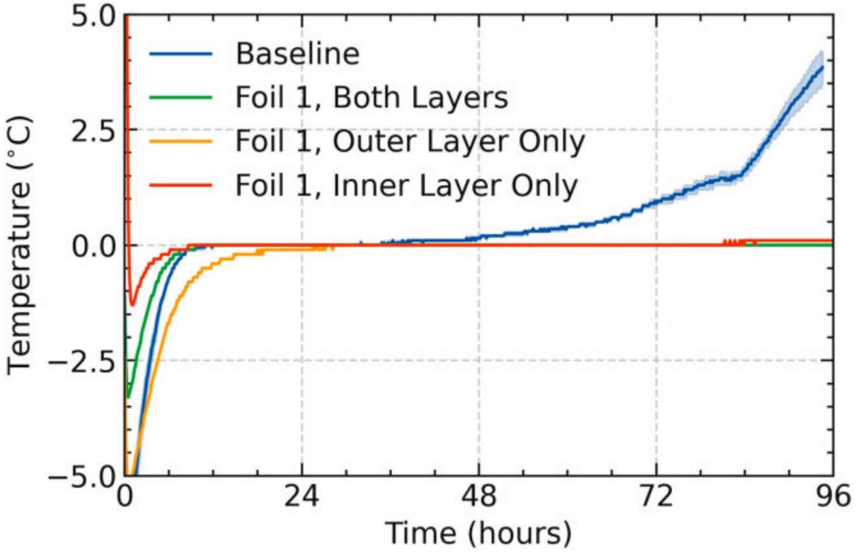
The role of aluminum foil in insulated boxes







Foil Type	Thickness	Thermal Conductivity (W/m-K)	Emissivity
Foil 1	3mm	0.001–0.005	0.05
Foil 2	3mm	0.01	0.12
Foil 3	3mm	0.001–0.005	0.08



- Insulation foils improve temperature stability primarily by reducing radiative heat transfer due to their low emissivity surface.
- Lower emissivity is more important than small differences in conductivity.
- Dual-layer aluminum foil insulation reduces heat gain by 57 % in eutectic cold boxes.
- The inner-layer placement is most effective because it directly limits radiation heat exchange with the eutectic plate, slowing PCM melting.
- Adding a second foil layer yields diminishing thermal benefit relative to cost.

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End

Thank you for your attention