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Evaluation And Impact Of Plastic Packaging On Food Safety And The Environment

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Abstract

This study investigates the impact of plastic food packaging on both environmental sustainability and food safety, using a dual approach combining a consumer-based questionnaire and laboratory analyses. A total of 121 consumers from the Tlemcen region were surveyed through a bilingual (Arabic-French) questionnaire composed of 19 questions. Results showed that over 85% of participants regularly purchase food packaged in plastic, yet only 27% reported sorting their plastic waste. Moreover, over 60% were unaware of the potential health risks associated with plastic additives such as bisphenol A (BPA) and phthalates.

Laboratory investigations focused on identifying the types of plastic materials (bottles, bags, food-grade films, and cups) and assessing their biodegradability. Plastics were characterized using buoyancy and solubility tests, revealing the presence of polyethylene terephthalate (PET)**,** polyethylene (PE)**,** polypropylene (PP)**,** and polystyrene (PS)**.** Biodegradation tests conducted over four weeks demonstrated limited degradation rates: bottles (2%)**,** bags (5%)**,** films (9%)**,** and cups (9%)**,** confirming the environmental persistence of these materials.

Microbiological analyses revealed the absence of faecal coliforms in tested samples of vacuum-packed meat, fresh cheese, and water after 24 and 48 hours of incubation at 37°C, indicating acceptable microbial safety under the tested conditions.

In conclusion, the findings highlight a pressing need to raise public awareness, promote alternative biodegradable packaging materials, and strengthen regulatory frameworks to reduce health and environmental risks associated with conventional plastic packaging. The study provides a basis for future work on toxicological risk assessment, biodegradation enhancement, and sustainable packaging policy in line with circular economy principles.

Keywords:
Plastic packaging, Food safety, Biodegradation, Environmental impact, Consumer perception

Résumé

Cette étude examine l'impact des emballages alimentaires en plastique sur la durabilité environnementale et la sécurité alimentaire, en utilisant une double approche combinant un questionnaire auprès des consommateurs et des analyses en laboratoire. Au total, 121 consommateurs de la région de Tlemcen ont été interrogés via un questionnaire bilingue (arabe-français) composé de 19 questions. Les résultats ont montré que plus de 85 % des participants achètent régulièrement des aliments emballés dans du plastique, mais que seulement 27 % déclarent trier leurs déchets plastiques. De plus, plus de 60 % ignorent les risques potentiels pour la santé liés aux additifs plastiques tels que le bisphénol A (BPA) et les phtalates.

Les analyses en laboratoire ont porté sur l'identification des types de matériaux plastiques (bouteilles, sacs, films alimentaires et gobelets) et l'évaluation de leur biodégradabilité. Les plastiques ont été caractérisés par des tests de flottabilité et de solubilité, révélant la présence de polyéthylène téréphtalate (PET), de polyéthylène (PE), de polypropylène (PP) et de polystyrène (PS). Des tests de biodégradation menés sur quatre semaines ont montré des taux de dégradation limités : bouteilles (2 %), sacs (5 %), films (9 %) et gobelets (9 %), confirmant la persistance environnementale de ces matériaux.

Les analyses microbiologiques ont révélé l'absence de coliformes fécaux dans les échantillons testés de viande sous vide, de fromage frais et d'eau après 24 et 48 heures d'incubation à 37 °C, indiquant une sécurité microbienne acceptable dans les conditions testées.

En conclusion, ces résultats soulignent l'urgence de sensibiliser le public, de promouvoir des matériaux d'emballage biodégradables alternatifs et de renforcer les cadres réglementaires afin de réduire les risques sanitaires et environnementaux associés aux emballages plastiques conventionnels. Cette étude constitue une base pour de futurs travaux sur l'évaluation des risques toxicologiques, l'amélioration de la biodégradation et une politique d'emballage durable, conforme aux principes de l'économie circulaire.

Mots-clés :

Emballage plastique, Sécurité alimentaire, Biodégradation, Impact environnemental, Perception des consommateurs

ملخص

تبحث هذه الدراسة في تأثير التغليف البلاستيكي للأغذية على كل من الاستدامة البيئية وسلامة الغذاء، باستخدام نهج مزدوج يجمع بين استبيان المستهلك والتحليلات المخبرية. تم استطلاع آراء 121 مستهلكًا من منطقة تلمسان من خلال استبيان ثنائي اللغة (العربية والفرنسية) يتكون من 19 سؤالًا. أظهرت النتائج أن أكثر من 85٪ من المشاركين يشترون بانتظام أغذية مغلفة بالبلاستيك، ومع ذلك أفاد 27٪ فقط بفرز نفاياتهم البلاستيكية. علاوة على ذلك، كان أكثر من 60٪ يجهلون المخاطر الصحية المحتملة المرتبطة بإضافات البلاستيك مثل بيسفينول أ (BPA) والفثالات. ركزت التحقيقات المخبرية على تحديد أنواع المواد البلاستيكية (الزجاجات والأكياس والأغشية الغذائية والأكواب) وتقييم قابليتها للتحلل البيولوجي. تم توصيف البلاستيك باستخدام اختبارات الطفو والذوبان، مما كشف عن وجود بولي إيثيلين تيريفثالات (PET) والبولي إيثيلين (PE) والبولي بروبيلين (PP) والبوليسترين (PS). أظهرت اختبارات التحلل البيولوجي التي أُجريت على مدى أربعة أسابيع معدلات تحلل محدودة في الزجاجات (2%)، والأكياس (5%)، والأغشية (9%)، والأكواب (9%)، مما يؤكد ثبات هذه المواد في البيئة.

كشفت التحاليل الميكروبيولوجية عن غياب البكتيريا القولونية البرازية في العينات المختبرة من اللحوم المعبأة في فراغ، والجبن الطازج، والماء، بعد 24 و48 ساعة من الحضانة عند درجة حرارة 37 درجة مئوية، مما يشير إلى سلامة ميكروبية مقبولة في ظل الظروف المختبرة.

وفي الختام، تُبرز النتائج الحاجة المُلحة إلى رفع مستوى الوعي العام، وتشجيع استخدام مواد تغليف بديلة قابلة للتحلل البيولوجي، وتعزيز الأطر التنظيمية للحد من المخاطر الصحية والبيئية المرتبطة بالتغليف البلاستيكي التقليدي. تُوفر الدراسة أساسًا للعمل المستقبلي في تقييم المخاطر السمية، وتعزيز التحلل البيولوجي، وسياسة التغليف المستدامة بما يتماشى مع مبادئ الاقتصاد الدائري.

الكلمات المفتاحية:

التغليف البلاستيكي، سلامة الغذاء، التحلل البيولوجي، الأثر البيئي، إدراك المستهلك

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Abbreviations

- **ASR:** Automobile shredder residue
- **BPA**: bisphenol A
- **D:** diffusion
- **DBP:** dibutylphthalate
- **DEHP:** di(2-ethylhexyl) phthalate
- **E:** energy
- **EFSA**: *European Food Safety Authority*
- **EPs:** endocrine Perturbations
- **FDA:** Food and Drug Administration
- **GC:** gas chromatography
- **GHG:** greenhouse gas
- **HDPE**: high density polyethylene
- **HPLC:** high-performance liquid chromatography
- **K:** kelvins
- **LDPE:** low density polyethylene
- **LMG:** overall migration limit
- **MP:** microplastic
- **MS:** mass spectrometry
- **MSW:** municipal solid waste
- **PCBs:** polychlorinated biphenyls
- **PE:** polyethylene
- **PET:** polyethylene terephthalate
- **PP:** polypropylene
- **PS:** polystyrene
- **PVC:** polyvinyl chloride
- **QM:** maximum concentration in the material
- **QMA:** maximum concentration per packaging unit
- **RDF:** Refuse derived fuel
- **SML**: specific migration limit
- **T:** temperature
- **TDI:** tolerable daily intake
- **UHMW**: ultra high molecular weight polyethylene

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GENERAL INTRODUCTION

In an era marked by globalization and mass consumption, plastic packaging plays a dominant role in the agri-food industry. Its widespread adoption stems from its functional properties: lightweight, flexibility, mechanical strength, impermeability, and low production cost (Geyer et al., 2017). These characteristics make it an ideal material for protecting food from microbial contamination, oxidation, and physical damage while extending shelf life (Marsh & Bugusu, 2007). However, this growing reliance on plastics raises significant environmental and health concerns, making their evaluation a critical issue for the future of food safety and ecological sustainability.

From a health perspective, plastic packaging can pose risks due to the migration of chemical components, such as phthalates, bisphenol A (BPA), or microplastics, into food (Muncke et al., 2020). This migration is exacerbated by improper usage, such as microwaving non-microwave-safe packaging or reusing single-use plastics (Lithner et al., 2011). Furthermore, in developing countries with weaker regulations, the lack of traceability and hygiene standards increases the risk of food contamination (Smith et al., 2018).

On the environmental front, plastic packaging is one of the leading sources of global pollution. According to the United Nations (UN, 2021), nearly 400 million tons of plastic are produced annually, with about **36%** destined for packaging—mostly single-use. Their short lifespan (sometimes just minutes of use) contrasts sharply with their persistence in the environment, where they take hundreds of years to degrade (Jambeck et al., 2015). A significant portion of this waste escapes recycling systems and ends up in natural ecosystems, contributing to ocean pollution (accounting for 85% of marine litter**,** per the European Commission, 2021), soil, and waterways. The gradual fragmentation of plastics into micro- and nanoplastics leads to widespread contamination of the food chain, with consequences for human health that are still not fully understood (Rochman et al., 2019).

To address these challenges, innovative solutions are emerging, such as bioplastics, edible packaging, and deposit-return systems. However, their adoption remains limited due to technical, economic, and regulatory constraints (European Bioplastics, 2022). A transition toward a circular economy, combined with better consumer awareness and stronger public policies, appears essential to reconcile food safety with environmental preservation (Ellen MacArthur Foundation, 2021).

This thesis therefore aims to analyze the impact of plastic packaging from a dual perspective: its role in food protection and its environmental consequences. It will also explore sustainable alternatives and mitigation strategies that could guide the agri-food industry toward more responsible practices.

Chapter I – Plastic Packaging in the Food Industry

I.1 Context and Use of Plastic Packaging

The modern food industry relies heavily on plastic packaging, which currently accounts for approximately 40% of all packaging used in Europe (PlasticsEurope, 2022). Their widespread adoption stems from a combination of unique properties that perfectly meet the needs of food preservation, transportation, and commercialization. These materials have gradually replaced traditional packaging (glass, metal, paper) due to their versatility and competitive cost.

The evolution of plastic packaging reflects the technological and societal transformations of the 20th century. Initially developed to meet military needs during the World Wars, these materials later expanded into civilian sectors, particularly the food industry. Their development was driven by major chemical innovations and the emergence of specialized corporations such as DuPont, BASF, and Dow Chemical.

I.1.1 History and Evolution of Plastic Packaging

The history of plastic packaging in the food industry dates back to the late 19th century with the invention of celluloid, but its widespread use truly began in the interwar period. Cellophane, invented in 1908 by Swiss chemist Jacques Brandenberger, marked a decisive turning point. This transparent, airtight material revolutionized fresh food packaging by combining product protection with visibility (Briston, 1988).

The post-war period saw the rise of synthetic polymers such as polyethylene (PE) and polypropylene (PP), whose mechanical and barrier properties surpassed those of natural materials. The 1950s and 1960s were the golden age of plastic food packaging, with the introduction of stretch films, PET bottles, and thermoformed trays. This period also coincided with the expansion of supermarkets and the rise of pre-packaged goods.

Recent decades have seen increasing sophistication in packaging, with the development of multilayer structures combining different polym

ers to optimize preservation properties. At the same time, environmental concerns have led to the emergence of new bio-based or biodegradable materials, though their market share remains small compared to conventional plastics.

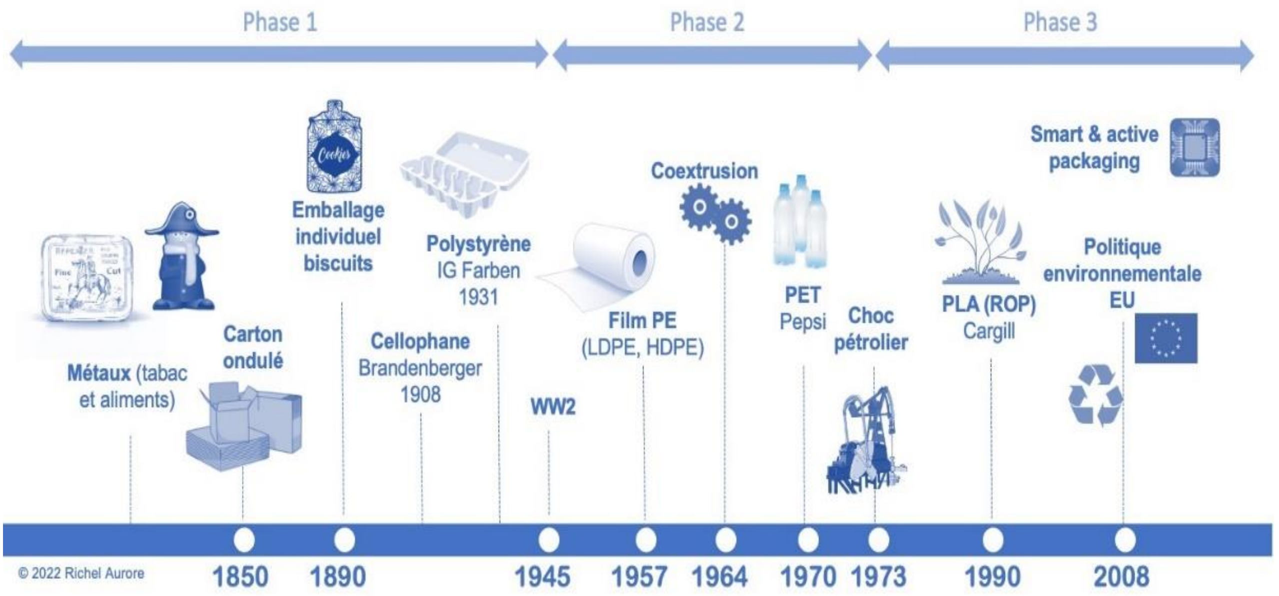


Figure I-1 Milestones in food packaging design from the Industrial Revolution to the present day (Richel, 2023)

I.1.2 Types of Plastics Used in Food Packaging

I.1.2.1 Polyethylene (PE)

Polyethylene (PE), the most widely used plastic in food packaging, exists in two primary forms: Low-Density Polyethylene (LDPE) and High-Density Polyethylene (HDPE)**.** Together, these account for over 40% of all plastic food packaging globally due to their versatility, safety, and cost-effectiveness (PlasticsEurope, 2023).

- **Key Characteristics**

1. **Material Properties**:

- **LDPE**: Branched polymer structure (density: 0.910–0.925 g/cm³) provides flexibility and clarity, ideal for films and squeezable packaging.
- **HDPE**: Linear polymer chains (density: 0.941–0.965 g/cm³) offer rigidity and strength, suited for rigid containers.
- Both are odorless, tasteless, and FDA/EFSA-approved for direct food contact (FDA, 2022).

2- **Thermal Behavior**:

- **LDPE**: Softens at ~90°C, melts at 115°C (Genin, 1963).
- **HDPE**: Higher heat resistance (up to 130°C), making it microwave-safe for some applications.

