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New Food Technologies and Packaging for Safety and Sustainability

Food Safety – Smart Solutions – Environmental Impact

Workshop on Innovative Food Product Development

Artemis Mastrotheodoraki, Chemist, Msc, PhD Candidate

July 2025

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Main Objectives

By the end of this module, students will be able to:

✅ Understand the principles and classification of novel food processing technologies
✅ Describe how non-thermal technologies improve food safety
✅ Identify examples of industrial applications and case studies
✅ Distinguish between active and intelligent packaging systems
✅ Evaluate new materials for sustainable food packaging (recycled, biodegradable, edible)
✅ Recognize relevant EU legislation and safety criteria for food technologies and materials

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Why Innovation in Food Technologies and Packaging Matters

Foodborne diseases remain a **global** concern, affecting 600 million people annually (WHO, 2020)

Modern consumers demand minimally processed, fresh-like, and clean-label foods (Asioli et al., 2017 – Trends in Food Science & Technology)

Thermal treatments **degrade nutritional and sensory quality**, leading to the development of non-thermal alternatives (Barba et al., 2018 – Food Research International)

Food **packaging** waste represents 36% of total **plastic waste** in the EU (European Parliament, 2023)

Smart packaging technologies can **monitor freshness and safety in real time**, enhancing supply chain transparency (Realini & Marcos, 2014 – Meat Science)

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From Heat to Innovation: Thermal vs Non-Thermal Food Processing

Aspect	Thermal Processing	Non-Thermal Technologies
Mechanism	Application of heat (e.g. pasteurization, sterilization)	Physical forces (pressure, electric fields, plasma,
Microbial Inactivation	Denatures proteins and enzymes, effective against bacteria/spores	Disrupts cell membranes or intracellular functions; effective mainly against vegetative cells
Nutrient Retention	Often degraded (e.g. vitamin C, B1, folates)	Better preservation of heat-sensitive nutrients
Sensory Quality	Alters flavor, color, texture (e.g. cooked taste, browning)	Maintains fresh-like appearance and sensory attributes
Energy Requirements	High energy input required for heating and holding phases	Generally lower energy input per unit of product processed (e.g. PEF, CAP)
Consumer Perception	Viewed as "processed" or "industrial"	Perceived as mild, "clean-label", more natural

Barba et al., 2017 Trends in Food Science & Technology

How Non-Thermal Food Technologies Work: Mechanisms of Action

Based on Type of Energy or Physical Force

- **Pressure-Based Technologies**
  - **High Hydrostatic Pressure (HHP)**
    Isostatic pressure leads to protein/enzyme denaturation and cell membrane rupture
    (*Patterson et al., 2018, World Journal of Microbiology and Biotechnology*)
- **Electrical-Based Technologies**
  - **Pulsed Electric Field (PEF)**
    Electroporation: Nanopores are formed in microbial membranes, causing leakage of cell contents
    (*Toepfl et al., 2006, Chemical Engineering and Processing*)
  - **Cold Atmospheric Plasma (CAP)**
    Reactive oxygen/nitrogen species cause oxidative damage to DNA, lipids, and proteins
    (Pankaj et al., 2018, Foods)
- **Acoustic-Based Technologies**
  - **Ultrasound (US)**
    Acoustic cavitation generates shear forces and local turbulence that disrupt microbial cells
    (*Chemat et al., 2011, Ultrasonics Sonochemistry*)
  - **Hydrodynamic Cavitation (HC)**
    Collapse of vapor bubbles creates shockwaves and shear forces that damage cell structures
    (*Chemat et al., 2017, Innovative Food Science & Emerging Technologies*)

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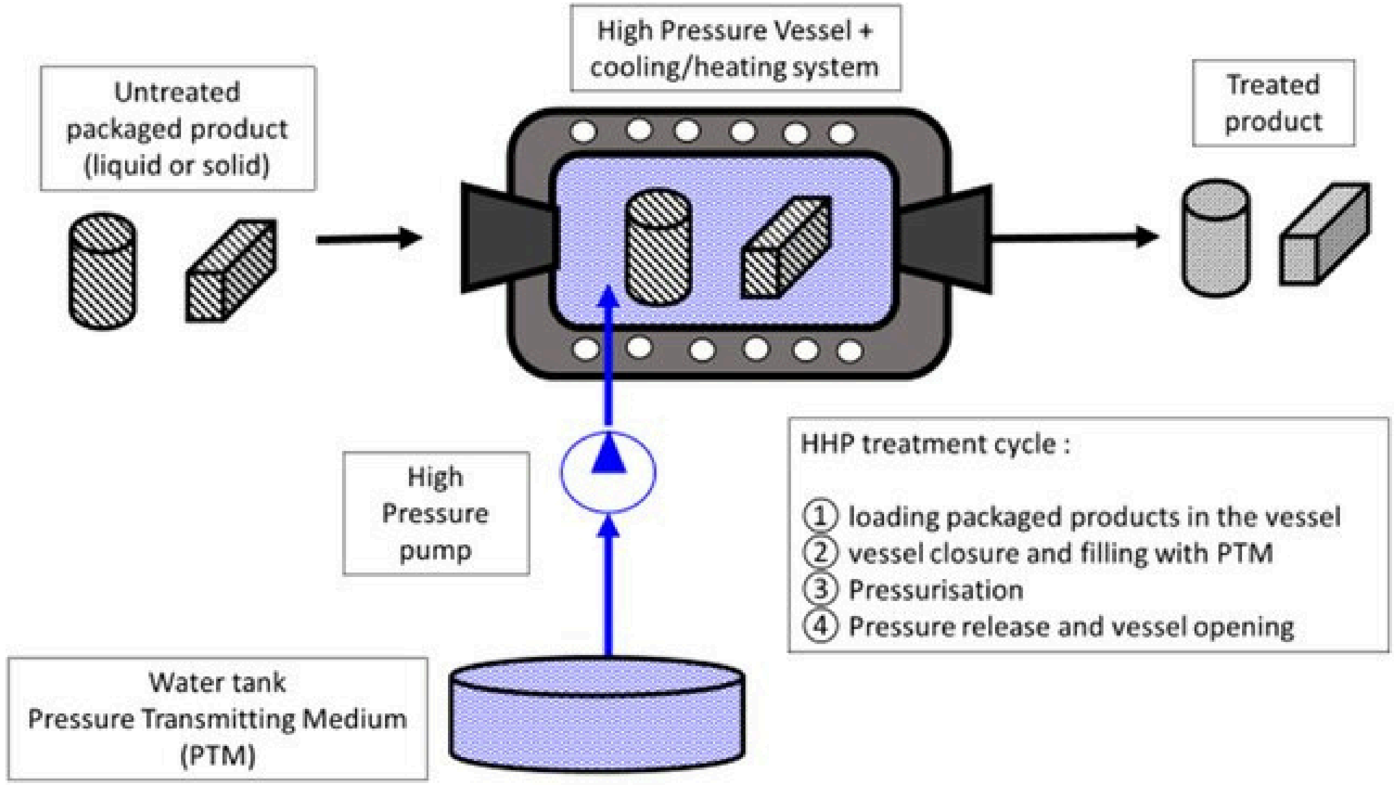
High Hydrostatic Pressure (HHP): Principles and Risks

🧪 What is HHP?

- Immersion of **packaged** food in water under 100–1000 MPa pressure
- Common industrial settings: **200–600 MPa, 20–60 °C, <5 min**
- Uniform (**isostatic**) pressure – affects all surfaces equally



Schematic layout of a High Hydrostatic Pressure (HHP) treatment (pilot-scale unit), adapted from Tappi et al., 2019.

🎯 Main Objectives

- Kill **pathogens** (bacteria, viruses, parasites)
- Extend **shelf life** by inactivating microbes & enzymes
- **Modify** food matrix (e.g. cold cooking)

⚠️ Risks & Considerations

- **Survival** of some **pathogens/spoilage microbes**
- **Risk** of **undesired** chemical reactions
- **Possibility** of increased **allergenicity**
- **Depends** on **pressure–temperature–time** conditions

Aganovic et al., 2021, Comp. Rev. Food Sci. Food Saf.

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Effects of HHP on Food Chemistry

🧪 Chemical Effects of HHP

- **Direct & indirect** impact on food ingredients and chemical reactions
- ↓ **Thermal contaminants**: Acrylamide, Furan
- **Suppressed reaction rates** under pressure
- **No new** or **unexpected** toxic compounds formed

Aganovic et al., 2021, Comp. Rev. Food Sci. Food Saf.

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Examples of HHP Applications in Food:

Fruit & Vegetable Products

- Fresh juices (e.g., orange, apple, pomegranate
- Guacamole, tomato salsa, fruit purees
- Maintains fresh taste, color, and nutrients

Meat Products

- Ready-to-eat dell meats (e.g., ham, turkey breast)
- Extends shelf life & inactivates *Listeria monocytogenes*
- Used in vacuum-packed sausages or cooked meats

Seafood

- Oysters and mussels - facilitates shucking & improves microbial safety
- Smoked salmon - improves shelf life & sensory quality

Dairy

- Yogurt, cheese - enhanced safety & textural modifications
- Can be used to inactivate spollage microbes without heat damage

Ready Meals

- Packaged meals like soups, rice dishes- safe without altering flavor
- Ensures microbial safety while preserving taste & texture

Journal of Agroalimentary Processes and Technologies, 22(3), 146–154.