3- **Food Packaging Applications**

Table I-1 Food packaging Application and Functional advantage

Type	Examples	Functional Advantage
LDPE	Bread bags, produce films, squeeze bottles	Flexibility, moisture barrier
HDPE	Milk jugs, yogurt tubs, cereal liners	Rigidity, chemical resistance

I.1.2.2 Polypropylene (PP)

Introduced commercially in 1957, polypropylene offers several advantages over polyethylene, including superior gloss, transparency, heat resistance, and mechanical properties (Genin, 1963). This rigid, colorless thermoplastic features remarkable surface hardness while maintaining the lowest density (0.905 g/cm³) among common thermoplastics. With a melting range of 165-170°C, PP retains its structural integrity up to 100°C - remaining solid even at PE's melting temperature. However, its brittleness below 0°C limits frozen food applications unless biaxial orientation treatment is applied to improve strength and reduce gas permeability.

PP demonstrates exceptional abrasion resistance, mechanical strength, and dimensional stability regardless of humidity fluctuations. When properly surface-treated, its transparency allows high-quality printing using standard polyethylene inks. The material continues to show strong market growth, particularly in biaxially oriented films, with production capabilities now established globally (Genin, 1963).

Figure I-2 Yogurt tubs (Example of Types of Plastics Used in Food Packaging (Polypropylene (PP)

I.1.2.3 Polyethylene Terephthalate (PET)

PET represents a semi-aromatic polyester thermoplastic with unique physicochemical properties including excellent thermoplasticity, crystallization capacity, and thermal stability (Quentin, n.d.). These characteristics directly influence both its synthesis parameters and industrial applications, particularly in food and beverage bottle manufacturing. To ensure adequate mechanical strength and gas barrier properties, PET resins for bottles must maintain a minimum average molecular weight of 24,000 g/mol. Though exhibiting low water absorption, residual moisture can induce undesirable hydrolysis during processing.

Industrial PET production employs two primary methods:

1. Direct esterification of ethylene glycol with terephthalic acid
2. Transesterification of dimethyl terephthalate with ethylene glycol

Both processes involve sequential prepolycondensation and polycondensation stages, with transesterification being the preferred industrial route due to easier polymer purification and superior final product quality (Feigenbaum, 2006).

Figure I-3 Water bottles (Example of Types of Plastics Used in Food Packaging (Polyethylene Terephthalate (PET)

I.1.2.4 Polystyrene (PS)

Since its introduction, polystyrene has become indispensable in packaging applications due to its optical clarity, mechanical performance, and aesthetic qualities (Genin, 1963). Its exceptional moldability and ease of sheet forming make it ideal for diverse applications, even replacing wax-coated paper cups in beverage vending machines in some markets.

PS packaging appears in three principal forms:

1. Biaxially oriented films for external packaging, which shrink when heated to conform to product shapes
2. Thicker sheets for thermoformed containers (cups, pots, etc.)
3. Moldable powders for creating various packaging containers and boxes

This versatility has secured PS's position as a key material in industrial packaging solutions (Genin, 1963).

Figure I-4 Takeout containers (Example of Types of Plastics Used in Food Packaging (Polystyrene (PS)

I.1.3 Properties and Food Packaging Applications

Plastic polymers have become indispensable in food packaging due to their unique combination of protective properties, cost-effectiveness, and manufacturing versatility. Each type of plastic offers distinct advantages for specific food applications based on its chemical structure and physical characteristics. The following table details the seven major classes of food-contact plastics, including their molecular formulas, key material properties, primary applications in the food industry, and recycling identification codes. This classification system helps manufacturers select appropriate materials while enabling proper waste management and recycling processes (Arabi & Saidi, 2013; PlasticsEurope, 2023).

Table I-2 : Properties and Food Packaging Applications of Major Plastics

(Adapted from Arabi & Saidi, 2013 with updated technical specifications)

Polymer Type	Chemical Formula	Key Properties	Primary Food Applications	Recycling Code
PET (Polyethylene Terephthalate)	$(C_{10}H_8O_4)$□	- High clarity - Excellent gas barrier - Heat resistant (up to 70°C)	- Beverage bottles (water, soda) - Cooking oil containers - Oven-safe food trays - Retort pouches	#1
HDPE (High-Density Polyethylene)	(C_2H_4)□	- Rigid structure - Moisture resistant - Chemical inertness	- Milk jugs - Juice bottles - Cereal box liners - Freezer containers	#2
PVC (Polyvinyl Chloride)	(C_2H_3Cl)□	- High clarity - Oil resistance - Contains chlorine (37%)	- Shrink sleeves - Cling films (limited use) - Jar seals - Blister packs	#3
LDPE (Low-Density Polyethylene)	(C_2H_4)□	- Flexible - Good moisture barrier - Low melting point (105°C)	- Bread bags - Squeeze bottles - Frozen food packaging - Stretch films	#4
PP (Polypropylene)	(C_3H_6)□	- Heat resistant (140°C) - Chemical resistant - Fatigue resistant	- Microwave containers - Yogurt cups - Syrup bottles - Reusable food containers	#5
PS (Polystyrene)	(C_8H_8)□	- Rigid or foamed - Good insulation - Brittle below 0°C	- Disposable cutlery - Meat trays - Egg cartons - Hot drink cups	#6
Other (e.g., Polycarbonate)	Varies	- High impact resistance - Temperature stable	- Baby bottles - Water cooler jugs - Baking equipment	#7

Figure I-5 Plastic materials in contact with food and water (3D PRINT, 2020)

I.1.4 Advantages of Plastic Packaging: Key Benefits and Industry Impact

Plastic packaging has become indispensable across multiple industries, particularly in food and beverage, pharmaceuticals, and logistics, due to its unique combination of functional, economic, and environmental benefits. Its widespread adoption is supported by decades of technological innovation and material optimization (PlasticsEurope, 2023). Below, we detail the four primary advantages that make plastic the material of choice for modern packaging solutions.

I.1.4.1 Lightweight Properties

Plastics are significantly lighter than traditional materials like glass or metal, offering substantial advantages in transportation and handling:

- **Logistics Efficiency**: A plastic bottle weighs up to **90% less** than a glass equivalent, reducing fuel consumption and CO_2 emissions during transport (Paris, 2024).

- **Consumer Convenience**: Lightweight packaging enhances portability for end-users (e.g., bottled water, snack pouches).
- **Energy Savings**: Lower weight decreases energy use in supply chains by up to **40%** compared to alternatives (Ellen MacArthur Foundation, 2022).

I.1.4.2 Durability and Product Protection

Plastic packaging provides unmatched physical and chemical resistance, ensuring product integrity:

- **Moisture & Gas Barriers**: HDPE and PP films block humidity and oxygen, extending shelf life of perishables by **50–300%** (Institut Veolia, 2019).
- **Impact Resistance**: Absorbs shocks during transit, reducing damage rates for fragile goods (e.g., electronics, glass bottles in plastic sleeves).
- **Temperature Stability**: Certain plastics (e.g., PP) withstand freezing (-40°C) and microwave heating (up to 140°C) without degradation (FDA, 2023).

I.1.4.3 Design Flexibility and Innovation

The adaptability of plastics enables tailored solutions for diverse needs:

- **Form Variability**: From rigid tubs (yogurt containers) to flexible films (shrink wrap), plastics accommodate any product shape.
- **Advanced Features**: Incorporation of:
    - *Smart labels* (time-temperature indicators)
    - *Active packaging* (O_2 scavengers for fresh meat) (POLYVIA, 2022).
- **User-Centric Designs**: Resealable zippers, spill-proof spouts, and single-dose pouches improve functionality.

I.1.4.4 Cost-Effectiveness and Scalability

Plastics dominate packaging markets due to economic advantages:

- **Production Efficiency**: Injection molding and blow molding allow high-speed manufacturing (10,000+ units/hour) (Graphic Packaging International, 2024).
- **Material Savings**: Requires **60% less material** by weight than paperboard for equivalent protection (American Chemistry Council, 2023).
- **Lifecycle Costs**: Lower logistics expenses offset higher recycling challenges (e.g., plastic crates vs. wooden pallets).

Table I-3 Plastic vs. Alternative Materials (*Industry reports (2020–2024), normalized for 500ml beverage containers)*

Criterion	Plastic	Glass	Metal	Paper
Weight	5–50g	200–500g	30–150g	20–100g
Shelf Life Extension	2x–5x longer	Moderate	High	Low
Production Cost	$0.01–0.10/unit	$0.10–0.50/unit	$0.05–0.30/unit	$0.03–0.20/unit

1.2. Challenges Associated with Plastic Packaging: Health and Environmental Concerns

1.2.1. Chemical Migration: Mechanisms and Concerning Substances

The migration of chemical substances from packaging to food involves complex physicochemical mechanisms. Plastic additives such as plasticizers, stabilizers, and antioxidants are not chemically bound to the polymer matrix and can therefore migrate into food. This process primarily follows the laws of molecular diffusion and solubilization, with kinetics influenced by temperature and contact time.

The most concerning migrants include:

- **Phthalate Migration**
  As the most widely used plasticizers (constituting 30-40% of flexible PVC by weight), phthalates like DEHP and DINP exhibit concerning migration patterns:

- Primary health risks: Endocrine disruption (particularly affecting testosterone production) and reproductive system abnormalities

- Migration drivers:
  - Temperature: Increases by 400% when heated from 20°C to 60°C
  - Food matrix: Fatty foods absorb 5-10× more phthalates than aqueous foods
  - Contact time: 50% increase after 30 days storage in PVC-wrapped meats

- **Bisphenol A (BPA) Migration**

This polycarbonate component demonstrates alarming characteristics:

- Migration increases 15-fold when containers are microwaved
- Health impacts occur at doses 50× lower than current FDA limits (Vom Saal et al., 2007)
- Replacement compounds (BPS, BPF) show similar endocrine-disrupting properties

- **Antimony Leaching from PET**

The PET production catalyst presents unique risks:

- Migration accelerates exponentially above 60°C (common in vehicle interiors/shipping containers)
- Detected in 78% of bottled waters after 6-month storage (Westerhoff et al., 2022)
- Chronic exposure linked to:
  - Pulmonary toxicity
  - Cardiovascular issues
  - Possible carcinogenicity (Group 2B IARC classification)

Table I-4 Maximum Detected Migration Levels in Common Scenarios

Substance	Food Simulant	Conditions	Concentration (µg/kg)	Regulatory Limit
DEHP	Olive oil	40°C/10d	2,300	1,500
BPA	3% Acetic acid	70°C/2h	85	50
Antimony	Water	60°C/7d	6.2	5.0

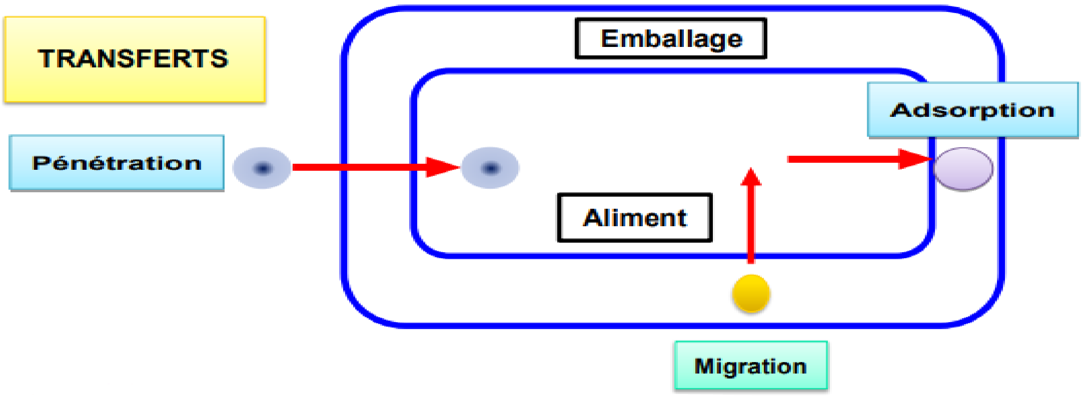


Figure I-6 Material exchanges between materials and their environment, according to (Endrizzi et al., 2009).

1-2-2 Factors Influencing Chemical Migration in Plastic Food Packaging

The transfer of chemical substances from plastic packaging materials to food products constitutes a significant food safety challenge. This migration phenomenon is influenced by three primary factors that interact in complex ways to determine the extent of chemical transfer.

1-2-2-1 Temperature Effects

Temperature serves as the most critical factor influencing migration rates from plastic packaging. Scientific studies demonstrate that migration follows the Arrhenius equation, where each 10°C increase in temperature approximately doubles the migration rate of chemical additives (Riquet, 1998). This relationship becomes particularly concerning for several common usage scenarios:

For polyethylene terephthalate (PET) beverage containers, research shows that storage at 60°C (a temperature easily reached in vehicles during summer months) causes antimony migration to increase by 4-8 times compared to storage at room temperature (Westerhoff et al., 2022). Microwave heating presents even greater risks, with studies indicating that heating polycarbonate containers to 70-100°C can accelerate bisphenol A (BPA) migration by 15-30 times compared to room temperature conditions (Vom Saal et al., 2007).

The underlying mechanisms involve both increased molecular mobility within the polymer matrix and enhanced solubility of migrants in food matrices at higher temperatures. As temperature rises, the free volume between polymer chains expands, allowing greater movement of additives. Simultaneously, many food constituents become more effective solvents for plastic additives at elevated temperatures (Muncke et al., 2020).

1-2-2-2 Duration of Contact Considerations

The length of time food remains in contact with plastic packaging significantly affects chemical migration through well-characterized diffusion processes. Migration follows Fickian diffusion kinetics, where the amount of substance transferred is proportional to the square root of time during the initial phase (Chagnon, 2015). This relationship leads to several important observations:

Short-term storage (less than 24 hours) typically results in minimal migration for most crystalline polymers like PET and high-density polyethylene (HDPE). However, amorphous plastics such as polystyrene (PS) and polyvinyl chloride (PVC) show measurable migration even during brief contact periods. Medium-term storage (1-30 days) demonstrates linear increases in migration for nearly all plastic types. A comprehensive study of bottled water found that phthalate levels increased by approximately 50% after three months of storage in PET containers (Montuori et al., 2008).

Long-term storage scenarios (beyond six months) present particular concerns as some systems approach equilibrium conditions where migration rates stabilize. This is especially problematic for shelf-stable products with extended expiration dates, where continuous low-level migration can lead to significant cumulative exposure (Muncke, 2011).

1-2-2-3 Food Composition Effects

The chemical composition of packaged foods dramatically influences their capacity to extract substances from plastic packaging. Three primary food characteristics determine migration potential:

Lipid content represents perhaps the most significant factor. Fatty foods including dairy products, oils, and fatty meats can extract 5-10 times more lipophilic compounds like phthalates and UV stabilizers compared to aqueous foods (Grob et al., 2006). This occurs because many plastic additives are themselves lipophilic and therefore more soluble in fatty matrices.

Acidity also plays a crucial role. Foods with pH below 4.5 significantly increase the leaching of metal catalysts like antimony from PET, with studies showing 200-400% greater migration in acidic versus neutral conditions (Shotyk & Krachler, 2007). The mechanism involves protonation of metal complexes at low pH, increasing their solubility in the food matrix.