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Pulsed Electric Field (PEF)

🔬 Core Principle

- Non-thermal food processing using **high-voltage** pulses (0.5–100 kV/cm)
- **Pulse** duration: microseconds to nanoseconds
- Induces **electroporation** → pores form in cell membranes
- Used for **microbial inactivation, extraction, and tissue softening**

✅ Advantages

- Preserves **nutritional & sensory quality**
- Allows **aseptic** filling of liquids
- Effective pre-treatment for **drying, pressing, dehydration**
- **Energy-efficient & rapid** compared to thermal methods

🧬 Mechanism of Action

- **Electroporation stages**:
  Increase in transmembrane potential
  Formation of hydrophilic pores
  Leakage of intracellular compounds
  Pore shrinkage or collapse
- **High-intensity PEF** → irreversible cell damage → cell lysis
- Enhances **heat & mass transfer** and compound **extraction**

Adapted from Zhou et al., 2023. Trends in Food Science & Technology

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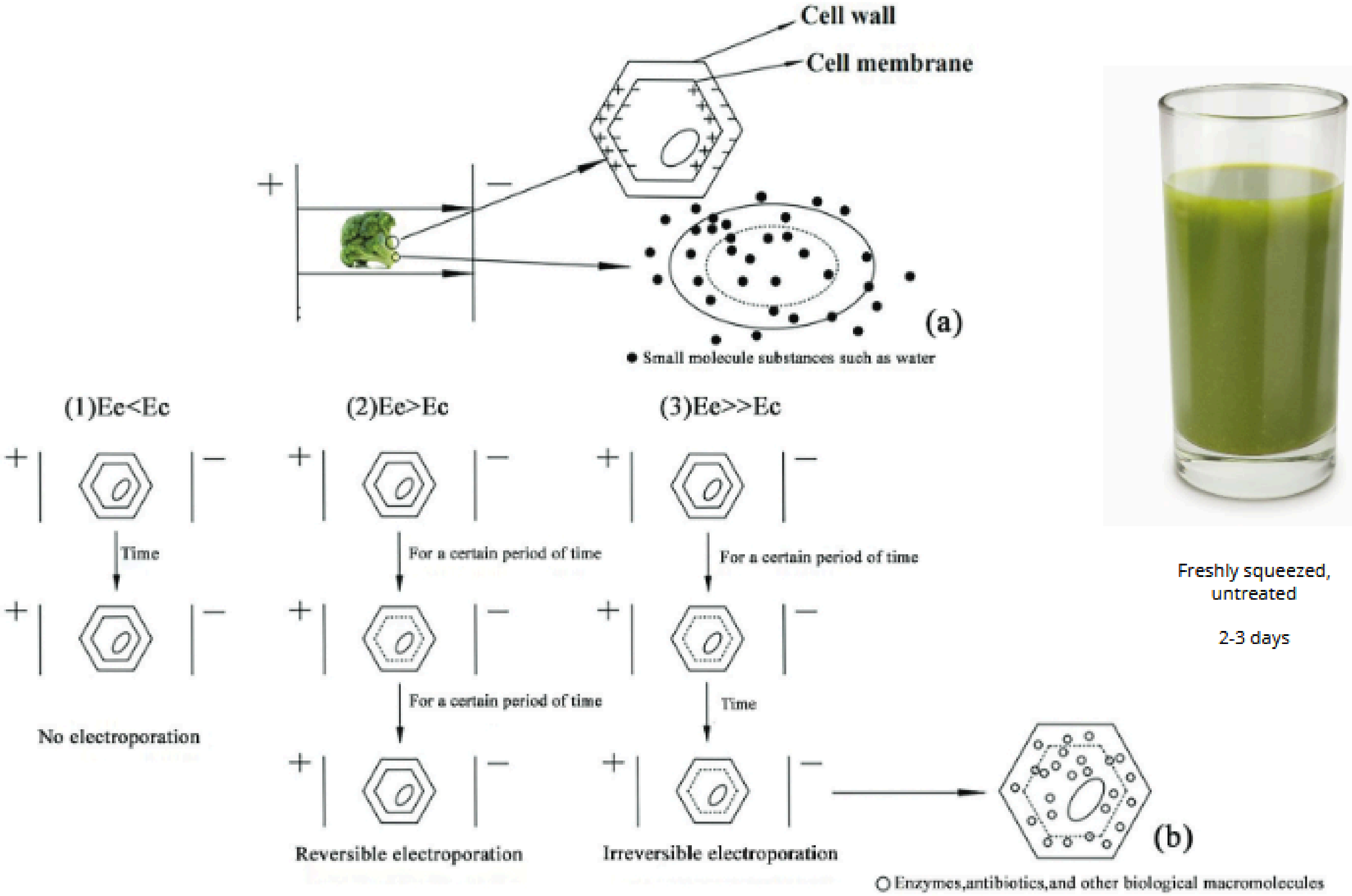
Pulsed Electric Field (PEF): Mechanism of Action and Applications



Adapted from Zhou et al., 2023. Trends in Food Science & Technology

Freshly squeezed, untreated	Thermally treated	elea PEF treated with PEF Advantage™ Pipe
2-3 days	3-4 weeks	Approx. 3 weeks and more

Benefits of Pulsed Electric Field processing for food industry, Elea, Stefan Toeplf

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Pulsed Electric Field (PEF): Applications

Examples of PEF Applications in the Food Industry

Fruit & Vegetable Processing

- Juice yield improvement (e.g., orange, carrot, tomato)
- Drying acceleration in vegetables

Liquid Foods

- Microbial inactivation in juices and milk
- Commercialized for orange juice, apple juice, milk alternatives

Potato Processing

- Reduction of cutting force and oil uptake during frying (French fries)

Extraction Processes

- Enhanced extraction of bioactive compounds

Meat Products

- Tenderization of meat cuts

Adapted from Puértolas & de Marañón, 2012, Food Chemistry; Zhou & Wang, 2016, Innovative Food Science & Emerging Technologies; Barba et al., 2015, Food Research International; Zhao et al., 2020, Journal of Food Process Engineering; Toepfl et al., 2006, Food Reviews International.

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Cold Atmospheric Plasma (CAP): Principles & Advantages

🔬 What is Plasma?

- Considered the **4th state of matter** (after solid, liquid, gas)
- Composed of i**ons, electrons, radicals, UV photons, and excited molecules**
- Exists **naturally** and can be **man-made**

✅ Advantages

- Works at **atmospheric** pressure
- Uses ambient air as working gas (**cost-effective**)
- **Compatible** with existing production lines
- **Safe** for **heat-sensitive** materials
- (surface temp < 50 °C)
- **Short treatment time** (seconds to minutes)
- Highly **scalable** and flexible system design

⚙️ Generation of Cold Plasma

- Created by applying **electric** energy (RF, MW, AC, or DC) to a gas
- **Common gases:** air, O_2, N_2, He, Ar, or mixtures
- **Typical methods:**
  Dielectric Barrier Discharge (DBD)
  Plasma Jet
  Corona Discharge
  Gliding Arc

Adapted from: Misra et al., Appl. Sci. 2021, 11, 4809

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Cold Atmospheric Plasma (CAP): Applications

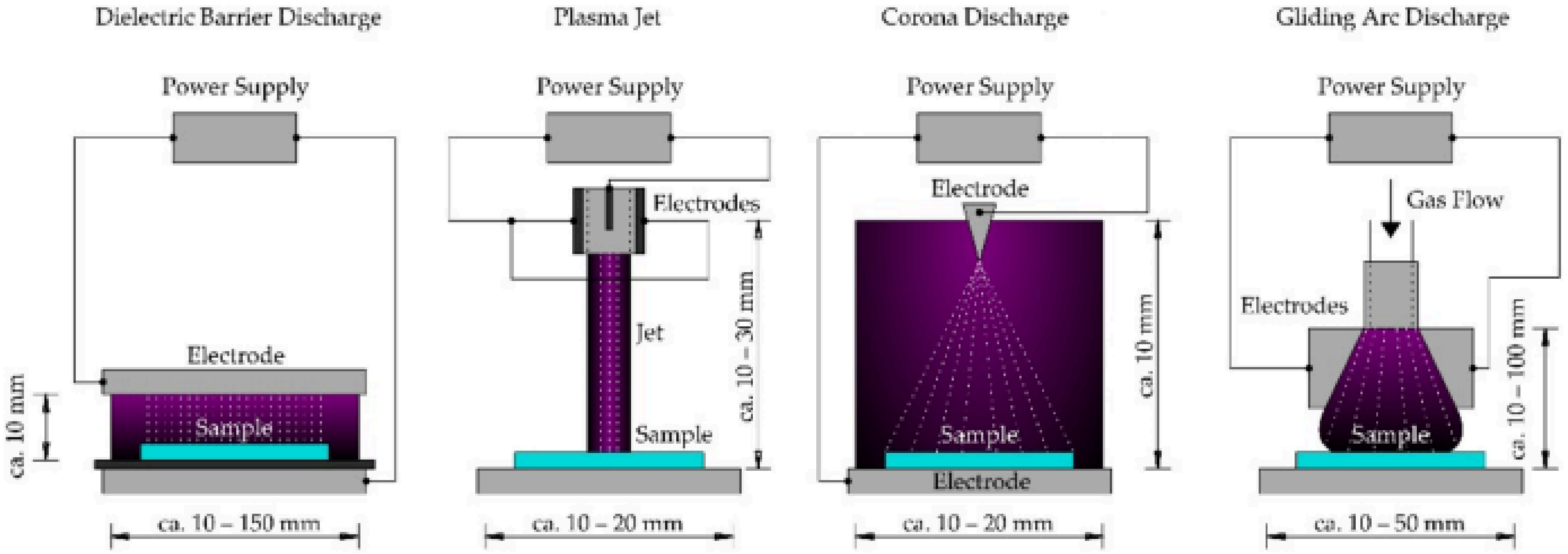

Figure 1. Schematic drawing of diverse cold atmospheric pressure plasma devices.

Adapted from: Misra et al., Appl. Sci. 2021, 11, 4809

Physicochemical properties of brown rice according to the characteristics of cultivars treated with CAP

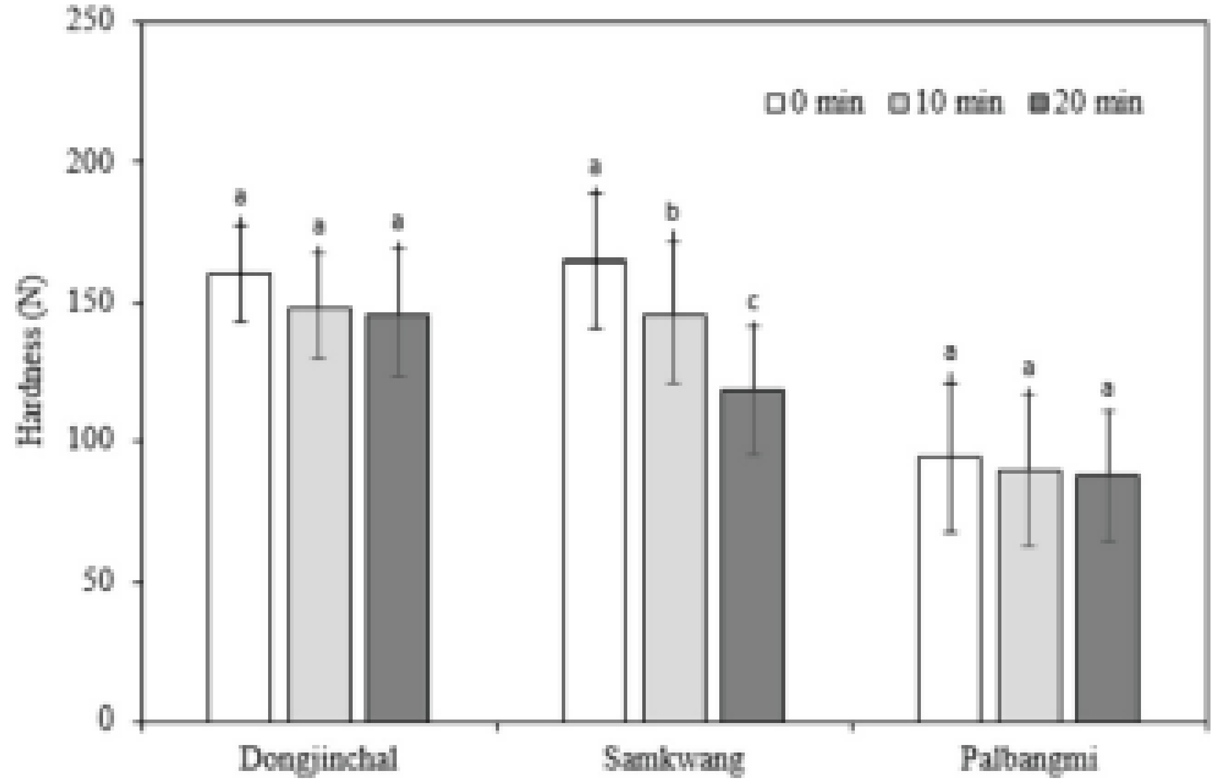

Fig. 2. Hardness (N) of brown rice according to characteristics of cultivars

Adapted from: Misra et al., Trends Food Sci. Technol., 2019, 89, 47–58

Food Chemistry 316 (2020) 126372
Contents lists available at ScienceDirect
Food Chemistry
journal homepage: www.elsevier.com/locate/foodchem
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Efficacy of low pressure DBD plasma in the reduction of T-2 and HT-2 toxin in oat flour

Maja Kiš[a,*], Slobodan Milošević[b], Ana Vulić[d], Zoran Herceg[c], Tomislava Vukušić[c], Jelka Pleadin[d]

Meat Science 159 (2020) 107942
Contents lists available at ScienceDirect
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In-package decontamination of chicken breast using cold plasma technology: Microbial, quality and storage studies

Rkia Moutiq[a], N.N. Misra[b,c,*], Aubrey Mendonça[a,b], Kevin Keener[a,b]
[a] Department of Food Science and Human Nutrition, Iowa State University, Ames, IA, USA
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ΕΡΓΑΣΤΗΡΙΟ ΧΗΜΕΙΑΣ
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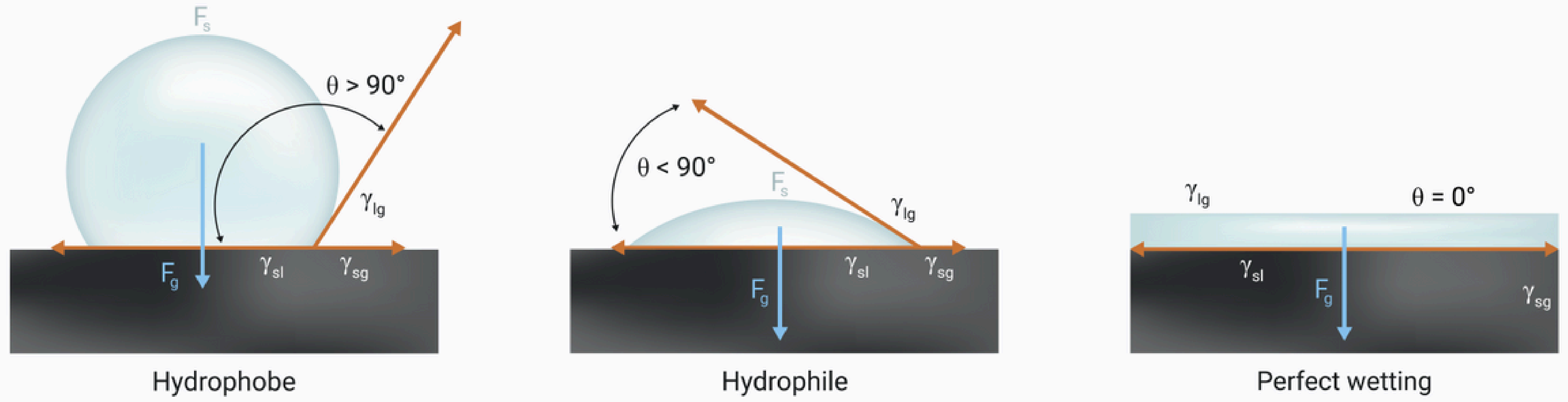
Cold Atmospheric Plasma (CAP): Applications

Effect 1 – Stable Hydrophobic Surface Formation
Cold plasma treatment has been used to fabricate hydrophobic and superhydrophobic surfaces; the hydrophobic surface remains stable without hydrophilic recovery 30 days after treatment

Effect 2 – Mechanism: Increased Hydrophobic Functional Groups
Increase in hydrophobic groups is known to increase the surface hydrophobicity of polymers and biopolymer films after cold plasma treatment

Diagram illustrating the balance of interfacial tensions that define the water contact angle (θ) on a surface. CAP treatment alters surface energy and chemistry, increasing θ and resulting in hydrophobic or superhydrophobic behavior.



What CAP Does
Cold Atmospheric Plasma (CAP) modifies the surface energy by:

- Introducing non-polar groups (e.g. $-CH_3$, $-CF_3$)
- Etching surface topography, increasing roughness
- Increases the contact angle θ

As a result, treated surfaces become hydrophobic (θ > 90°) or even superhydrophobic (θ > 150°).

Adapted from Dimitrakellis & Gogolides, 2018, Adv. Colloid Interface Sci.; Gao et al., 2025, Comprehensive Review on Biopolymer Surface Modification.

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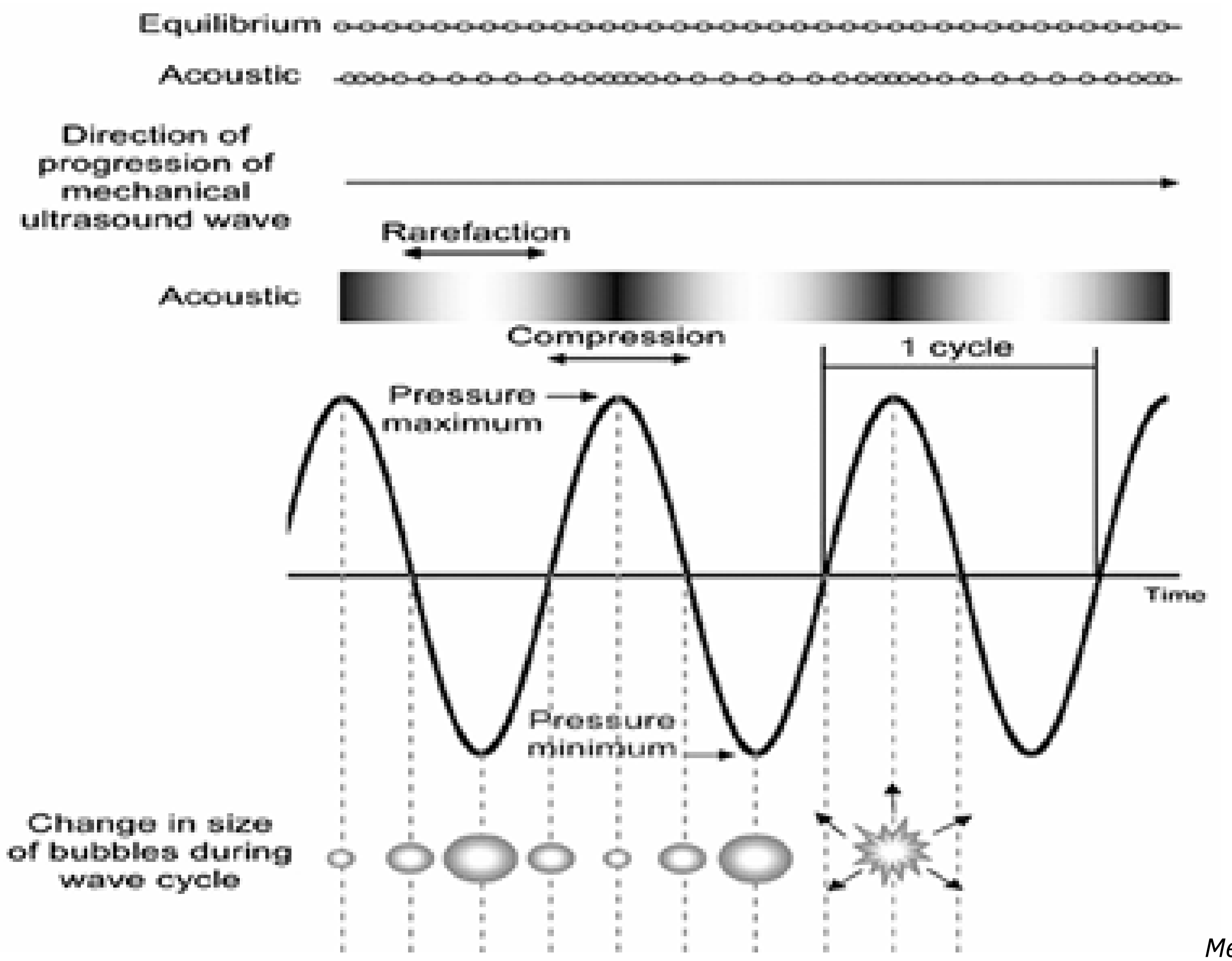
Ultrasound (US): Principle and Mechanism of Action

🔬 Core Principle

- Sound waves with **frequencies** above the human hearing range (typically **>20 kHz**).
- In food processing, **low-frequency (20–100 kHz)** and **high-power (10–1000 W/cm²)** ultrasound is used



Primary mechanism is acoustic cavitation

- **Formation, growth, and violent collapse of microbubbles** in a liquid medium.
- This collapse generates localized **high temperature (~5000 K) and pressure (~1000 atm)**, producing intense shear forces.
- These effects lead to **mechanical, thermal, and chemical changes** in the food matrix.