Alcohol content represents another important consideration. Beverages containing more than 10% ethanol by volume have been shown to increase migration of PET oligomers by approximately eight-fold compared to water (Aznar et al., 2016). This effect results from alcohol's ability to swell polymer matrices and solubilize a wider range of organic compounds.

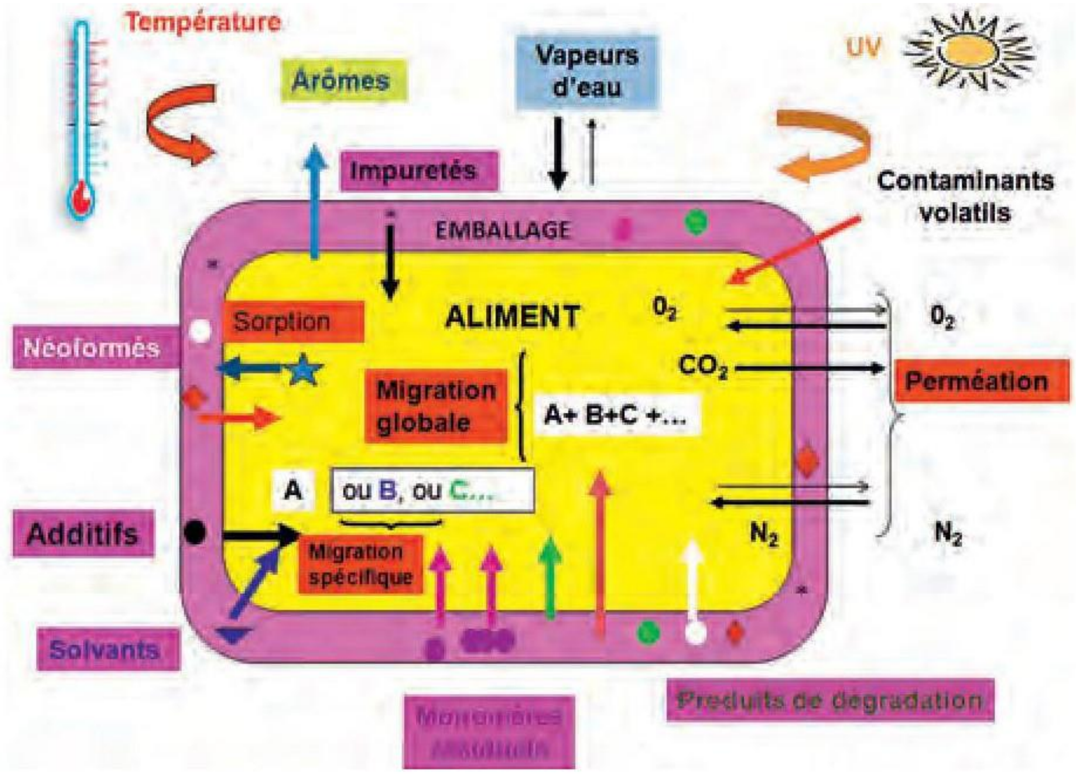


Figure I-6 Migration of substances between packaging and food (Chagnon, 2015)

1.2.3 Impact on Food Safety: Health Risks of Plastic Packaging

Plastic packaging, widely used in the food industry, poses significant risks to human health due to the presence of endocrine-disrupting chemicals (EDCs) such as bisphenol A (BPA) and phthalates. These chemical substances can migrate from packaging into food, exposing consumers to varying levels of these compounds. EDCs interfere with the endocrine system, altering hormonal functions and increasing the risk of hormone-dependent cancers, particularly breast, prostate, and testicular cancers (Damstra et al., 2002). Recent studies indicate that chronic exposure to these chemicals, even at low doses, can lead to developmental disorders, metabolic diseases, and reproductive health issues (WHO, 2022).

BPA, commonly used in plastic packaging, bottles, and epoxy resins, remains particularly concerning. Animal studies demonstrate that in utero or early childhood exposure to low BPA doses can cause mammary gland hyperplasia and prostate cancer later in life (Vom Saal et al., 2007). These effects occur at doses 50-100 times lower than current safety thresholds established by regulatory agencies, raising concerns about human exposure through plastic-packaged foods. Of particular note, a 2021 meta-analysis found that 93% of canned food samples contained detectable BPA levels, with concentrations exceeding EU safety limits in 18% of cases (Geens et al., 2021).

Phthalates, used as plasticizers to increase flexibility, are also present in food packaging and can migrate into foods, especially when heated. These substances have been linked to endocrine disruption, reproductive health risks, and potential hormone-dependent cancer development (Rudel et al., 2011). Recent biomonitoring data shows that DEHP (a common phthalate) metabolites are detectable in 98% of the U.S. population, with children showing 2-3 times higher exposure levels than adults (CDC, 2022). Food packaging contributes approximately 30-40% of total phthalate exposure in the general population (Serrano et al., 2020).

Moreover, plastic packaging may contain other hazardous chemicals like dioxins and polychlorinated biphenyls (PCBs), which are persistent organic pollutants. Although banned in many countries, these substances can still contaminate food through packaging or environmental exposure (Hoyer et al., 1998). Dioxins bioaccumulate in the food chain and have been associated with a 30-50% increased breast cancer risk among women with occupational exposure (IARC, 2016). Recent studies also suggest that microplastics from degraded packaging may act as carriers for these toxic compounds, potentially increasing their bioavailability (Smith et al., 2023).

In conclusion, plastic packaging presents real health risks due to migration of chemicals like BPA, phthalates, and dioxins into food. While direct epidemiological evidence remains challenging to establish due to the multifactorial and long-term nature of carcinogenesis, experimental data and human exposure measurements justify precautionary measures to limit use of these materials, especially for vulnerable populations like pregnant women and young children (Kortenkamp, 2007). Current risk assessments may underestimate cumulative exposure effects, as humans are typically exposed to complex mixtures of these chemicals through multiple sources simultaneously (Trasande et al., 2020).

1.2.4 Environmental Challenges of Plastic Packaging

Plastic packaging presents critical environmental challenges that extend across ecosystems and human health. The durability that makes plastics valuable for packaging also creates persistent environmental problems that are now reaching crisis proportions.

1.2.4-1 Accumulation of Plastic Waste

Global plastic production has increased exponentially from 2 million tons in 1950 to over 400 million tons annually in 2022 (PlasticsEurope, 2023). Food packaging accounts for approximately 36% of this total, generating massive waste streams:

- Only 9% of plastic waste gets recycled, while 79% accumulates in landfills or the natural environment (UNEP, 2022)
- Packaging plastics can persist for:
  - PET bottles: 450 years in marine environments
  - LDPE films: 100-200 years in terrestrial systems
  - PS containers: Potentially indefinite in landfill conditions

This accumulation overwhelms waste management systems, particularly in developing nations where collection infrastructure is inadequate. The OECD (2022) estimates that plastic leakage to environment will triple by 2060 without intervention.

1.2.4-2 Ecosystem Pollution and Impacts

Plastic packaging waste infiltrates all environmental compartments with devastating consequences:

- **Marine Environments:**

- 11 million metric tons enter oceans annually (Jambeck et al., 2022)
- 86% of sea turtle species and 44% of seabird species have ingested plastics (UNEP, 2021)
- Microplastics (<5mm) now outnumber zooplankton in many marine ecosystems

- **Terrestrial Systems:**

- Agricultural soils contain up to 23,000 microplastic particles per kg from degraded packaging (Rillig et al., 2022)
- Freshwater systems show 50% reduction in aquatic insect populations due to plastic contamination

- **Human Health Pathways:**

- Microplastics detected in:
    - 83% of tap water samples globally (WHO, 2022)
    - 90% of commercial sea salt brands
    - Human placentas and bloodstream (Ragusa et al., 2022)

1.2.4-3 Climate Change Contributions

The plastic packaging lifecycle generates significant greenhouse gas emissions:

- Production: 1 kg of PET emits 3.5 kg CO_2e (CIEL, 2023)
- Incineration: Releases 16% of global dioxin emissions
- Degradation: Methane release from landfills containing plastics

1.2.4-4 Emerging Concerns

Recent research reveals additional threats:

- Chemical leaching from packaging waste creates toxic hotspots
- Nanoplastics (<1µm) penetrate biological membranes
- Plastic additives disrupt soil microbial communities

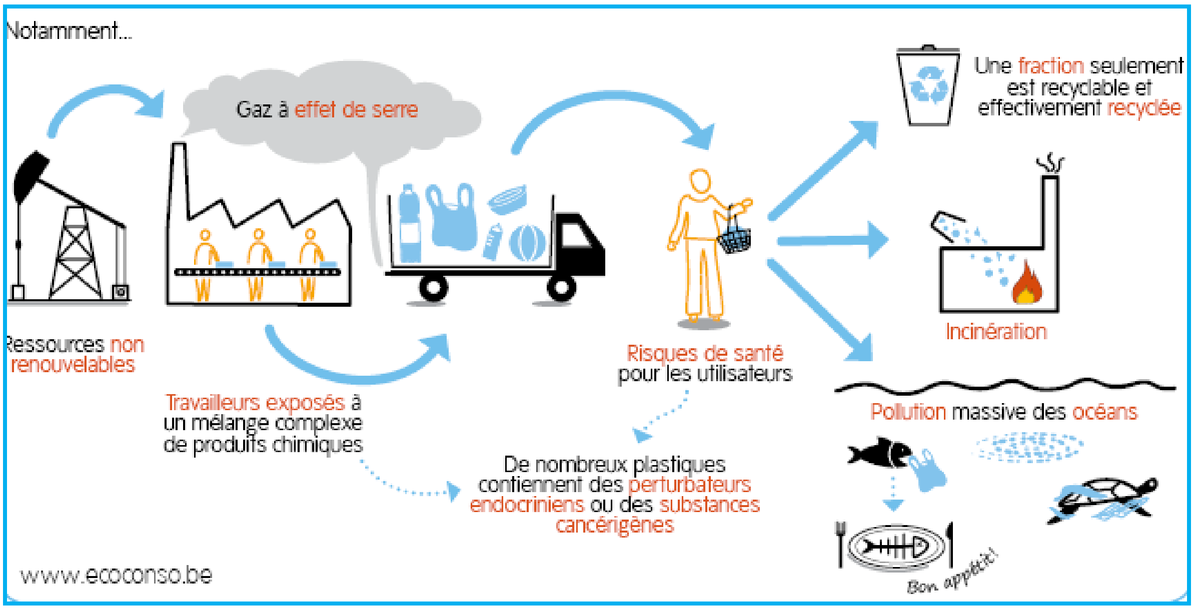


Figure I-7 The environmental and health impacts of plastics (Écoconso, 2019)

1.3. Regulations and Standards for Plastic Food Packaging

The global use of plastic food packaging has necessitated the development of comprehensive regulatory frameworks to ensure consumer safety and environmental protection. These regulations address multiple aspects including material composition, chemical migration limits, and end-of-life management. International standards established by organizations like the FDA, EFSA, and ISO aim to minimize health risks while maintaining packaging functionality. Recent scientific advancements have led to increasingly stringent requirements, particularly concerning endocrine-disrupting chemicals and microplastics. The following sections examine these regulatory approaches in detail, highlighting key standards, testing protocols, and emerging requirements that shape the plastic packaging industry.

1.3.1 International Standards and Regulatory Frameworks

The U.S. FDA and European EFSA have established complementary but distinct approaches to regulating food contact materials:

- **FDA Regulations (21 CFR 174-186)**:
  - Requires pre-market approval for food contact substances
  - Mandates extensive migration testing under intended use conditions
  - Maintains specific authorizations for polymer types (e.g., 21 CFR 177.1520 for polyolefins)
- **EFSA Standards (EC 1935/2004):**
  - Operates a positive list system with over 900 authorized substances
  - Conducts rigorous safety evaluations including:
    - ✓ Toxicological assessment
    - ✓ Exposure modeling
    - ✓ Cumulative risk analysis

Recent studies demonstrate the effectiveness of these frameworks in reducing chemical migration. For instance, BPA levels in canned foods decreased by 76% following EU restrictions (Geens et al., 2022). However, challenges remain in assessing non-intentionally added substances (NIAS) and mixture effects.

1.3.2. Migration Limits and Testing Protocols

Chemical migration limits form the cornerstone of plastic packaging regulations worldwide. The European Union's specific migration limits (SMLs) are particularly comprehensive, setting individual thresholds for hundreds of substances based on toxicological data. These limits are calculated using complex algorithms that consider acceptable daily intake values, typical consumption patterns, and potential cumulative effects. For example, the SML for bisphenol A was recently reduced from 0.05 mg/kg to 0.00004 mg/kg following new evidence about its endocrine-disrupting properties.

Testing protocols have evolved significantly to better simulate real-world conditions. Current methods employ food simulants that mimic various food properties, with testing durations and temperatures designed to represent the product's expected shelf life. Advanced analytical techniques including high-performance liquid chromatography coupled with mass spectrometry (HPLC-MS/MS) can detect contaminants at parts-per-billion levels. These sophisticated methods are necessary to identify potentially harmful substances that may migrate from packaging into food, even in minute quantities.

Table I-5 **EU Migration Limits for Food Contact Plastics**

(Directive 2002/72/EC as amended, Bach 2011)

Limit Type	Definition	Threshold Value	Testing Method
Overall Migration Limit	Total non-volatile substances	60 mg/kg food or 10 mg/dm^2	EN 1186 (simulant testing)
Specific Migration Limit	Individual regulated substances	Based on TDI (e.g., BPA=0.05 mg/kg)	HPLC-MS/MS analysis
QM Restriction	Maximum content in material	Typically 0.1-5 mg/kg polymer	Extraction testing
QMA Provision	Surface concentration limit	0.05 mg/6 dm^2	SEM-EDS analysis

1.3.3. Recent Regulatory Developments and Future Trends

Recent years have seen dramatic changes in plastic packaging regulations driven by emerging scientific understanding. The European Union's comprehensive ban on bisphenol A and its analogs in all food contact materials represents one of the most significant regulatory shifts. This decision followed extensive research demonstrating health risks at exposure levels previously considered safe (EFSA, 2023; Geens et al., 2012). Similar restrictions are being implemented for phthalates and other plasticizers, with many jurisdictions moving toward full phase-outs of these substances (Rudel & Perovich, 2009; ECHA, 2022).

The growing focus on circular economy principles has led to new regulations governing recycled content in food packaging. These measures aim to balance sustainability goals with food safety concerns, particularly regarding potential contaminants in post-consumer recyclates (EFSA, 2021; Hahladakis & Iacovidou, 2018). Digital watermarking technologies are being mandated in some regions to improve sorting accuracy and facilitate higher-quality recycling (HolyGrail 2.0, 2023). Looking ahead, regulators are developing frameworks to address emerging challenges including microplastic contamination and the use of biodegradable alternatives, ensuring that food packaging safety keeps pace with technological and environmental developments (UNEP, 2021; Koelmans et al., 2022; European Commission, 2020).

II- Impact of Plastic Packaging on food Safety

II.1. Migration of Chemical Compounds

Plastic packaging, although essential for food preservation and transportation, can release chemical substances into the food they contain. This migration phenomenon results from various physical and chemical mechanisms, influenced by factors such as temperature, food type, and contact duration. Certain compounds, such as phthalates and bisphenol A (BPA), are particularly concerning due to their potential health effects, including endocrine disruption and long-term toxicity.