Ultrasound Enhancements

✅ Improves **mass transfer, cell disruption, mixing, emulsification**
✅ Aids in **extraction, crystallization, drying, and freezing**
✅ Works as a **stand-alone or in combination** (e.g., thermosonication)
✅ A **green**, non-thermal method: low energy use, preserves nutrients

Adapted from:
Chemat, F., Rombaut, N., Sicaire, A. G., Meullemiestre, A., Fabiano-Tixier, A. S., & Abert-Vian, M. (2017). Ultrasound assisted extraction of food and natural products. Mechanisms, techniques, combinations, protocols and applications. A review. Ultrasonics Sonochemistry, 34, 540–560. https://doi.org/10.1016/j.ultsonch.2016.06.035
Adapted from: Ultrasound and Food Technology: A Review, ScienceDirect, 2019. https://doi.org/10.1016/j.ultras.2019.02.008

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Ultrasound (US): Applications

Decontamination of maize using US treatment

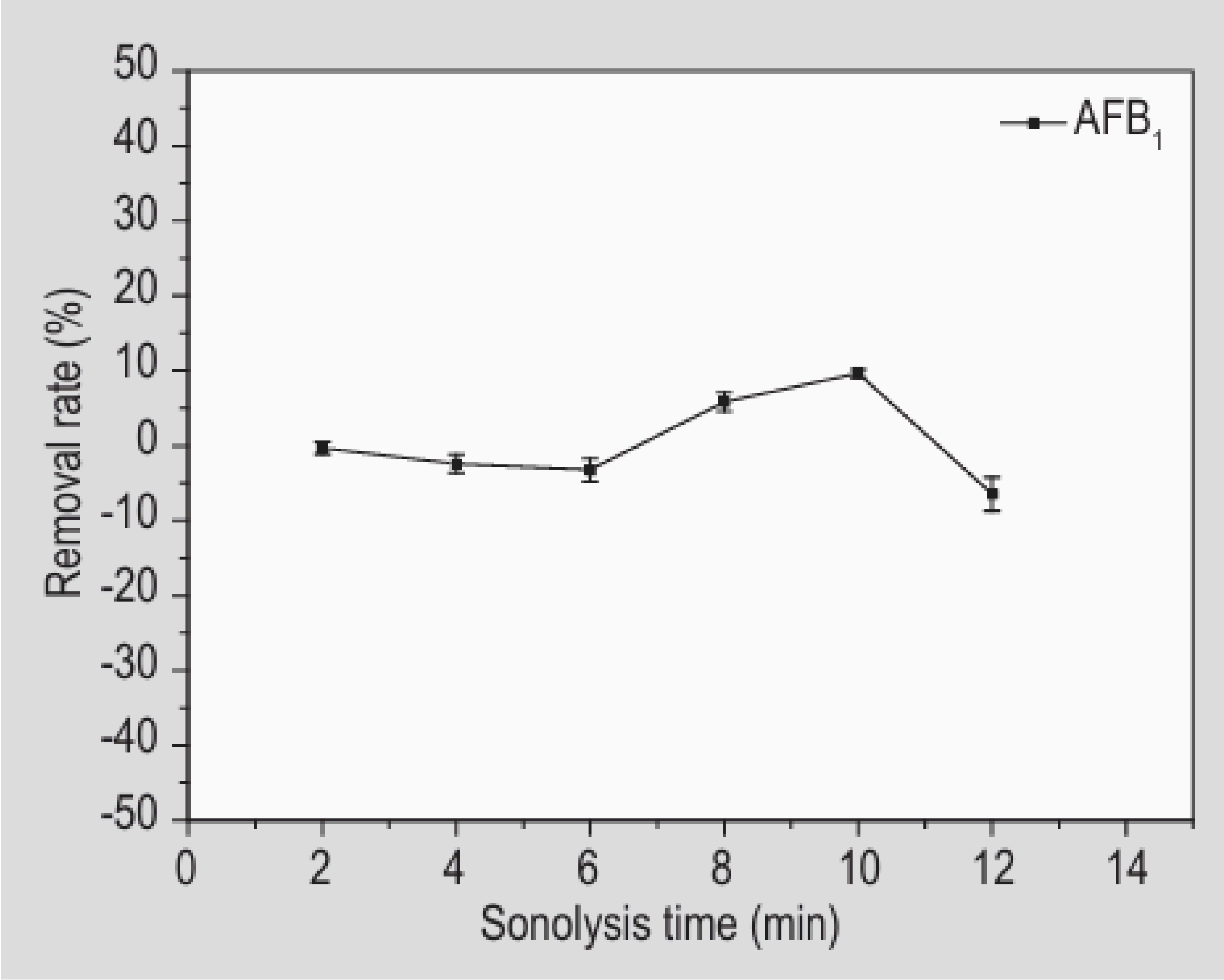

Figure 5. Influence of sonolysis time on the degradation of aflatoxin B_1 in maize.

Adapted from: Liu, Y., Yang, Y., Chen, Y., & Ye, X. (2019). Ultrasound for microcystins degradation: A review. World Mycotoxin Journal, 12(2), 149–161

Ultrasound Treatment Preserves More Ascorbic Acid Than Thermal Processing in Juices

P. Khandpur, P.R. Gogate / Ultrasonics Sonochemistry 27 (2015) 125–136 131

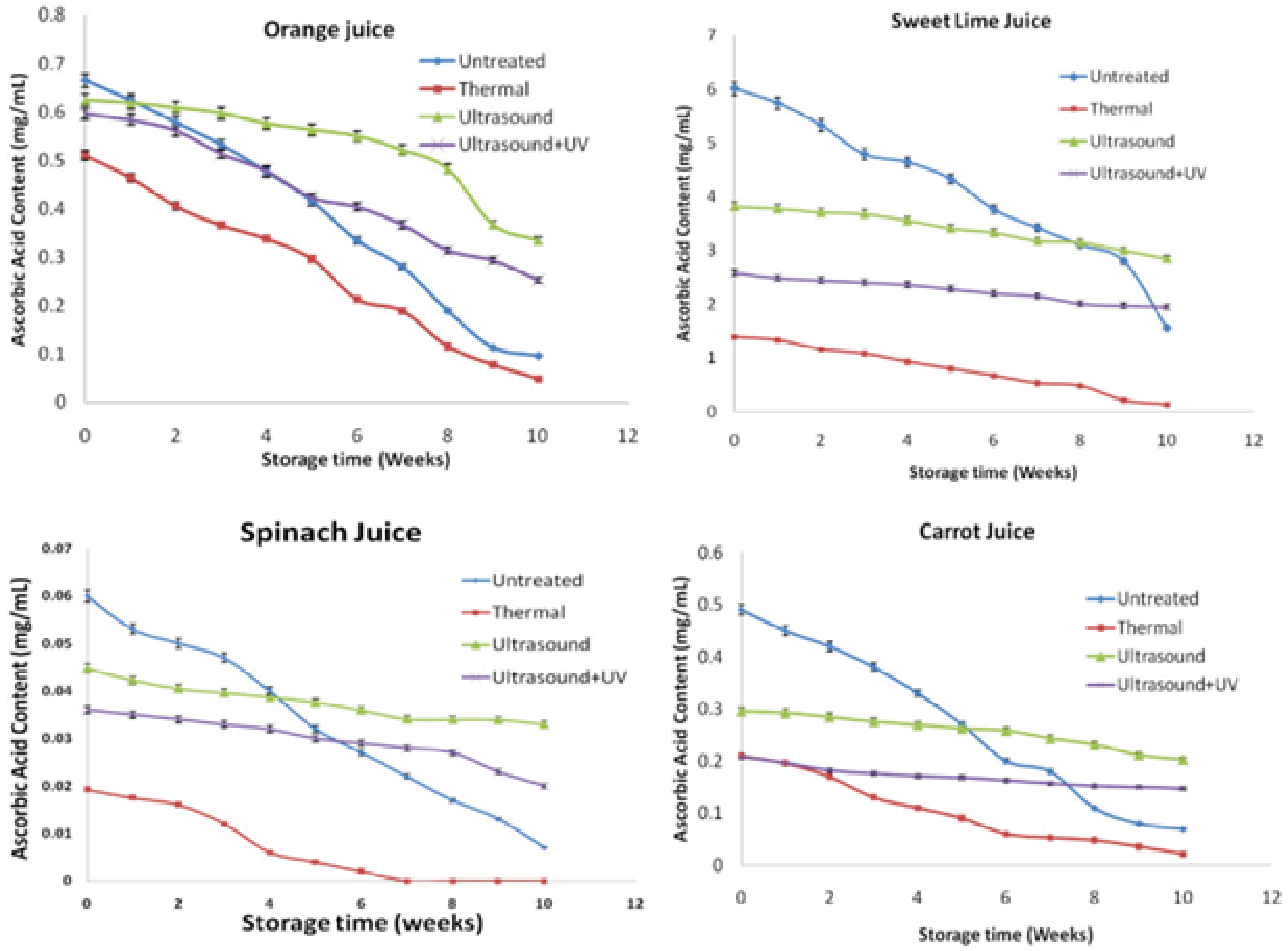

Fig. 1. Changes in ascorbic acid content of juices treated with different methods during storage at 4 °C for 10 weeks (ultrasound parameters: ultrasonic horn with frequency of 20 kHz, power dissipation of 100 W, duty cycle as 50% and treatment time of 15 min; UV parameters: 2 UV lamps of 8 W each).

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Ultrasound (US): Applications

Ultrasound-Assisted Emulsification of Oil–Water Mixtures

- Ultrasound reduces droplet size through cavitation-induced shear, forming stable **emulsions** without surfactants.
- Resulting emulsions show **fine** droplet size distribution and remain stable (no phase separation) for ≥30 days.

https://www.youtube.com/watch?v=v8qHKwiBvhI&ab_channel=HielscherUltrasonics

Adapted from Li & Xiang, 2019, PLOS ONE; Kobayashi et al., 2015, Physics Procedia

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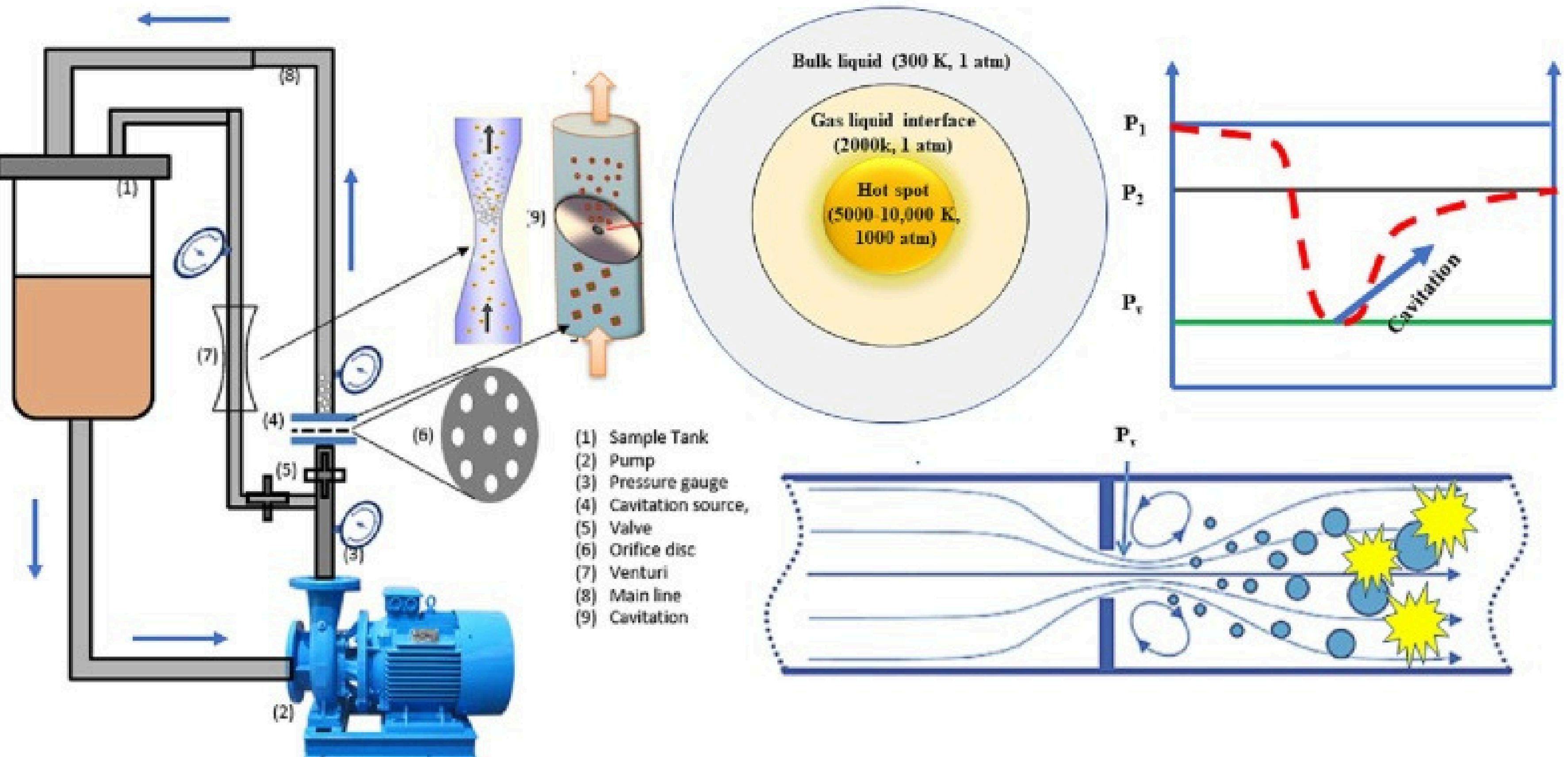
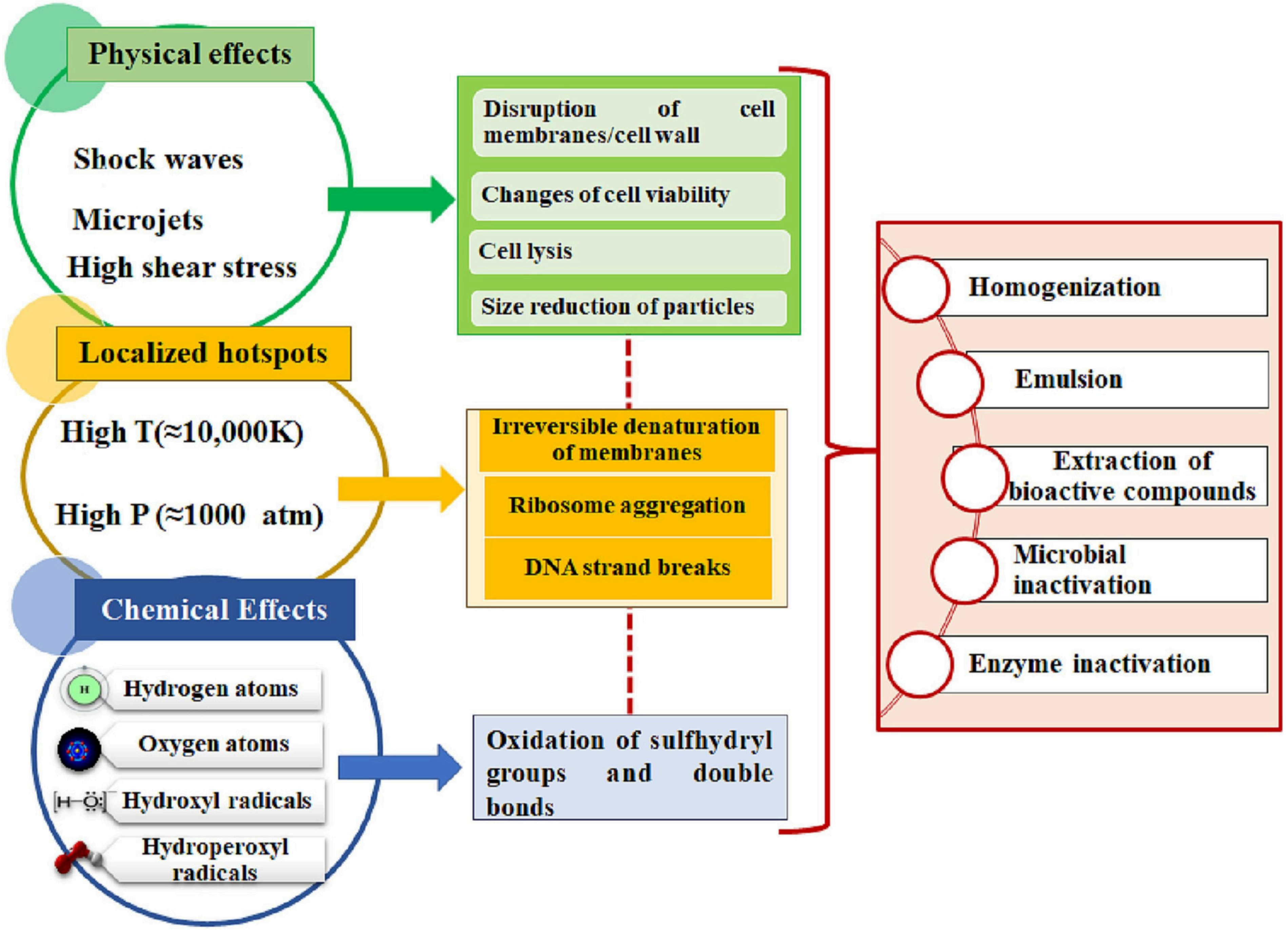
Hydrodynamic cavitation (HC): Principle

✅ Basic Principle

- HC is a phenomenon where vapor **bubbles** form and **collapse** violently in a liquid due to localized pressure fluctuations.
- It is typically **induced** by:
  - Passing fluid through a constriction (e.g., orifice plate, venturi tube).
  - This creates zones of low pressure, initiating cavitation bubbles.
  - The collapse of these bubbles generates intense local temperature (~5000 K) and pressure (~1000 atm), along with strong shear forces and micro-jets.
- These extreme microenvironments can modify the **physicochemical** properties of food systems.