II.1.1 Migration Mechanisms

The migration of additives and monomers from plastics into food is governed by fundamental physicochemical mechanisms, primarily driven by molecular diffusion laws and chemical interactions. These processes are explained by:

- **Transfer via Concentration Gradient**

  - Migrating molecules (e.g., residual monomers and unbound additives) naturally move from high-concentration zones (plastic matrix) to low-concentration zones (food), following Fick's laws (Knight & Creighton, 2004; Compette & Ernoult, 2000).
  - This molecular flow passes through pores and free spaces in the polymer structure (Knight & Creighton, 2004; Philibert et al., 2002).

- **Solubility Differential Mechanism**

  - Lipophilic additives (e.g., phthalates, stabilizers) preferentially migrate into fatty foods via oil/water partitioning, determined by their octanol-water partition coefficient (Log P) (Knight & Creighton, 2004; Kouamé, 2004). Example: DEHP (phthalate) migration from PVC film into fatty cheese.
  - Polar monomers (e.g., caprolactame from polyamides) diffuse more into aqueous matrices (Knight & Creighton, 2004; Philibert et al., 2002).

- **Transfer Dynamics**

  - Initial phase: Surface migration via desorption of molecules adsorbed at the plastic-food interface (Knight & Creighton, 2004; Compette & Ernoult, 2000). Example: BPA migration in water bottles exposed to sunlight.
  - Diffusion-controlled phase: Transfer limited by polymer matrix diffusion rate, following Fick's first law:

$$J = -D\frac{\partial C}{\partial x}$$

Where:

- ✓ *J*: Migratory flux (mass transfer per unit time and area)
- ✓ *D*: Diffusion coefficient (molecular mobility in the medium)
- ✓ $\partial C/\partial x$: Concentration gradient (Knight & Creighton, 2004; Philibert et al., 2002).

Table II-6: Types of Migrants (*adapted from* (Knight & Creighton, 2004; Philibert et al., 2002., Kouamé, 2004)

Type of Migrant	Origin	Dominant Mechanism
Residual monomers	Incomplete polymerization	Free molecular diffusion
Non-reactive additives	Plasticizers, stabilizers	Solvent/polymer partitioning
Oligomers	Short polymer chains	Brownian motion

Experimental studies on PVC show a two-stage kinetic process: rapid initial migration (0–24 h) followed by a slow diffusion-controlled phase (Philibert et al., 2002; Kouamé, 2004). Techniques like IR spectroscopy and HPLC track these dynamics (Philibert et al., 2002; Knight & Creighton, 2004).

Migration can be unidirectional (plastic → food) or bidirectional, with simultaneous absorption of food compounds altering polymer structure (Knight & Creighton, 2004; Philibert et al., 2002). Regulations distinguish global migration (total mass transfer) from specific migration (targeted compounds), both critical for health risk assessments (Knight & Creighton, 2004; Compette & Ernoult, 2000).

II-1-2 Factors Influencing Migration (Temperature, pH, Food Lipophilicity)

- ✓ **Temperature:**

  Diffusion coefficient (DD) follows the Arrhenius equation. In glassy polymers near their glass transition temperature (TgTg), the WLF model applies (Etienne & David, 2002).

- ✓ **pH:**

  The pH of the food plays a crucial role in the migration of additives and monomers from the plastic to the food. Acidic or basic conditions can influence the solubility and reactivity of the chemical compounds present in the packaging (Bach, 2011)

- ✓ **Acidic environments**: Foods with a low pH, such as fruit juices or vinegar-based preserves, can accelerate the degradation of certain plastics, thereby increasing the migration of chemical substances. For example, bisphenol A (BPA) in epoxy resins is more likely to be released under acidic conditions.
- ✓ **Basic environments**: Similarly, a high pH can affect the stability of polymers and facilitate the migration of certain additives, although the effect is generally less marked than in acidic environments.
- ✓ **Neutrality and interactions**: Neutral foods (pH ≈ 7) generally limit migration, but other factors such as temperature and food lipophilicity can interact with pH and alter the diffusion rate of chemical compounds.

  Thus, the pH of the food, in combination with other parameters, strongly influences the migration process of plastic additives and monomers.

- **Lipophilicity:**

  The lipophilicity of food plays a key role in the migration of plastic additives and monomers into foodstuffs. The lipophilic substances contained in plastic packaging, such as phthalates and certain antioxidants, have a particular affinity for fatty environments. Foods rich in lipids, such as oils, dairy products, fatty meat or fish, encourage greater extraction of these compounds. This migration is also influenced by the nature of the polymer used: certain plastics, such as PVC or polyethylene, contain additives that dissolve more easily in fats. In addition, factors such as temperature and the length of contact between the food and the packaging can accelerate this phenomenon, increasing exposure to chemical contaminants. It is therefore essential to take into account the lipophilicity of foods when assessing the risks associated with the migration of plastic substances in the food chain. (Ricard, 2011)

II-1-3- Hazardous Migrants from Plastic Packaging

The transfer of chemical substances from plastic food packaging into consumables represents a significant food safety challenge.

II-1-3-1 Critical Compounds and Sources

- ✓ **Phthalates (DEHP, DBP, DIBP)**: Phthalates (DEHP, DBP, DIBP)

Phthalates are plasticisers commonly used in food packaging, notably in PVC, composite boards containing layers of aluminium and plastic, and in certain polypropylenes as catalyst residues. Their migration into food is strongly influenced by their lipophilic affinity, which means that they are released to a greater extent in the presence of fatty foods. In addition, temperatures above 40°C lead to an exponential increase in their transfer. Studies have shown concentrations of up to 53,579 ng/g in processed dishes such as frozen ravioli (Wayne Labs, 2025).

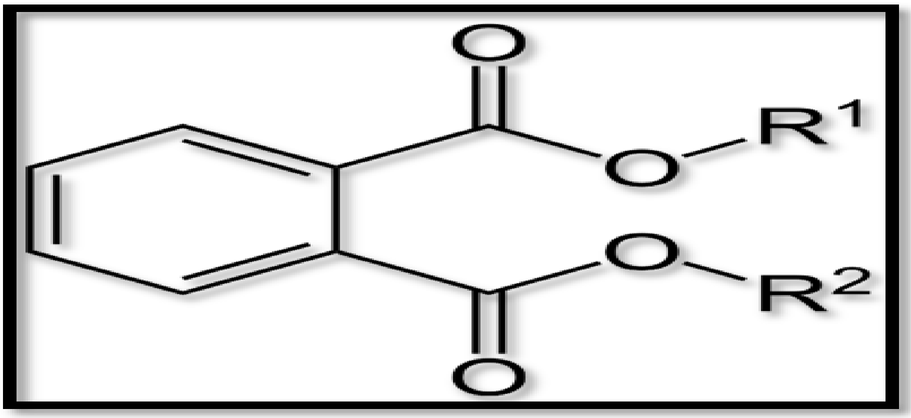


Figure II-8:General structure of phthalates(Federal Office of Public Health (FOPH,2021))

- ✓ **BPA: Bisphenol A (BPA)**

BPA is mainly found in the inner linings of food cans, where it is used in the form of epoxy resins, as well as in polycarbonates used in the manufacture of feeding bottles and reusable tableware. Recent studies have shown that 79% of foods tested were contaminated with BPA, with concentrations as high as 105 ng/g in some cans. This is all the more worrying given that BPA is a recognised endocrine disruptor (Manzoor et al., 2022).

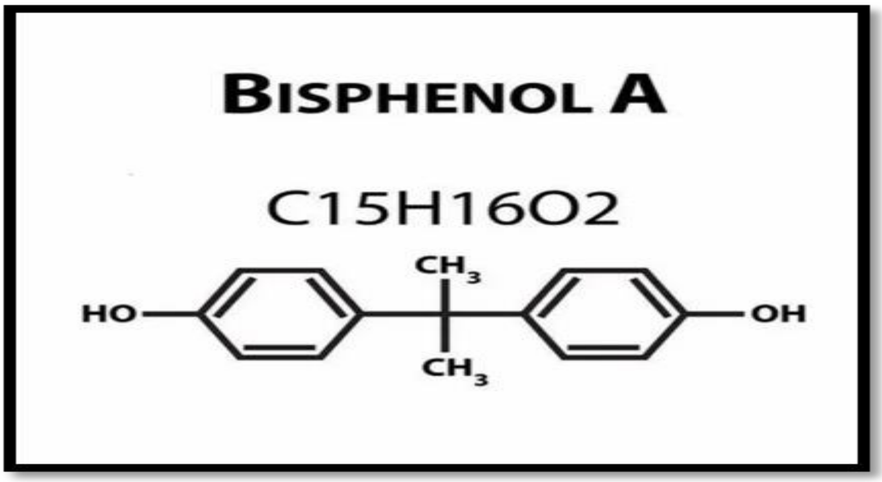


Figure II-9 General structure of phthalates(Federal Office of Public Health (FOPH),2021)

- ✓ **Antimony**

Antimony is used as a catalyst in the manufacture of polyethylene terephthalate (PET), a material used in water bottles and some food trays. Its migration into food is influenced by the acidity of liquids, such as fruit juices, and by storage temperature. Analyses have revealed concentrations of between 200 and 900 µg/g in some PET packaging, raising questions about its potential impact on human health (Turner &Filella, 2017).

- ✓ **Styrene**

Styrene is a compound found in expanded polystyrene packaging, often used for cups and meat packaging. It is also used in certain containers designed for microwave use. Migration of styrene into food is particularly marked when the temperature rises: it is multiplied by 4 when food is heated to 70°C compared to 25°C. In addition, its release is greater in lipid matrices such as milk and cheese, thus increasing consumer exposure to this potentially carcinogenic substance (Sadighara et al., 2022).

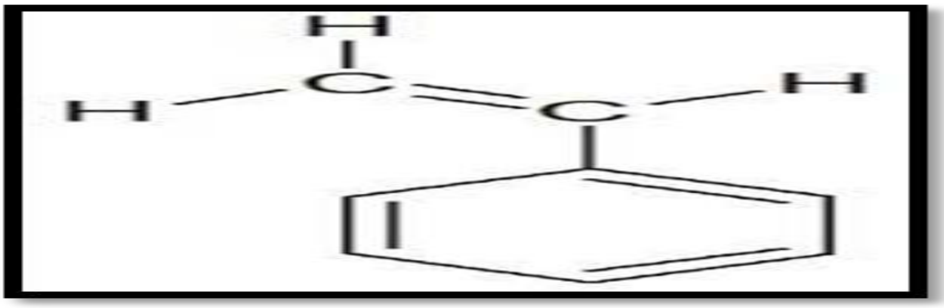


Figure II- 10 General structure of styrene (N. Bonnard, 2019)

II-1-3-2 Effects on human health

- Endocrine disruption: Bisphenol A (Vandenberg, L. N., et al. (2012).) and phthalates (Swan, S. H., et al. (2005) are known to impair fertility, as demonstrated by several studies carried out on rats.

- Neurotoxicity: Exposure to styrene has been associated with cognitive loss and neurological disorders (Cruzan, G., et al. (2018).

- **Carcinogenicity:** Styrene is classified by the International Agency for Research on Cancer (IARC) as a probable carcinogen (IARC. (2019).

Although polyethylene terephthalate (PET) is often considered a safer alternative, its behaviour under certain conditions remains a cause for concern. One study has shown that variations in pH and temperature can lead to the release of phthalate derivatives, even in this material. It is therefore essential to maintain continuous monitoring, particularly for the most vulnerable populations, such as infants and pregnant women, who are frequently exposed to these substances via feeding bottles and cans (Fox, 2024).

Migration mechanisms describe the transfer of substances from plastic materials to food. This phenomenon depends on many factors, such as the nature of the plastic, the additives, the temperature, the contact time and the type of food. A good understanding of these mechanisms is essential to prevent health risks. It also helps guide the choice of packaging materials. Finally, this knowledge supports the development of reliable analysis methods and effective regulatory standards.

II-2 Case Studies on Food Contamination

The impact of plastic packaging on food quality has been widely documented through various case studies. This research has revealed that certain plastic additives migrate into food, particularly under favourable conditions such as exposure to heat or prolonged storage.

Cases of contamination by BPA in tins and by phthalates in fatty foods are good examples of the risks involved. Such contamination is all the more worrying for vulnerable groups such as infants, pregnant women and the elderly, who are more sensitive to the effects of these substances.

II.2.1 Examples of contamination

- Migration of BPA into cans.

Bisphenol A (BPA) is a chemical compound used in the manufacture of epoxy resins, which are often used as internal linings in cans to prevent corrosion and preserve food quality. However, studies have shown that BPA can migrate from these linings into food, raising concerns about food safety.

A survey conducted by Health Canada revealed the presence of BPA in almost all of the 78 canned food products analysed. Concentrations varied according to the type of product:

Canned tuna had the highest levels, with an average of 137 ng/g and a maximum of 534 ng/g. canned soups followed with an average of 78 ng/g, with condensed soups showing higher levels than ready-to-serve soups. On the other hand, canned tomato pastes showed lower levels of BPA, with an average of 1.1 to 2.1 ng/g.

These variations suggest that factors such as the nature of the food, the type of coating used and storage conditions may influence BPA migration. Although the concentrations detected are below the established safety limits, the systematic presence of BPA in canned foods highlights the need for ongoing monitoring and the exploration of safer alternatives for food packaging materials.

It is important to note that, despite regulations aimed at limiting the use of BPA, traces of this compound continue to be detected in certain food products. For example, one study found low levels of BPA in a can of soda and a tin of white beans, even after this substance was banned from food containers in France.

These observations reinforce the importance of increased vigilance and ongoing research to fully understand the implications of BPA migration in food and to protect public health(Bureau of Chemical Safety, Food Directorate, Health Products and Food Branch,2009).

- **Migration of phthalates into fatty foods packaged in PVC:**

Phthalates, notably di(2-ethylhexyl) phthalate (DEHP) and dibutylphthalate (DBP), are commonly used as plasticisers in polyvinyl chloride (PVC) to improve its flexibility. However, these compounds can migrate from PVC packaging into foods, particularly those rich in fat, due to their lipophilic nature (Bouchoul et al., 2018).

One study analysed 238 ready meals packaged in plastic and detected DEHP and DBP in 91.5% of the samples. Concentrations of these phthalates increased over time in food, while decreasing in packaging, confirming a gradual migration into food. Fatty foods, such as cakes, had higher concentrations of phthalates, suggesting an increased affinity of these compounds for lipid matrices (Yang et al., 2019).

In addition, a survey by the Swedish Chemicals Agency (KEMI) revealed the presence of DEHP in more than 80% of the packaging materials tested, including those used for food products intended for children. This finding highlights the prevalence of DEHP in food packaging and the potential for migration into fatty foods (Food Packaging and Consumer Safety, 2024).

Factors influencing phthalate migration include storage time and temperature, as well as the nature of the food. Fatty foods favour increased migration due to the affinity of phthalates for lipids (Yang et al., 2019). Therefore, it is essential to monitor and regulate the use of phthalates in food packaging, particularly for high-fat foods, to minimise the health risks to consumers (Bouchoul et al., 2018).

II.2.2 Impact on vulnerable groups

Children, pregnant women, the elderly. Endocrine disruptors (EDs) are chemical substances that alter the hormonal functioning of living organisms, leading to a range of adverse effects on human health. Vulnerable groups, such as children, pregnant women and the elderly, are particularly sensitive to these disruptions: (Rasooly et al., 2024).

Children and pregnant women:

Exposure to POPs during pregnancy can have serious consequences for the development of the foetus. EPs can cross the placental barrier, affecting the development of the foetus's organs and hormonal systems, which can lead to birth defects, neurodevelopmental disorders and long-term health problems. Children exposed to POPs may experience growth problems, abnormal sexual development and an increased risk of chronic illness in adulthood.

Seniors:

Although specific data on the impact of EPs in the elderly is limited, it is reasonable to consider this population to be vulnerable due to physiological changes associated with ageing, such as reduced liver and kidney function, which may affect the body's ability to eliminate these substances. In addition, the accumulation of EPs over the course of a lifetime can contribute to the development of chronic diseases such as diabetes, cardiovascular disease and certain cancers.

In conclusion, it is essential to protect vulnerable groups from exposure to endocrine disrupters by strengthening regulations, raising public awareness of the potential sources of these substances and promoting healthy lifestyles to minimise the associated risks.

II.3. Analysis and detection methods:

Various analytical methods are used to better understand and control the migration of chemical substances from packaging to food. These techniques enable contaminants to be detected and quantified accurately, even at very low concentrations. Gas chromatography(GC) and liquid chromatography (HPLC), often coupled with mass spectrometry (MS), areamong the most effective approaches. However, these analyses require rigorous protocols and standardised sampling methods to guarantee reliable and comparable results.

II.3.1 Analytical techniques:

Phthalates, bisphenol A (BPA), antimony and styrene are compounds of concern due to their potential presence in food contact materials and their adverse effects on human health. Various analytical techniques are commonly used to detect and quantify these substances (Grinbaum et al., 2019).

- Gas chromatography (GC): This technique is frequently used to analyse phthalates and styrene. It allows the volatile compounds present in a sample to be separated, making it easier to identify and quantify them.

- High-performance liquid chromatography (HPLC): HPLC is particularly useful for analysing bisphenol A (BPA) and certain less volatile phthalates. It offers efficient separation of non-volatile or thermolabile compounds, which is essential for accurate analyses.

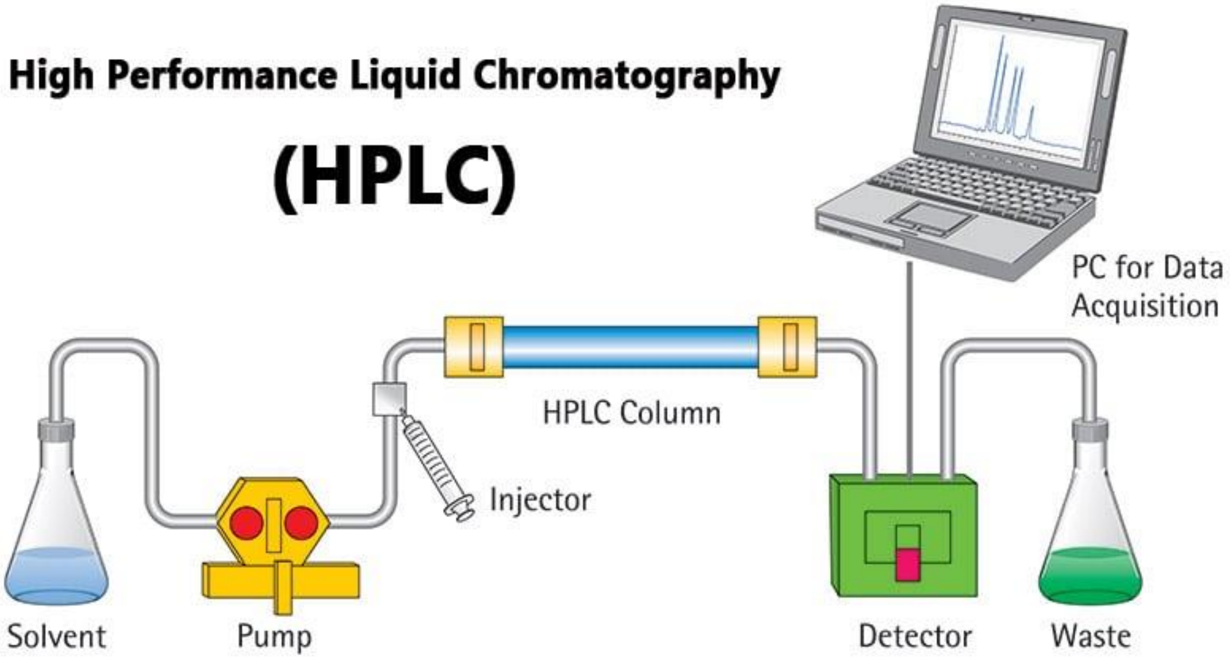


Figure II-11: Diagram of a high-performance liquid chromatography (HPLC) system used to analyse BPA and phthalates. https://microbenotes.com/

- **Mass spectrometry (MS):** Often coupled with chromatographic techniques (GC-MS or HPLC MS), mass spectrometry enables precise identification of compounds based on their mass-tocharge ratio. This combination improves the sensitivity and specificity of analyses, making it possible to detect low concentrations of contaminants. The application of these analytical techniques is essential to ensure food safety by detecting the presence of contaminants such as phthalates, BPA, antimony and styrene in food products.

II.3.2 Detection limits:

The detection limits of analytical methods are essential for accurately identifying contaminants at very low concentrations in food matrices. The sensitivity and specificity of these methods vary according to the technique used, the nature of the contaminant and the complexity of the food matrix.

- **Gas chromatography coupled to mass spectrometry (GC-MS):** This technique is commonly used to detect contaminants such as bisphenol A (BPA) in foods. For example, a method using GC-MS after extraction and derivatisation achieved a limit of quantification of around 0.01 mg/kg for BPA in food matrices. (Analytical, 2024)
- **High-performance liquid chromatography coupled to tandem mass spectrometry (LC-MS/MS):** analysis of BPA using LC-MS/MS demonstrated a limit of quantification of approximately 10 µg/kg in polymeric materials. (Analytical, 2024)
- **Detection by fluorescence:** Some endocrine disruptors, such as BPA, exhibit natural fluorescence, allowing them to be detected without prior derivatisation. Studies have reported detection limits for BPA of between 0.20 and 0.31 ng/L using fluorescence, without a sample concentration step (Assoumani, 2009).

It is important to note that sample preparation, particularly the extraction and purification steps, has a significant influence on the sensitivity and specificity of analytical methods. The use of internal standards, such as deuterated BPA, can improve accuracy by correcting for extraction and ionisation variations. (Murphy, 2022)

In summary, the choice of analytical method depends on the specific objectives of the analysis, the nature of the contaminant being investigated and the food matrix being studied. Modern techniques offer high sensitivities, enabling the detection of contaminants at very low concentrations, which are essential for ensuring food safety.

II.3.3 Sampling standards:

Sampling standards for the analysis of chemical migrants in foodstuffs are based on rigorously established international protocols and specific national regulations, guaranteeing a harmonized and reliable approach to assessing the risks associated with materials incontact with food. These standards define a set of fundamental principles that must be scrupulously respected to ensure that the samples taken are representative and that the results obtained are reliable.

One of the key principles of sampling is the need to guarantee the representativeness of the samples by taking samples from different points in the food batch in order to best capture the potential variations present within the product being analysed (Hervé, 2021).

These samples must then be combined to form a homogeneous composite sample, thereby minimising analytical bias linked to local disparities observed in the batch tested (FAO/WHO, 2023). In addition, specific precautions must be taken to avoid any external contamination likely to alter the chemical composition of the migrants detected, in particular by using refrigerated storage for volatile substances to avoid their evaporation before analysis (National Health and Family Planning Commission of the People's Republic of China, 2016).

Another essential aspect of the sampling protocol is the stratification of samples, which consists of dividing foodstuffs into several categories according to various criteria such as the geographical origin of the product (Annor, 2009), the seasonality of its production, or the type of packaging used, particularly when it is made of plastics, metals or composite materials (National Health and Family Planning Commission of the People's Republic of China, 2016).

Table II- 07 Protocols specific to plastic migrants

Parameter	Technical requirements (GB Chinese standards)	References
Contact area	Calculation based on actual material/food area	GB 5009.156
Surface/volume ratio (S/V)	6 dm^2 for 1 L of food simulant	GB 31604.1
Food simulants	Selection according to pH/lipids (olive oil, ethanol, acetic acid)	EU regulation
Test temperature	40°C for 10 days (accelerated conditions)	

With regard to migrants from plastics, precise technical requirements are defined by the standards in force, in particular those established by Chinese regulations (GB 5009.156-2016). For example, the contact surface between the food and the material is calculated on the basis of the actual area of interaction between these two elements (National Health and Family Planning Commission of the People'sRepublic of China, 2016). Similarly, the surface/volume (S/V) ratio applicable for migration testing is set at 6 dm^2 of material per 1litre of food simulant, in accordance with the requirements of GB 31604.1-2015 (National Health and FamilyPlanning Commission of the People'sRepublic of China, 2015).

In addition, the selection of food simulants to be used in tests is determined according to the physico-chemical properties of the food concerned, taking into account in particular its pH and lipid content, which implies the use of substances such as olive oil, ethanol or acetic acid (European Commission Joint Research Centre, 2015).

Validated analytical protocols include several essential steps designed to guarantee the integrity of the samples and the accuracy of the results. For example, sample pre-treatment requires materials to be cut without causing thermal or mechanical alterations that could modify the migration of the substances studied (National Health and Family Planningn Commission of the People's Republic of China, 2016). In addition, the use of standardized migration pools is common practice in order to limit analytical variations (National Health and Family Planning Commission of the People's Republic of China, 2015). In terms of quality control, it is imperative to carry out screening tests to ensure that the overall migration of substances does not exceed the regulatory threshold of 60 mg/kg (National Health and Family Planning Commission of the People'sRepublic of China, 2015), while specific analyses of monomers, particularly bisphenol A (BPA) and phthalates, should be carried out nusing high-performance liquid chromatography coupled with mass spectrometry (European,Commission Joint Research Centre, 2015).

III- Environmental Impact of Plastic Packaging

III.1. Plastics Packaging Life Cycle:

III.1.1 Production:

Manufacture of plastic packaging is largely based on the extraction and conversion of fossil resources such as crude oil and natural gas. This production phase is particularly energy- intensive and contributes significantly to greenhouse gas (GHG) emissions. In 2019, the global production of plastics reached 460 million tones, generating around 1.8 billion tonnes of GHGs, which represents almost 3.4% of global emissions. The majority of these emissions (nearly 90%) come from processes linked to the exploitation and treatment of fossil fuels. (OECD, 2022)

Recent studies have also shown that some plastics release greenhouse gases such as methane and ethylene when exposed to sunlight. This increases their contribution to global warming, even after they have been used. These emissions are particularly high when plastics are in the open air, compared with when they are immersed in water (UNEP, 2021).

Finally, the methods used to manage plastic waste in some countries, notably open incineration, further amplify their environmental impact. This type of combustion releases fine carbon particles, which are extremely powerful pollutants whose warming potential is estimated to be 5,000 times greater than that of carbon dioxide (CO_2) (Sea, 2022).

III.1.2 Use:

The lifespan and reusability of packaging are key factors in assessing its environmental impact. Reusable packaging, particularly in the food industry, has been shown to significantly reduce greenhouse gas emissions compared to single-use options.Reusable containers have lower GHG emissions when used multiple times. For example, a reusable container used 100 times can reduce GHG emissions by 83% compared to a single-use container (Yadav et al, 2024).

The lifespan and reusability of packaging is crucial; increased reuse can significantly reduce environmental impacts (Helmes et al., 2022).Reusable takeaway food containers show a substantial reduction in global warming potential (GWP) with increased use. For example, a container used 100 times has a GWP of 0.007 kg of CO2 equivalent per use, compared with 0.020 kg of CO2 equivalent for a single-use container (Yadav et al., 2024).

III.1.3 End-of-life management:

The different end-of-life options, including recycling, incineration and landfill, have distinct environmental impacts. Recycling, particularly mechanical and chemical methods, can reduce the impacts of climate change and resource scarcity (Helmes et al., 2022). Landfill, although still common, is less favourable because of the long-term environmental effects, although it can be optimised to minimise emissions (Izhar & May, 2020). The transport of waste for EoL (end-of-life) treatment also contributes to GHG emissions, with incineration and recycling facilities generating higher emissions than landfill sites (Mousania et al, 2024).

According to a number of studies (including those by the OECD ((Organisation for Economic Co-operation and Developmen), the Ellen MacArthur Foundation and UNEP(United Nations Environment Programme), waste transport accounts on average for between 1% and 5% of total GHG emissions associated with the life cycle of plastics.

III.2. Plastic pollution and ecosystems

III.2.1 Accumulation in the environment:

Plastic pollution is a pervasive environmental problem affecting oceans, soils and waterways, with significant implications for ecosystems. The accumulation of plastic waste, whether microplastics or large debris, is a threat to marine and terrestrial environments. The persistence and resistance of plastics to natural degradation exacerbates their impact, leading to long-term environmental challenges. The following sections explore the different dimensions of plastic pollution and its ecological consequences.

- **Écosystèmes marins**

Plastic pollution of marine environments is a major concern, with more than 300 million tones of plastic produced each year, and around 75% of marine litter is plastic (Sofi, 2020).marine organisms ingest microplastics, which are spread in surface waters and sediments, affecting species at different trophic levels (Pshenichnov, 2024)(Sofi et al, 2020)habitat degradation and the introduction of invasive species, further threatening marine biodiversity (‘Plastic Pollution and Its Impact on Aquatic Fauna’, 2022).

Figure III-12: Plastic pollution in marine ecosystems

https://www.wwf.fr/sengager-ensemble/relayer-campagnes/pollution-plastique

- **Terrestrial and freshwater ecosystems:**

While initial research focused on marine environments, recent studies highlight the accumulation of plastics in terrestrial and freshwater systems (Napper & Thompson, 2023). Microplastics from sources such as road paints and tyre wear have been identified, indicating a wider range of pollution than previously thought (Napper & Thompson, 2023). Contamination of soils and waterways disrupts ecological functions and poses risks to plant and animal life (‘Plastic Pollution and Its Impact on Aquatic Fauna’, 2022).

In conclusion,The accumulation of plastic waste in oceans, soils and waterways is a persistent threat to natural ecosystems. It highlights the need to improve waste management and reduce the production of single-use plastics.

III.2.2 Impact on flora and fauna:

Plastic pollution, particularly through the ingestion of microplastics (MP), is a major threat to marine and terrestrial ecosystems. These tiny plastic particles, less than 5 mm in size, are ubiquitous in aquatic environments and have been found in a variety of species, leading to adverse health effects and ecological imbalances. The following sections describe the, impact of microplastics on flora and fauna, focusing on their effects on ecosystems.

- **Impact on marine fauna**

- **Ingestion and bioaccumulation :** Marine organisms, including fish and crustaceans, Frequently ingest microplastics, leading to bioaccumulation in food webs ("Microplastics in Aquatic Ecosystems: Sources, Impacts, and Challenges for Biodiversity, Food Security, and Human Health - A Meta-Analysis", 2024) (Ali et al, 2024).A study by Farrell & Nelson (2013) showed that microplastics ingested by mussels (Mytilusedulis) are then transferred to crabs (Carcinusmaenas), which feed on them.