Adapted from: Patel, V. et al. (2023). Hydrodynamic cavitation-assisted food processing and preservation: A review. Journal of Food Engineering

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ΕΡΓΑΣΤΗΡΙΟ ΧΗΜΕΙΑΣ ΤΡΟΦΙΜΩΝ

Hydrodynamic cavitation (HC): Applications


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Comparative assessment of high-intensity ultrasound and hydrodynamic cavitation processing on physico-chemical properties and microbial inactivation of peanut milk

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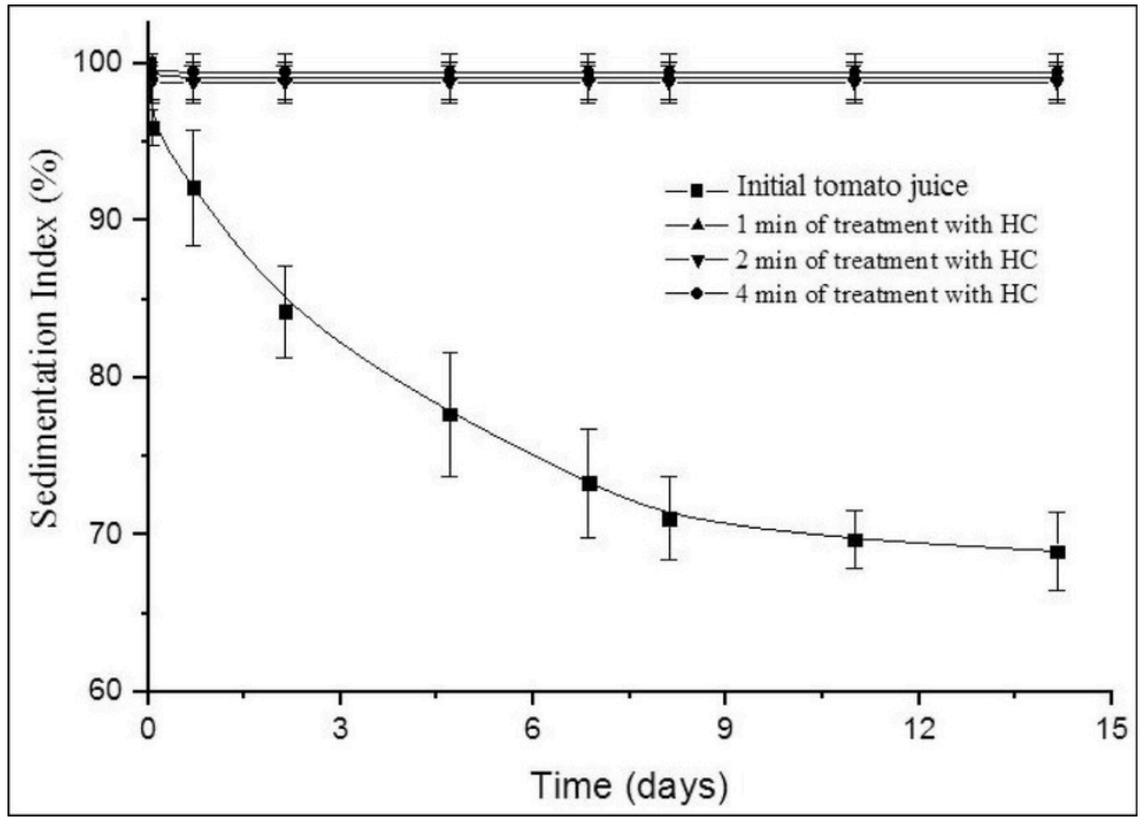
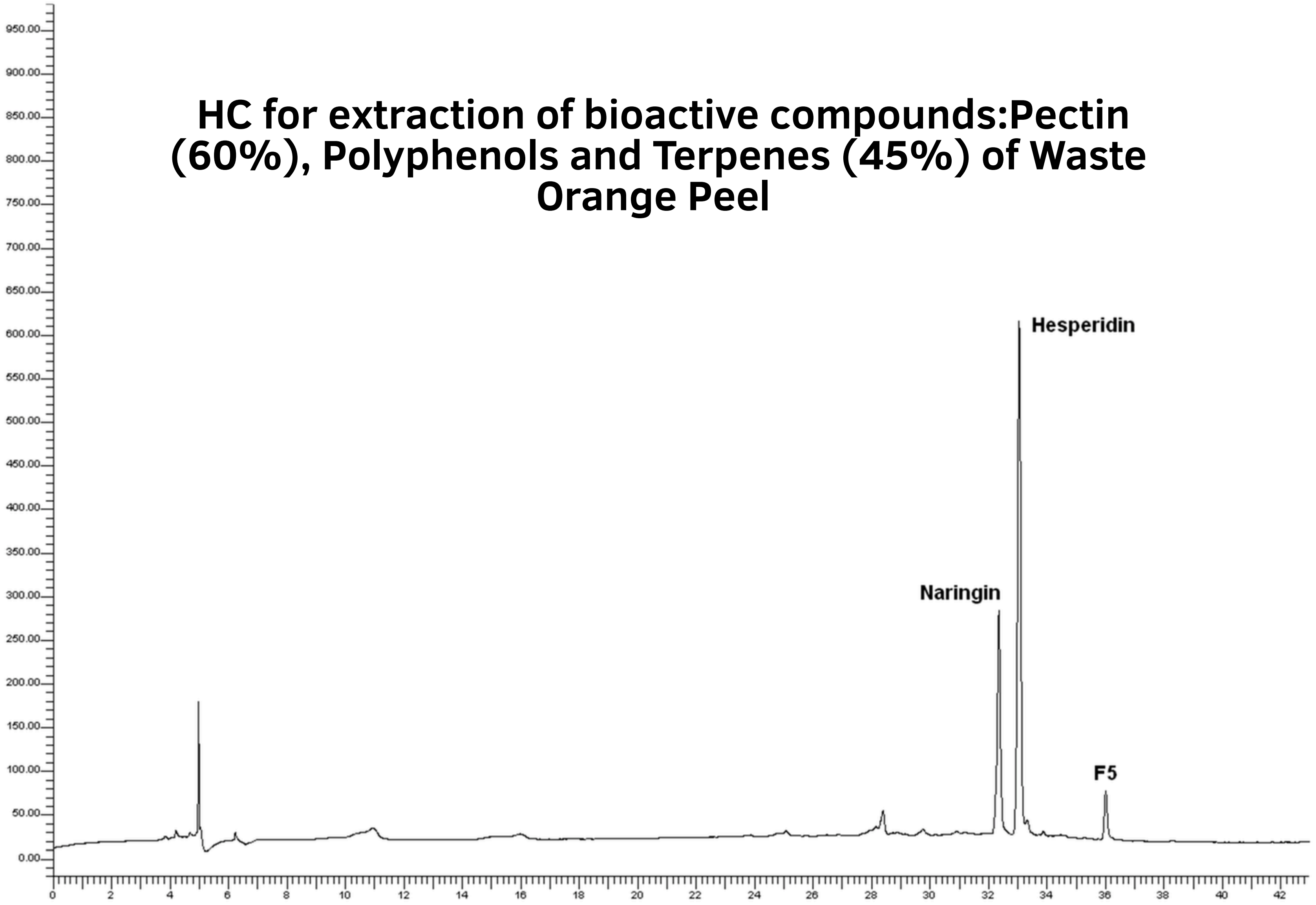
HC for microbial inactivation/sterilization/ cell disruption:
1.2 log reduction of total bacteria at 10 bar pressure



HC for physiochemical properties and quality improvement:
Reduced the particle size.
Increased apparent viscosity.
Sedimentation affected in reduction in tomato juice.
Adapted from: Terán Hilares et al., Innov. Food Sci. Emerg. Technol., 2023, 88, 103402.

HC for extraction of bioactive compounds:Pectin (60%), Polyphenols and Terpenes (45%) of Waste Orange Peel



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Εθνικόν και Καποδιστριακόν Πανεπιστήμιον Αθηνών
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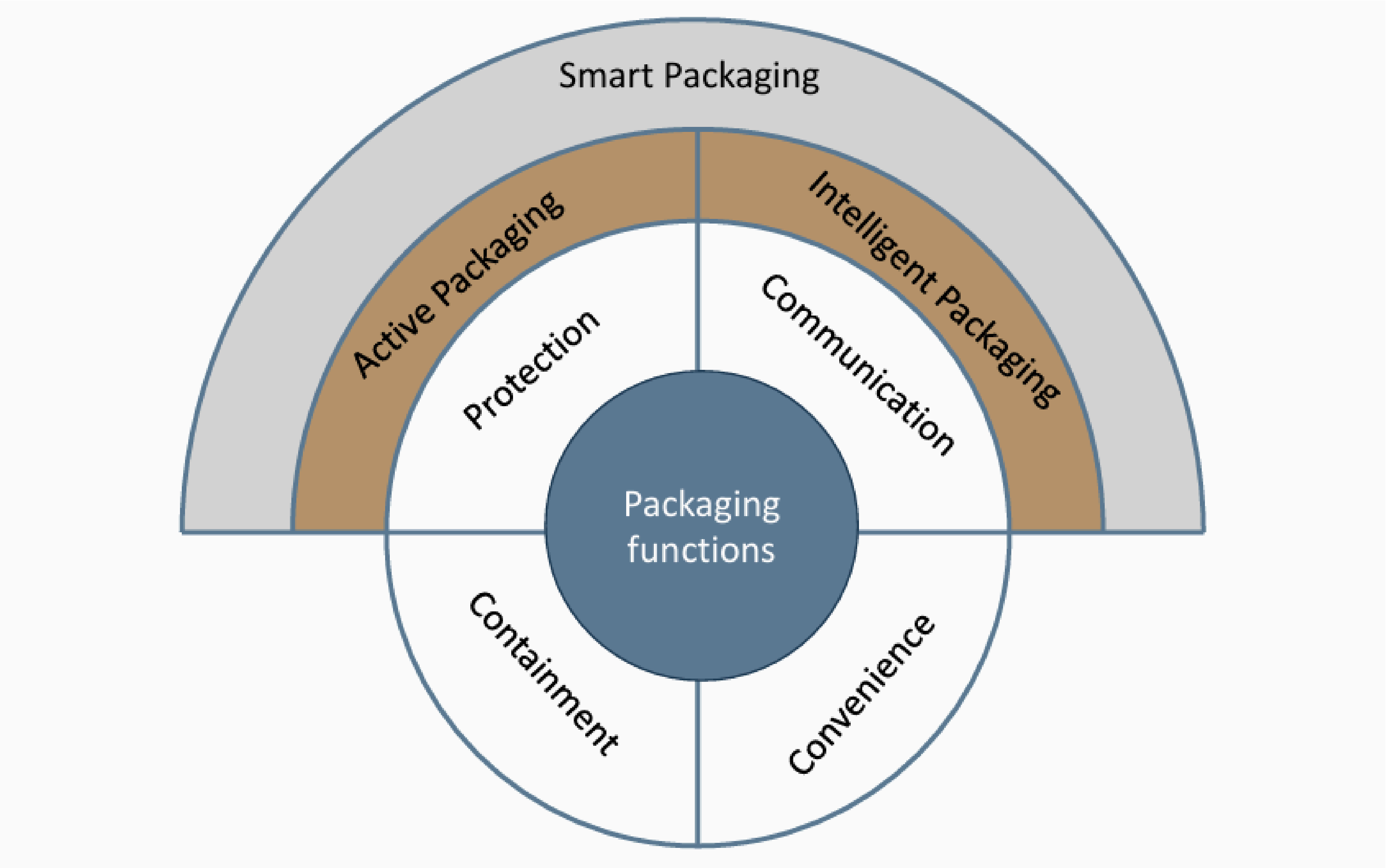
Shaping the Future of Food: Innovative Packaging Solutions