- **Effects on health:** Ingestion can cause oxidative stress, reproductive problems and even death due to digestive blockages or internal injuries (Garés & Pires, 2024) (Amaral et al., 2024).

- **Trophic transfer:** Microplastics can transfer pollutants across trophic levels, affecting not only marine life but also humans who consume seafood ("Microplastics in Aquatic Ecosystems: Sources, Impacts, and Challenges for Biodiversity, Food Security, and Human Health - A Meta-Analysis", 2024) (Amaral et al., 2024).

- **Impact on terrestrial ecosystems**

- Soil contamination: microplastics can migrate from aquatic systems to terrestrial environments, impacting soil health and plant growth.

- Effects on flora: Limited studies indicate that microplastics can disrupt plant nutrient uptake and growth, although further research is required (Reshi et al., 2023).

- **Balance of ecosystems :**

The ubiquitous nature of microplastics threatens biodiversity and ecosystem stability, requiring urgent measures for waste management and pollution control ("Microplastics in Aquatic Ecosystems: Sources, Impacts, and Challenges for Biodiversity, Food Security, and Human Health - A Meta Analysis", 2024) (Reshi et al., 2023).

Although the focus has been on aquatic ecosystems, the potential impacts on terrestrial environments and human health remain underexplored, highlighting a critical area for future research and policy intervention.

In summary, the ingestion of microplastics by marine animals and their effects on ecosystems demonstrate the scale of the ecological consequences of plastic pollution. Biodiversity, both terrestrial and aquatic, is directly threatened by this contamination.

III.2.3 Microplastics:

The following sections describe the formation, dispersion and impact of microplastics on the food chain.

- **Formation of microplastics**

- Sources: Microplastics come from both primary sources (small manufactured plastics) and secondary sources (degradation of large plastic articles) (Saeedi, 2023) (Kushbu et al.,2024).
- Chemical composition: They are made up of various thermoplastics and thermosets, which can adsorb toxic chemicals from the environment, increasing their harmful potential (Saeedi, 2023) (Kushbu et al., 2024).

- **Dispersion in ecosystems**

- **Environmental ubiquity:** Microplastics are present in terrestrial, aquatic and atmospheric environments, with significant accumulation in marine ecosystems (Altaf, 2021)("Microplastics in agroecosystems-impacts on ecosystemfunctions and foodchain", 2022).
- **Transport mechanisms:** they enter food chains through ingestion by aquatic organisms, Bioaccumulate at higher trophic levels and can also affect terrestrial plants (Kushbu et al., 2024) ("Microplastics in agroecosystems-impacts on ecosystemfunctions and foodchai", 2022).

- **Impact on the food chain**

- **Biological effects:** Ingestion of microplastics can cause physical damage, growth retardation, reproductive problems and immune system disruption in marine species (Dehaut& Duflos, 2023) (Kushbu et al., 2024).

Although the main focus has been on marine organisms, the implications of microplastics extend to terrestrial ecosystems and human health, requiring further research and policy interventions to mitigate their impact.

III.3. Plastics Waste Management Strategies:

Plastic waste management strategies, particularly mechanical and chemical recycling technologies, face significant challenges related to sorting, contamination and the quality of recycled materials. Although mechanical recycling is a long-standing method, it is often hampered by issues such as contamination and material degradation, which can result in lower quality recycled products (Knauer, 2022) (Sambyal et al., 2024). Conversely, chemical recycling represents a promising alternative by converting mixed plastics back into monomers, but it also faces obstacles such as high operational costs and scalability issues (Biessey et al, 2023) (Jiang &Bateer, 2025).

III.3.1 Recycling:

Recycling is defined as the process of collecting and treating materials that would otherwise be discarded as waste, to transform them into new products. This practice not only conserves resources, but also minimises environmental impact by reducing the need for raw materials and cutting greenhouse gas emissions. The growing complexity of waste management, driven by global consumerism, requires innovative recycling strategies and technologies to deal with different types of waste (Introduction, 2022)

III.3.3.1 Mechanical Recycling

A. Inspection of Inputs

Before any treatment, the plastic waste is carefully inspected to detect the possible presence of contaminants (organic residues, metals, incompatible materials …) . This stage also enables to identify the types of plastics present to ensure that they are compatible with the plant’s processing capacity. Some recycling plants specialize in a single type of plastic , while others can process several.

B. Washing and shredding:

The accepted plastics are then shredded into flakes or flakes and washed to remove any remaining impurities, such as labels, adhesives or product residues. The water used in this phase is not harmful to the environment: it can be filtered, purified and reused in a closed circuit in the process.

C. Sorting by flotation:

When the stream contains different types of plastic, these can be separated using a flotation tank. This process is based on the difference in density between the polymers: some plastics (such as polypropylene) float to the surface, while others (such as PET) sink. This physical sorting makes it possible to better isolate each type of plastic to optimise the quality of the final recyclate.

D. Drying:

Clean plastic pellets should be carefully dried to remove any residual moisture. Even small amounts of water can alter the properties of the melted plastic and compromise the quality of the final product.

E. Melting:

The dry pellets are fed into an extruder, where they are heated and melted under the combined effect of heat and pressure. It is essential to adapt the temperature according to the type of polymer, as each plastic has a specific melting temperature.

F. Filtration :

Once liquefied, the plastic passes through a very fine filter designed to remove any remaining impurities or contaminants that may have resisted the previous cleaning stages.

G. Granulation:

The filtered plastic is then cooled, generally in the form of filaments, and cut into small granules. These granules are then packaged for storage, marketing or dispatch to production sites (Djaouti Sonia, 2015).

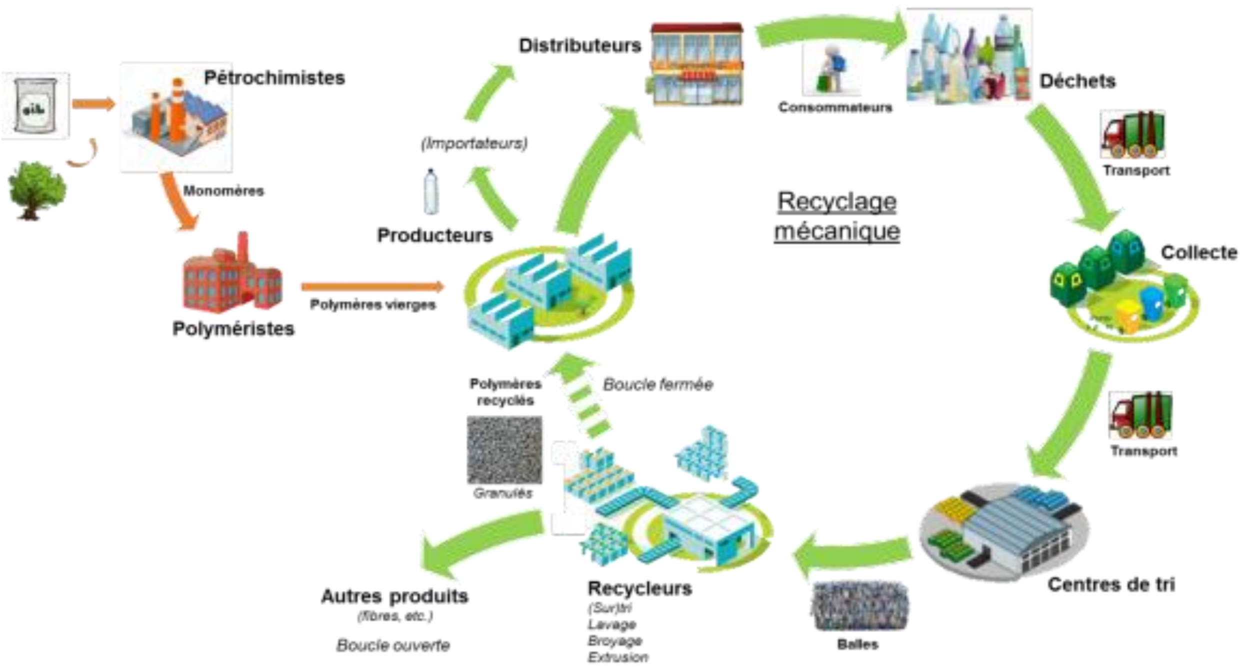


Figure III- 13:Plastics value chain: from resource to post-consumer waste recycling(IFP Energies nouvelles (IFPEN[1])

III.3.1.2Chemical recycling of plastics :

Chemical recycling of plastic waste refers to the process of breaking down plastics into their constituent monomers or other useful chemicals by various chemical methods. This approach is essential for tackling the growing plastic waste crisis and promoting a circular economy, in which materials are reused rather than thrown away. Chemical recycling encompasses several techniques, including pyrolysis, gasification, hydrothermal conversion and solvolysis, which convert plastic waste into valuable raw materials or fuels (Sadia et al., 2024) (Choi & Lee, 2024) (Nurgaliyev et al., 2024) (Nurgaliyev et al., 2024).

[1]**IFP** : Institut Français du Pétrole

EN : Énergies Nouvelle

- Key techniques in chemical recycling

- Pyrolysis: This method involves heating plastic waste in the absence of oxygen, resulting in the production of oils and gases that can then be refined into fuels or chemicals (Nurgaliyev et al., 2024).
- Gasification: Similar to pyrolysis, gasification converts plastics into syngas, which can be used for energy production or as a chemical feedstock (Choi & Lee, 2024).
- Hydrothermal conversion: This technique uses water at high temperatures and pressures to break down plastics into smaller molecules (Choi & Lee, 2024).
- Solvolysis: involves the use of solvents to break down plastics into monomers, enabling potential depolymerisation (Trzebiatowska, 2022).

- **Limits and challenges**

- **Sorting challenge:**

Different types of plastic: The presence of different types of plastic, such as polyethylene (PE), polypropylene (PP), etc., complicates the classification process. Each type has different properties, which makes it difficult to achieve high-quality separation (Sable et al., 2024) (Oyewale et al., 2023).

Traditional or automated sorting: traditional sorting methods, although accurate, are expensive and have a low throughput. Automated sorting techniques are being developed to overcome these limitations, but they require significant investment and technological advances (Oyewale et al., 2023).

- **Pollution problems :**

Food scraps and other contaminants: Contaminants such as food scraps can seriously degrade the quality of recycled plastics, particularly materials such as PE. This contamination requires additional cleaning processes, which increases the cost and complexity of recycling (Sable et al., 2024).

Medical and electronic waste: highly contaminated plastic waste from medical and electronic sources poses new challenges as it requires specialised handling and treatment to ensure safe and efficient recycling (Prajapati et al., 2021).

- **Quality of recycled materials:**

Homogeneity of materials: The quality of recycled plastics depends largely on the homogeneity of the recycled raw materials. Variability in raw materials leads to inconsistencies in recycled products, affecting their marketing and application (Alassali et al., 2021).

Economic feasibility: The lower value of recycled materials compared to virgin plastics poses an economic challenge. This disparity hinders investment in recycling infrastructure and technology development (Sable et al., 2024).

- **Levels of impurities in recycled plastics:**

- **General findings:** Impurities in recycled plastic packaging waste (PPW) have been estimated at between 4.40% and 6.90%, which has a significant impact on recycling rate calculations (Waszczyłko-Miłkowska et al., 2024).
- **Sources of contamination:**Common contaminants include product residues, labels and adhesives, which can lead to quality problems during recycling(Auer et al., 2023) .
- **Thresholds of acceptability:** Research indicates that for some applications it is necessary to maintain contamination levels below 1,000 ppm to comply with regulations and ensure material safety(Strobl et al., 2021).

III.3.2 Energy recovery :

Energy recovery through incineration with energy recovery is a viable solution for managing municipal solid waste (MSW) and automotive shredder residue (ASR). This process not only reduces reliance on landfill, but also converts waste into usable energy, contributing to a circular economy. The following sections describe the key aspects of this approach.

III.3.2.1Incineration process and energy recovery:

Incineration of ASR and solid waste can recover significant amounts of energy; It has been shown that co-incineration of ASR with refuse derived fuel (RDF) in a fluidized bed combustor can recover 27% of the energy value of ASR while keeping emissions below regulatory limits (Vermeulen et al., 2012). The EU R1 energy efficiency standard considers incineration as energy recovery, and projections indicate that municipal solid waste in regions such as Izmir has huge potential for energy production (Başaran, 2022).

III.3.2.2 Challenges and considerations:

The heterogeneous composition of RDF poses challenges for energy recovery, and its properties need to be improved for efficient incineration (Santos et al., 2023). Although incineration is a mature technology, alternative technologies such as gasification are emerging due to reduced costs and emissions, indicating the need for ongoing evaluation of waste-to-energy technologies (Santos et al., 2023).

- **Impact on GHG emissions:**

Energy recovery from plastic waste has a significant impact on greenhouse gas (GHG) emissions, presenting both challenges and opportunities for climate change mitigation. Various studies highlight the benefits of recycling and energy recovery methods, particularly chemical recycling, which can significantly reduce GHG emissions compared to traditional incineration. The following sections deal with these aspects:

- **GHG emissions from chemical recycling**:

Chemical recycling of mixed plastic waste generates greenhouse gas benefits of around 0.82 kg CO2e per kg of waste processed, which could potentially rise to 1.37 kg CO2e by 2030 through process optimization and decarbonization efforts(Hulst et al., 2022).This approach not only reduces emissions, but also avoids the production of raw materials, thereby enhancing its environmental benefits.

- **Energy recovery and GHG reduction:**

Incineration with energy recovery can also reduce greenhouse gas emissions, with one study suggesting that in certain scenarios (Yaman, 2020).

However, the effectiveness of energy recovery varies and the combination of several recovery measures can achieve greater reductions in GHG emissions than relying on a single approach (Judl et al., 2023).

III.3.2.3 Saving resources and environmental impact:

Recycling plastic waste can save significant resources. One study estimates that every tone of recycled packaging plastic saves 853kg of CO2 equivalent, indicating a strong potential for reducing greenhouse gases (Menikpura et al., 2014). Recovering energy from plastic waste not only helps to reduce greenhouse gas emissions, but also brings economic benefits by providing alternative energy sources, particularly in areas with high plastic waste production (Ghodrat&Samali, 2018)

III.3.3 Sustainable Plastics Waste Management Alternatives:

Sustainable alternatives to traditional plastics, such as bioplastics, compostable packaging and source reduction strategies, are gaining ground as solutions to mitigate plastic pollution. Bioplastics, derived from renewable resources, are a biodegradable option that can significantly reduce environmental impact. However, challenges remain in terms of scalability and cost-effectiveness, requiring collaboration across sectors for successful implementation. The following sections examine the key aspects of these alternatives:

- **Bioplastics:**

- **Definition and types:** Bioplastics are made from renewable resources and can be biodegradable or compostable. Common types include PLA (Polylactic Acid), PHA (Polyhydroxyalkanoates)and PBS (Polybutylene Succinate) (Jabeen et al., 2024) (Cruz et al., 2022).
- **Applications:** They are used in a variety of industries, including packaging, agriculture and biomedical devices, demonstrating their versatility (Jabeen et al., 2024).
- Environmental benefits: Bioplastics can reduce greenhouse gas emissions and plastic waste, contributing to a more sustainable future (Jabeen et al., 2024).