📦 Modern food packaging goes beyond protection — **it enhances safety, shelf life, and sustainability**.
🧪 Driven by **consumer demand, environmental concerns, and technological advancements**.
♻️ Focus on **smart, active, and sustainable packaging systems**.
🌍 Plays a key role in **reducing food waste** and improving resource efficiency.



Adapted from: Erasmus+ Module 4.3 and sources including Marsh & Bugusu (2007), Arora et al. (2020), Singh et al. (2021), Venkatesh et al. (2021).

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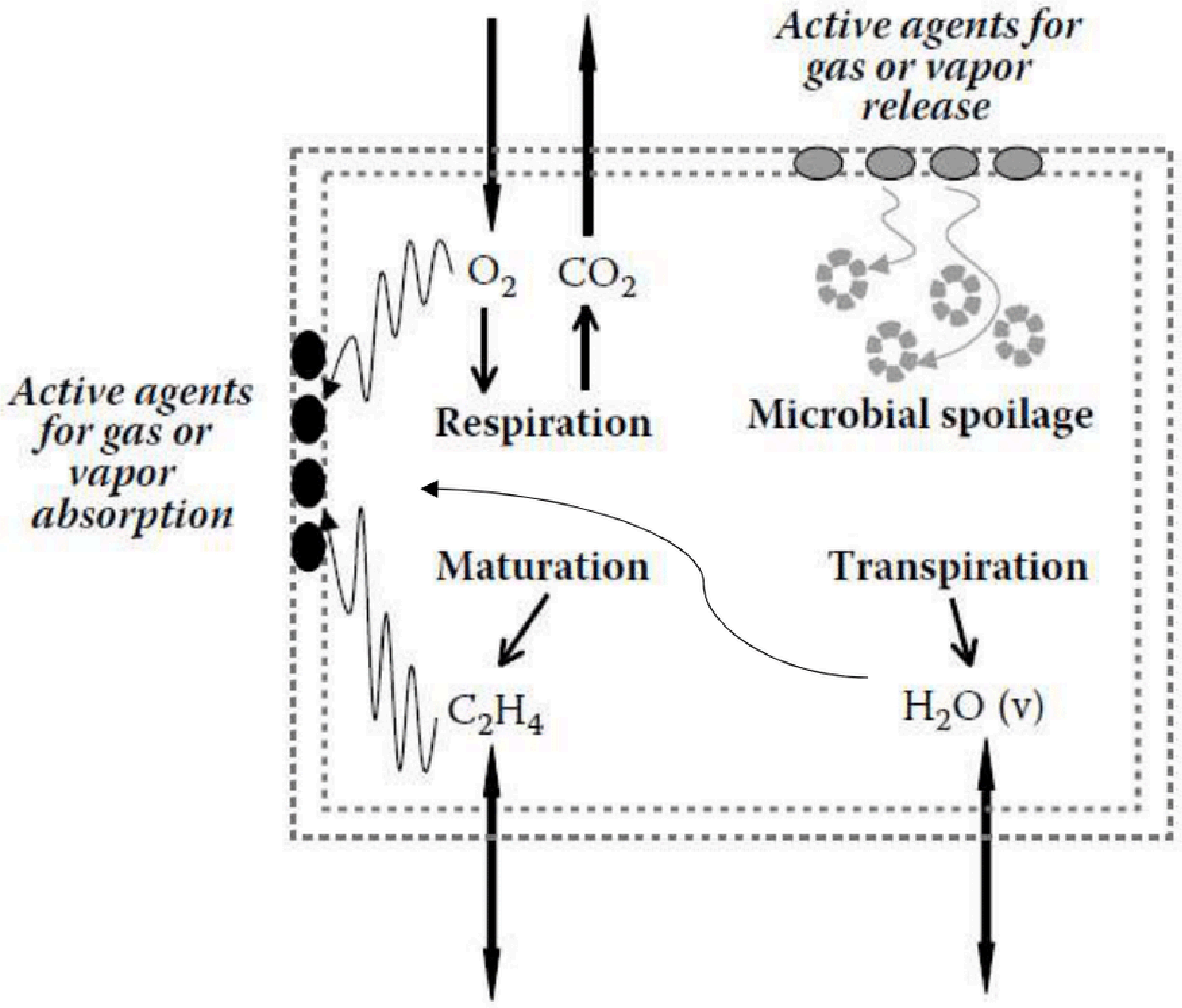
Smart Packaging: Overview

🟠 Active Packaging	🔵 Intelligent Packaging
• Preserves **food quality & safety**	• **Monitors** product condition
• **Interacts** with the internal environment	• **Detects** temperature, gas levels, freshness
• **Examples**: oxygen scavengers, antimicrobial films	• **Examples**: time-temperature indicators, RFID/NFC tags
• **Extends** shelf life	• **Communicates** with consumer/supply chain
EU REGULATION	Regulation (EC) No 1935/2004: Ensures safety and inertness of food contact materials Regulation (EC) No 450/2009: Sets rules for active/intelligent packaging EFSA approval is required before market use Labelling must clearly indicate non-edible components Requires Declaration of Conformity across the supply chain Ensures consumer safety while enabling innovation

Adapted from: Fonseca et al., Module 4.3 – New Food Packaging, Erasmus+ BIP; Vilela et al. (2018); Han et al. (2018)

Active Packaging in Action

- **Active** packaging systems **interact** with the food or the atmosphere inside the package.
- They aim to **reduce spoilage**, **control gas composition** (e.g., O_2, CO_2, ethylene), and preserve freshness by **absorbing or releasing** substances.
- **Used** in: meat, fruit, dairy, seafood



Adapted from: Fonseca et al., Module 4.3 – New Food Packaging, Erasmus+ BIP; Vilela et al. (2018); Han et al. (2018)

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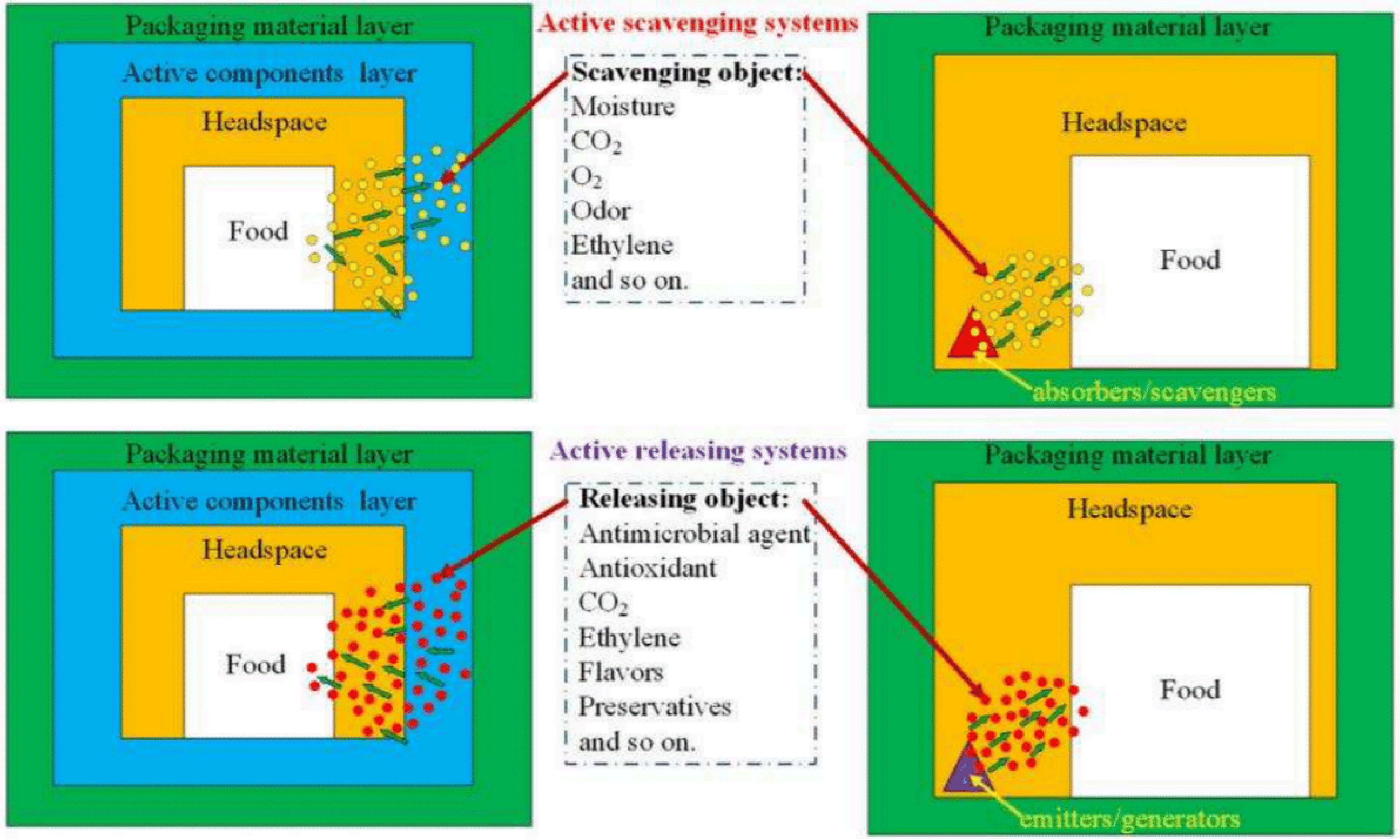
Examples of Active Packaging Technologies