- **Compostable packaging:**

- Consumer perception: There is a common misconception that all bioplastics are compostable; however, true compostability requires specific conditions (Sullivan, 2023).

- Research initiatives: Studies, such as those conducted at the University of South Florida, are exploring the effectiveness of bioplastics in home composting environments (Sullivan, 2023).

  - **Source reduction:**

- Importance: it is crucial to reduce the overall consumption of single-use plastics. This can be achieved through innovative packaging solutions and consumer education (Khandeparkar et al., 2024) (Cruz et al, 2022).
- Industry trends: The food industry is increasingly focusing on sustainable packaging to minimise environmental impact, with an emphasis on the need for biodegradable materials (Khandeparkar et al, 2024).

  - **Example:**Unilever has put in place an ambitious strategy to reduce its use of virgin plastics by 50% by 2025. This includes the elimination of unnecessary packaging, the introduction of reusable or refillable packaging, and the use of alternative materials such as coated paper or compostable bioplastics. For example, in certain brands of cleaning products, Unilever has launched concentrated refill systems that use up to 70% less plastic than the standard format (Unilever, 2021). This approach combines innovation in design, communication with consumers and logistical adaptation, demonstrating that effective reduction at source is achievable on a large scale.

In short, effective management of plastic waste is based on the complementary nature of recycling, energy recovery and sustainable alternatives. However, only a reduction at source, supported by innovation and responsible policies, will make it possible to limit the environmental impact of plastics in the long term.

IV. Materials And Methods

IV.1 Study Framework and Context

This study was conducted at the Ppubionut research laboratory of the Faculty of Natural and Life Sciences, Earth and Universe, University of Tlemcen. It aims to assess the effects of plastic packaging on food safety and the environment through two complementary approaches:

1. A consumer survey involving 121 Algerian participants,
2. Laboratory analyses of food samples packaged in plastic obtained from the local market.

The objective of this survey is to assess consumer perceptions, knowledge, and behaviors regarding the use of plastic packaging in the agri-food sector and to evaluate its perceived impact on food safety and the environment. It complements technical laboratory analyses by providing a local societal perspective, essential for a comprehensive and circular approach to the problem.

This combined approach will provide a global view of the issues surrounding plastic packaging, while suggesting solutions for reconciling food safety and environmental protection.

IV.2 Description of the study area

The study was carried out in the wilaya of Tlemcen, located in north-west Algeria. Tlemcen is a major urban center in the region, characterized by a mix of traditional markets and modern retail outlets, making it an ideal location for investigating plastic packaging usage patterns in both formal and informal food distribution systems.

The study area encompasses:

- Local markets and supermarkets in Tlemcen city, where food samples were collected,
- Diverse consumer demographics across urban and semi-urban neighborhoods,
- Industrial zones near the city, which include small-scale food processing units relying heavily on plastic packaging.

IV.3 Consumer questionnaire survey

IV.3.1 Survey Objectives

The survey seeks to:

- Examine consumption habits of plastic-packaged foods,
- Assess perceptions of health and environmental risks associated with such packaging,
- Identify consumer knowledge regarding recyclability, labeling symbols, and plastic impacts,
- Determine preferences for more sustainable alternatives.

IV.3.2 Questionnaire Design

The questionnaire, was administered in both French and Arabic to ensure broad accessibility. It consists of 19 closed-ended questions, structured around the following themes:

- Purchasing habits of packaged products,
- Perceived impact on food quality,
- Awareness of health and environmental risks,
- Ecological attitudes (recycling, alternative preferences).

IV.3.3 Distribution Methodology

- Disseminated via Google Forms through social media and email,
- Data collection period: 1 month,
- Sample size: 121 Algerian consumers with diverse demographics (age, education level, geographic location).

IV.4 Physicochemical Analyses

IV.4.1 Plastic Type Identification

- **Objective:**
    - Identify plastic types used in food packaging
    - Assess their recyclability potential.

- **Materials used:**

- Packaging samples (bags, bottles, films),
- Saltwater (30 g/L),
- Pure acetone,
- Scissors, glass bowls.
-

- **Procedure:**

Cut into 1x1 cm pieces

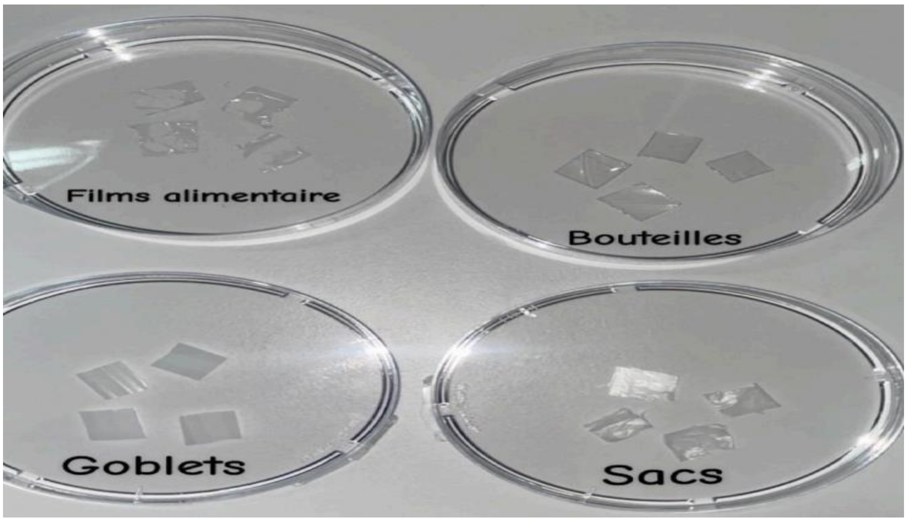


Figure IV-14: Sample pieces

➢ **Flotation test:**

Immerse the samples in salt water.

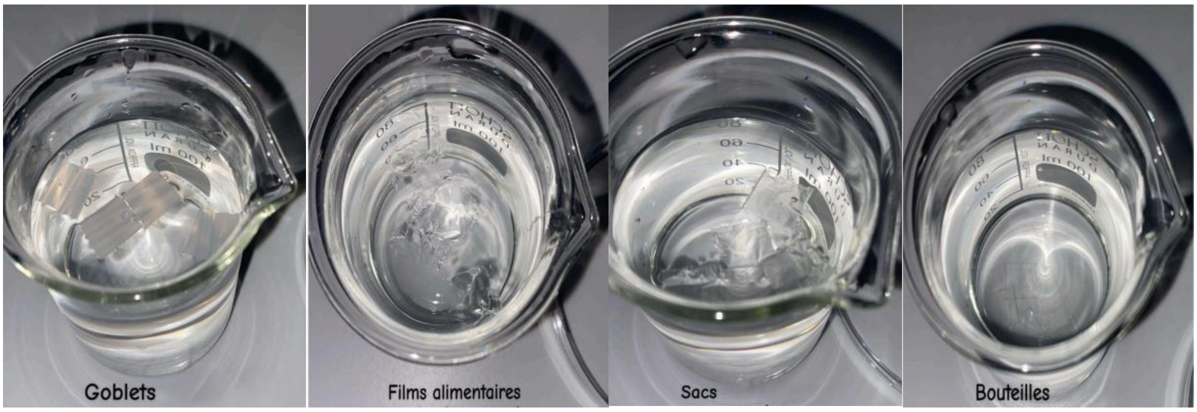
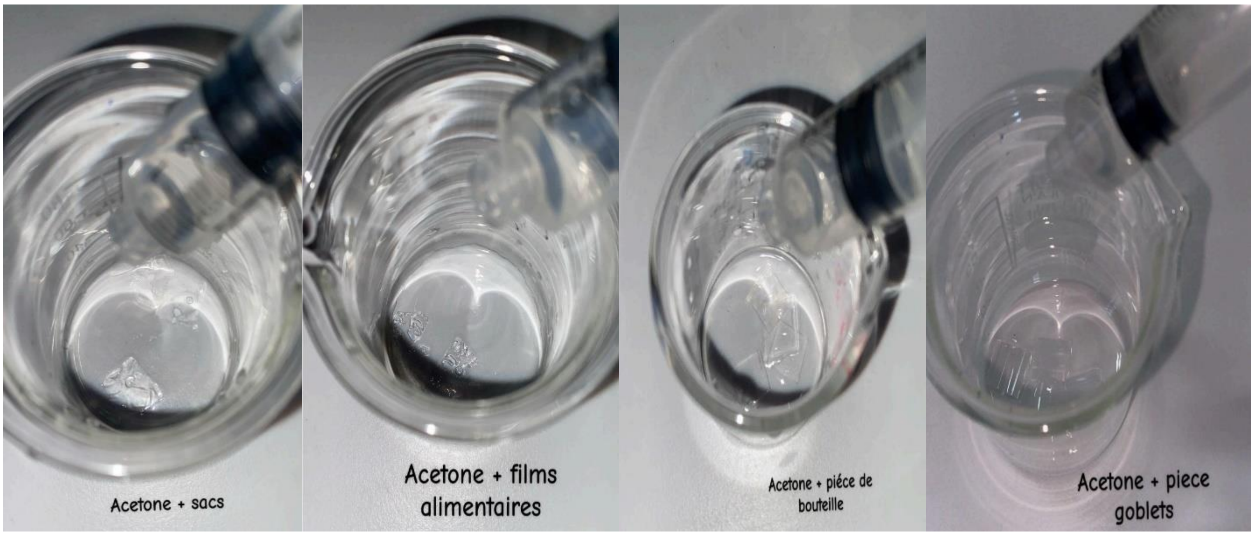


Figure IV-15: Flotation test

- **Flotation test:** Floting samples indicate **PE or PP** (highly recyclable), while sinking samples suggest **PET or PVC**.

➢ **Solubility test:**

Add a few drops of acetone to the plastic samples



FigureIV- 16: Solubility test

- **Acetone solubility test:** Dissolution indicates **polystyrene (PS)**, considered less safe.

IV.4.2 Plastic Biodegradation Test

- **Objective:** Evaluate plastic persistence in a simulated environment.

- **Materials used:**

  - Glass jars, compost/soil,
  - kitchen scale,
  - plastic samples.

Procedure:

- Burial of plastics in compost for 30 days**,**
- Weekly weighing to measure mass loss.

Formula:

$$\text{Biodegradation } \% = \frac{\text{Initial Weight} - \text{Final Weight}}{\text{Initial Weight}} \times 100$$

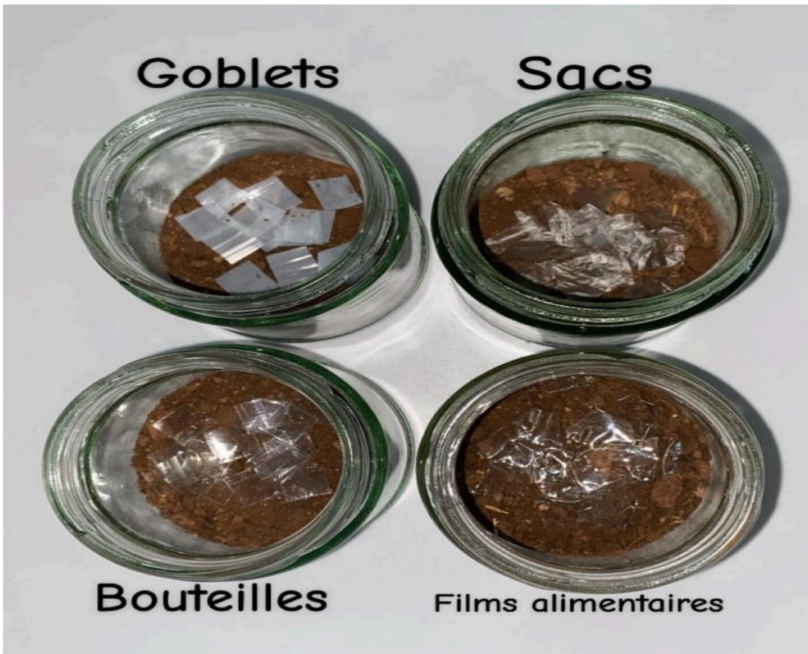


Figure IV- 17 : Biodegradation Test

IV.4.3 Microbiological Analysis

- **Objective:** Assess plastic packaging hygiene by detecting fecal coliforms in packaged foods.

- **Samples analyzed:**

▪ Fresh cheese (1g),
▪ Bottled water (1 mL),
▪ Vacuum-packed meat (1g).

Materials used:

▪ MacConkey agar,
▪ Petri dishes,

- Bunsen burner,
- pipettes,
- sterile knives
- MacConkey agar.
- Balance.

- **Procedure:**

  - Inoculation on agar, incubation at **37°C for 24–48 hours**,
  - Observation of **red colonies** indicating coliform bacteria.

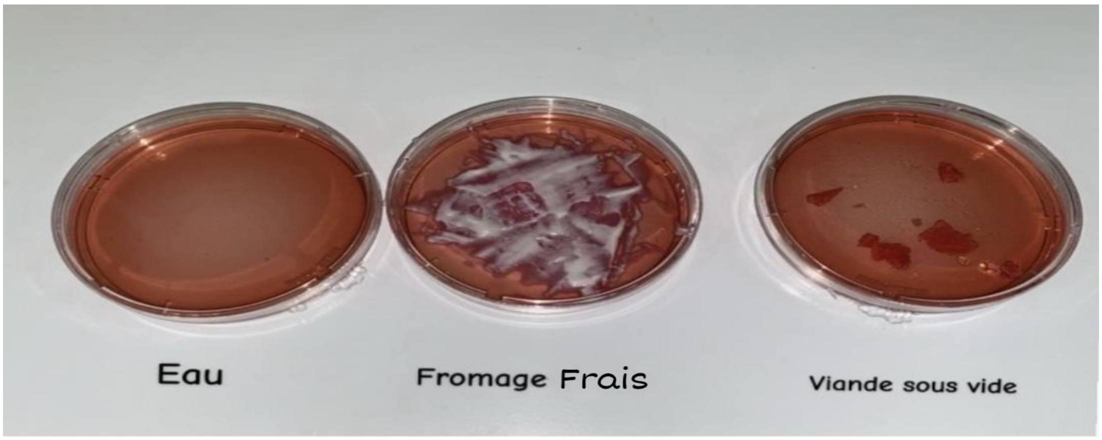


Figure IV- 18: inoculation of water, fresh cheese and vacuum-sealed meat samples onto Macconkey agar.

IV.5.**Data Presentation and Processing**

- Survey results will be analyzed using descriptive statistics (frequencies, percentages),
- Cross-tabulations will be performed
- Laboratory results will be presented in tables, figures, and photographs, with comparative interpretations.

V-1 Questionnaire Survey

This study involved administering a questionnaire to 121 consumers in Algeria's Tlemcen region to examine their behaviors, perceptions, and awareness levels concerning plastic food packaging. The collected data provides valuable insights into purchasing patterns, environmental consciousness, and consumers' understanding of the health and environmental risks associated with plastic packaging materials.

The findings help characterize how consumers interact with plastic-packaged goods while assessing their recognition of both the ecological impacts and potential health implications of such packaging solutions

V-1-1 Socio-demographic characteristics

V-1-1-1 Gender Distribution

A clear predominance of women (80%) was observed, which may reflect their greater involvement in household purchasing decisions, particularly for food items.