Type	Function	Examples / Applications
O_2 Scavengers	Prevent oxidation & spoilage	Ageless®, SHELFPLUS® – meat, bakery
Moisture Absorbers	Reduce microbial growth	SEAWELL™, FreshWell™ – fish, poultry
Ethylene Scavengers	Delay ripening, reduce waste	Green Bags™, $KMnO_4$ sachets – fruit
CO_2 Emitters	Inhibit microbes	Citric acid + $NaHCO_3$ – fresh produce
Antimicrobials	Prevent spoilage/pathogenic bacteria	Chitosan, essential oils – cheese, fruits

Adapted from: Fonseca et al. (2023), Vilela et al. (2018), Han et al. (2018), Otoni et al. (2016)

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Active Packaging: Commercial Solutions in Action

O_2 Scavenger – Ageless®

- **Removes** residual oxygen from the package
- Prevents **oxidation, rancidity, and mold**
- **Common** in meat, fish, nuts, bakery products

Moisture Absorber – FreshWell™ Pads

- **Absorbs water** and exudate
- **Reduces microbial growth and spoilage**
- **Used** in fresh poultry, seafood, red meat

Adapted from: Fonseca et al. (2023), Erasmus+ Module 4.3 – New Food Packaging, Mitsubishi Gas Chemical (Ageless®), MaxwellChase Technologies (FreshWell™), Vilela et al. (2018)

Intelligent Packaging: Monitoring & Communication Systems

🔍 Definition:

Intelligent packaging is designed to **detect, monitor, and communicate changes** in the condition of food or the packaging environment.

🎯 Purpose:

- **Ensure food safety** and **quality**
- **Alert t**he supply chain or consumers **to spoilage, temperature abuse, or gas build-up**
- **Improve traceability** and **decision-making**

Type	Function
⏳ **Time-Temperature Indicators (TTIs)**	Show cumulative exposure to heat over time
🧫 **Freshness Indicators**	Detect microbial activity or metabolites
🟡 **Gas Indicators (O_2, CO_2)**	Reveal gas buildup or leakage
💧 **Humidity Indicators**	Detect moisture accumulation
🔍 **Biosensors**	Sense oxygen, pathogens, or spoilage compounds
📶 **RFID / NFC Tags**	Enable wireless tracking and traceability

Adapted from: Fonseca et al. (2023), Erasmus+ Module 4.3 – New Food Packaging; Vilela et al. (2018)

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Intelligent Packaging: Commercial Solutions in Action

Time-Temperature Indicator – MonitorMark™ (3M)

- **Tracks cumulative exposure to high temperature**
- Irreversible **color change alerts for cold chain breaks**
- **Used in**: seafood, vaccines, dairy, ready meals

RFID Tagging – Avery Dennison

- Enables **wireless traceability and anti-counterfeiting**
- **Tracks location, temperature, and inventory status**
- **Used in:** fresh produce, pharmaceuticals, logistics

Adapted from: Fonseca et al. (2023), Erasmus+ Module 4.3 – New Food Packaging, 3M MonitorMark™, Avery Dennison RFID

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From Waste to Worth: Sustainable Packaging Materials

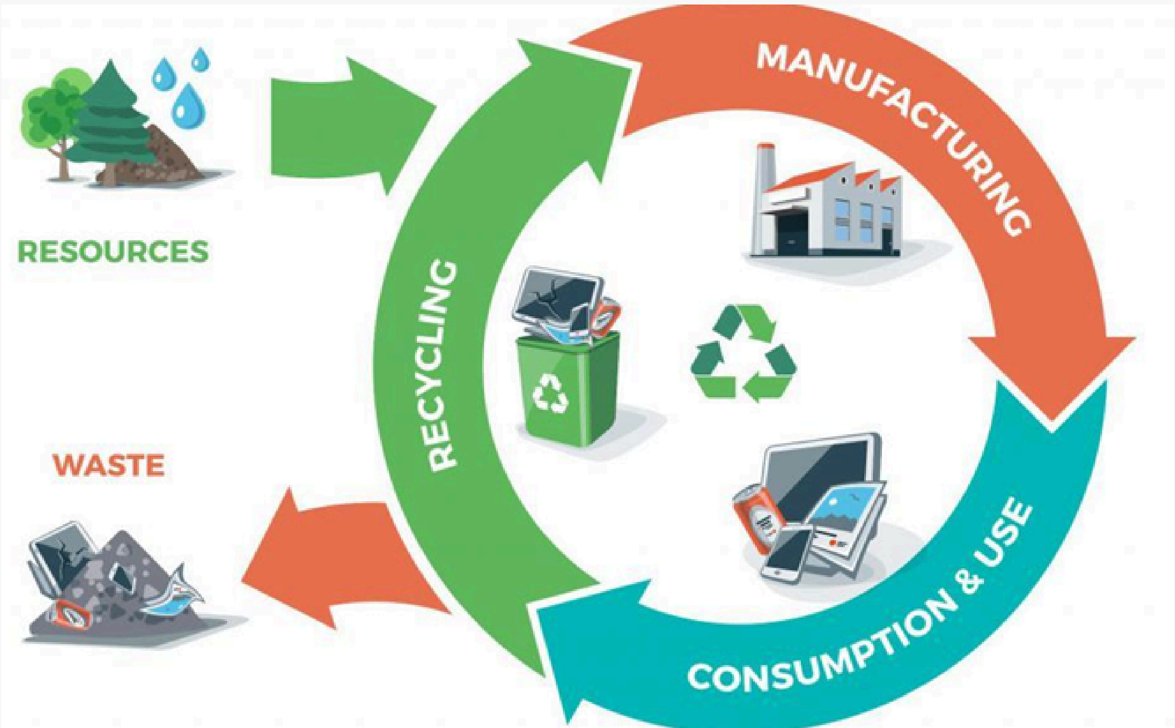
♻️ Problem

🌍 22 million **tonnes** of **plastic** leaked into oceans (2019)

♨️ 1.8 billion **tonnes** of **CO_2** from plastics annually

⚠️ **Microplastics** threaten ecosystems and human health

🗑️ **Low recycling rates**, landfill accumulation



Sustainable Solutions

♻️ **Recycled materials** (mechanical & chemical recycling)

🍃 **Biodegradable materials** (PLA, PHA, PBAT)

🥝 **Edible coatings** from natural or food waste

🔄 **Circular economy:** reuse, ecodesign, valorization

Adapted from Fonseca et al. (2023), Eurostat (2022), OECD

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Polylactic Acid (PLA): A Sustainable Packaging Alternative

🔬 What is PLA?

A **bio-based**, **biodegradable** polymer derived from renewable resources like **corn starch or sugarcane**.

🧪 Applications:

- **Used** in yogurt cups, salad containers, sandwich wrappers, and biodegradable films.
- Can be **combined** with active/intelligent components, e.g., antioxidant coatings or freshness indicators.

♻️ Advantages:

- **Biodegradable** under industrial composting conditions (reduces long-term waste).
- Good **mechanical** properties (transparency, strength).
- **Safe** for food contact; approved by FDA and EFSA.
-

⚠️ Limitations:

- Requires **industrial** composting (not home compostable).
- **Lower thermal resistance** than some fossil-based plastics.
- **Slower degradation** in natural environments (landfills, oceans).

Adapted from: Milovanovic et al., 2022; Gay et al., 2018; Jacob et al., 2020; Milovanovic et al., 2022; Wikipedia polylactic acid (2024).

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Polylactic Acid (PLA): A Sustainable Packaging Alternative

Examples of commercially available PLA-based food packaging: clear compostable salad containers and cutlery sets. PLA packaging offers a biodegradable, bio-based alternative to conventional plastics, commonly used in ready-to-eat meals and food service applications.

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Edible Coatings: Minimal Packaging, Maximum Impact

🍏 **Thin, edible layer applied directly to food**

- 🧪 **Made from alginate, chitosan, starch, often enriched with:**
- **→ Antioxidants, antimicrobials, vitamins**
- 🌍 **Fully biodegradable** and **compostable**
- 🍊 **Allows use of paper** or **compostable outer packaging**

Apeel: Plant-derived coatings for avocados and citrus.

Adapted from: Fonseca et al. (2023), Erasmus+ Module 4.3 – New Food Packaging, Vilela et al. (2018)

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The Future of Food Packaging: Smart, Circular, Sustainable

Key Trends:

- 🌐 **Digitalization:** QR codes, RFID, freshness indicators
- ♻️ **Circular economy:** waste-to-resource, reuse, valorization
- 🧠 **Multifunctional packaging:** protection, monitoring, communication
- 📊 **Market projected to reach $400B+ by 2030**

Adapted from Fonseca et al. (2023), Vilela et al. (2018), GII Research (2025)

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Questions

1. **Which non-thermal technology would you recommend for preserving fresh fruit juice, and why?**
2. **In what food applications does PEF offer clear advantages over thermal methods?**
3. **How does CAP alter surface hydrophobicity, and why is that important in food packaging?**
4. **How does cavitation contribute to emulsification and extraction in ultrasound processing?**
5. **What is the difference between active and intelligent packaging? Give a real-life example of each.**
6. **If you had to design a new product with extended shelf life and minimal processing, which technology and packaging solution would you combine, and why?**