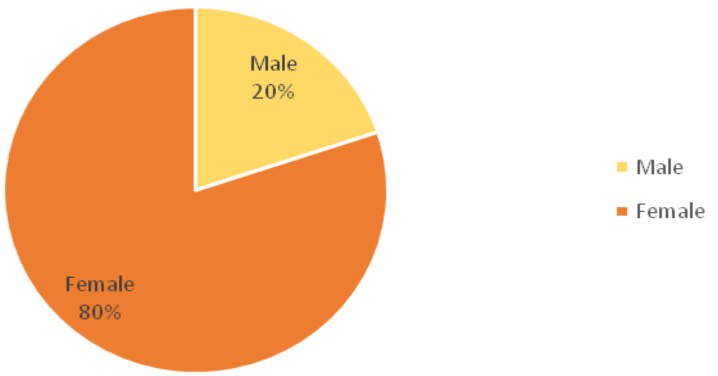


Figure V-19 Distribution of Participants by gender

V-1-1-2 Age Group Distribution

Young people aged 18 to 30 account for 86.8% of the sample, indicating that the results are largely influenced by this age group, which is potentially more aware of environmental issues.

Table V-8 Distribution of participants by age

	Number of participants	Percentage
under 18 years	3	2.5%
18–30 years	105	86.8%
31–50 years	13	10.7%
Over 50 years	0	0
Total	121	100%

V-1-1-3 Socio-professional status

Students (63.64%) predominate, confirming the high proportion of young people in the sample, which also influences the level of awareness observed.

Table V-9 Distribution of the sample by socio-professional class.

	Number of participants	percentage
Student	77	63,64%
Employee	24	19,83%
Free Worker	8	6,61%
Unemployed	12	9,92%
Retired	0	0%
Total	121	100%

The majority of participants (86.78%) have a university degree, compared with only 13.22% who have a secondary education.

V-1-2 Purchasing Behavior and Perception of Plastic Packaging

V.1.2.1 Purchase of Plastic-Packaged Products

97% of participants report buying plastic-packaged products, demonstrating the widespread use of this packaging type.

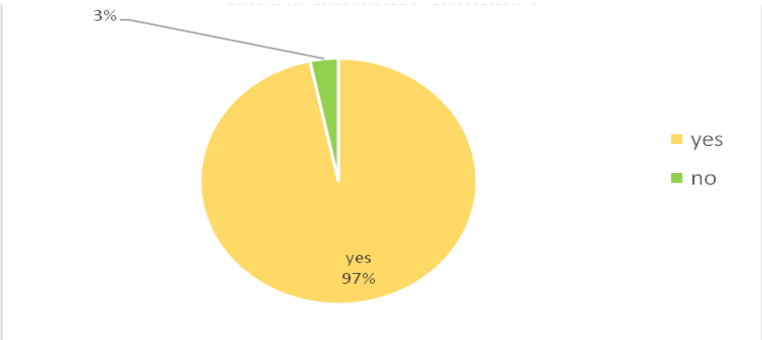


Figure V-20 Frequency of Purchasing Plastic Packaged Products

V.1.2.2 Purchase Frequency

The majority purchases these products regularly: 43% very frequently, 47.1% occasionally.

Table V-10 Frequency of Purchasing Plastic-Packaged Products

	Number of participants	Percentage
Very Often	52	43%
Sometimes	57	47,10%
Rarely	12	9,90%
Total	121	100%

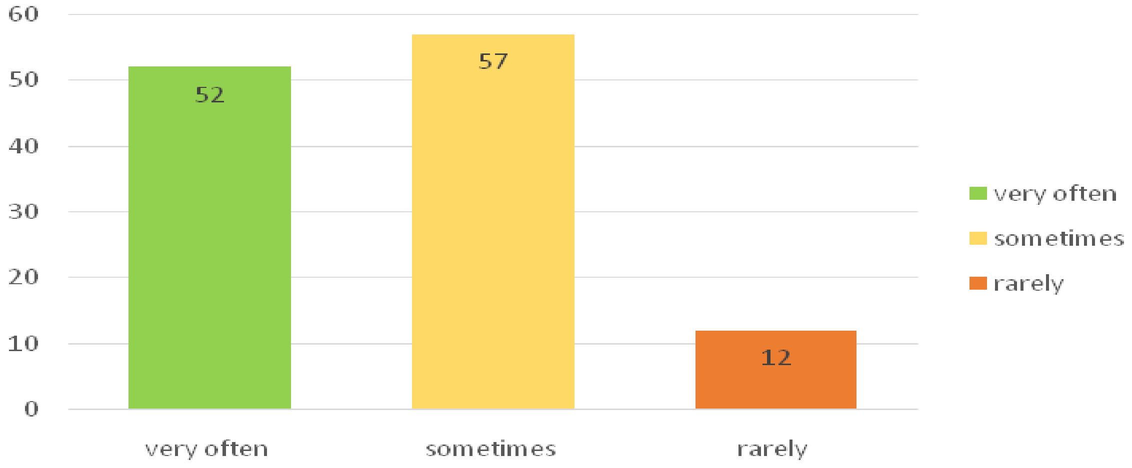


Figure V-20 Frequency of purchase of plastic-packed products

V.1.2.3 Avoidance of Excessive Packaging

57.85% of participants do not attempt to avoid excessive plastic packaging, revealing limited adoption of eco-friendly behaviors.

Table V-11 Avoidance of Excessive Plastic Packaging

	Number of participants	percentage
Yes	51	42,15%
No	70	57,85%
Total	121	100%

V.1.3 Perception of Plastic Impacts

V.1.3.1 Impact on Food Quality

A large majority of participants (84.3%) believe that plastic packaging has an impact on the quality of food products. Only 4.96% do not believe so, while 10.74% are unsure.

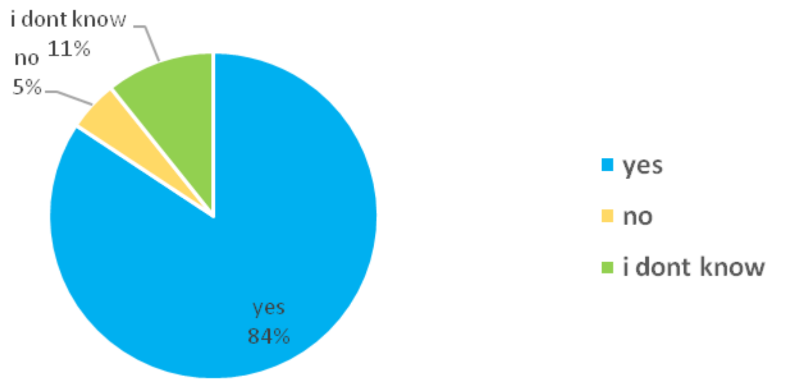


Figure V-21 Perception Of The Impact Of Plastic Packaging On The Quality Of Food Products

V.1.3.2 Environmental Impact

Almost all participants perceived the environmental impact of plastic packaging as negative (45.45%) or very negative (48.76%). Only 5.79% had a neutral perception and none considered the impact to be positive.

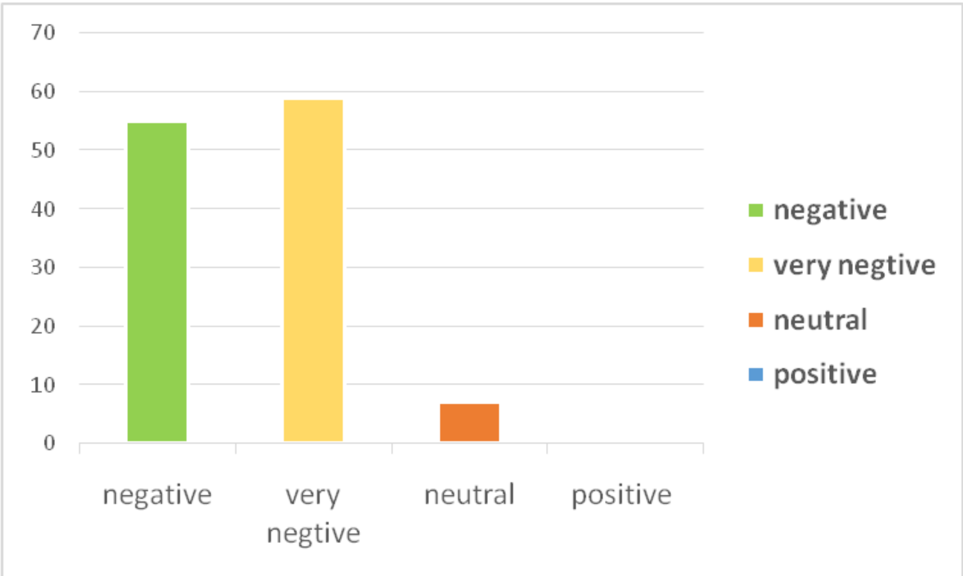


Figure V-22 Perception Of The Impact Of Plastic Packaging On The Environment

V.1.3.3 Main Concerns

57.85% worry about health effects, followed by 34.71% concerned about the environment. Fewer people were concerned about the additional cost (4.13%) or gave mixed answers (3.31%).

Table V-12 Major concerns associated with plastic packaging.

	Number of participants	percentage
On Health	70	57,85%
On The Environment	42	34,71%
Extra Coast	5	4,13%
Other Responses	4	3,31%
Total	121	100,00%

V.1.4 Attitudes Towards Alternatives and Sustainability

V.1.4.1 Preference for Alternatives

An overwhelming majority (86%) prefer alternatives to plastic packaging, with only 2% opposed. A small percentage (12%) say it depends on circumstances.

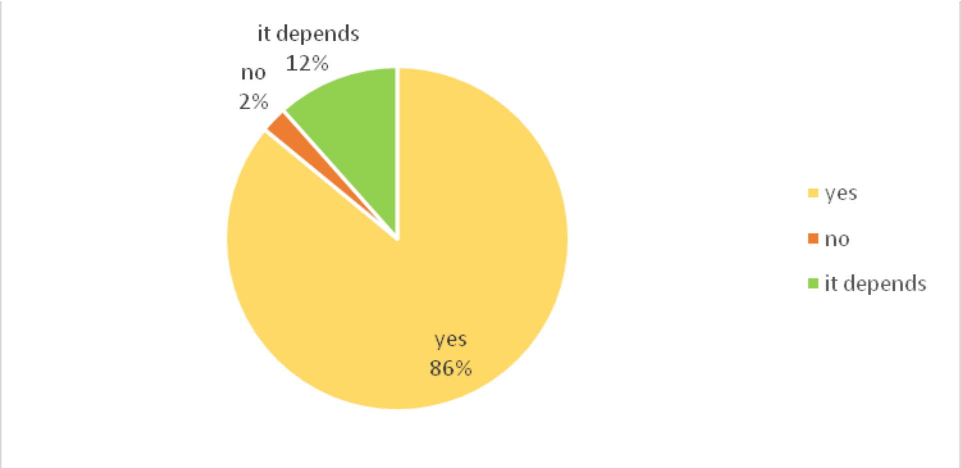


Figure V-23 Participants' preference for alternatives to plastic packaging.

V.1.4.2 Awareness of Health Risks

50% of participants (61 people) declared they were aware of the health risks associated with the use of plastic packaging in the food sector. 39% (47 people) said they were only partially aware of these risks. Only 11% (13 people) were not at all aware of the risks

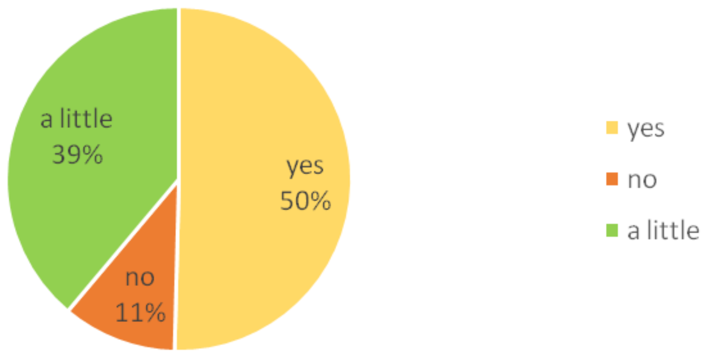


Figure V-24 Awareness Of The Health Risks Of Plastic Food Packaging

V.1.4.3 Recycling of Plastic Packaging

Only 4% systematically recycle. Recycling remains marginal despite declared interest

According to the results , the majority of participants never (34,70%) or rarely (31,40%) recycle their plastic packaging, while a limited number sometimes (29,75%) and very few always (4,13%) do.

This indicates a low overall commitment to recycling, although 70% of participants declared they were in favour of recycling

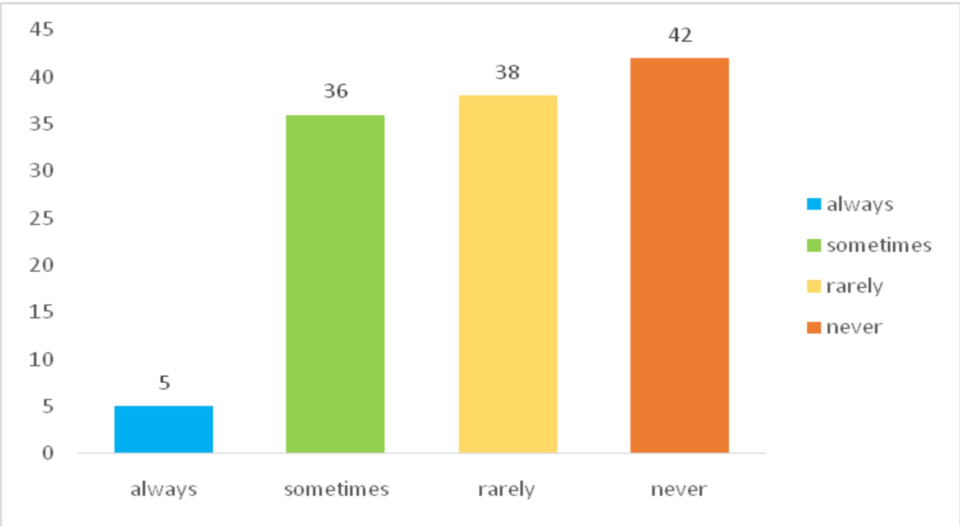


Figure V-25 Frequency Of Recycling Of Plastic Packaging By Participants

V.1.4.4 Knowledge of Recycling Symbols

The study shows that 60% do not recognize recycling symbols. This reveals a lack of specific environmental education.

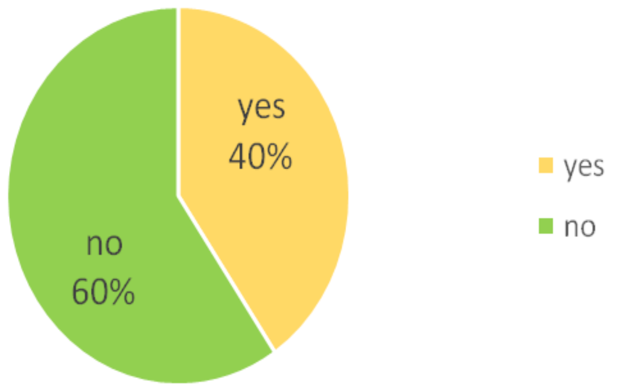


Figure V- 26 Frequency of Knowledge of Recycling Symbols

V.1.4.5 Awareness of recyclability in purchasing:

35% take recyclability into account, 26% sometimes, and 39% not at all. This behavior deserves attention in awareness policies.

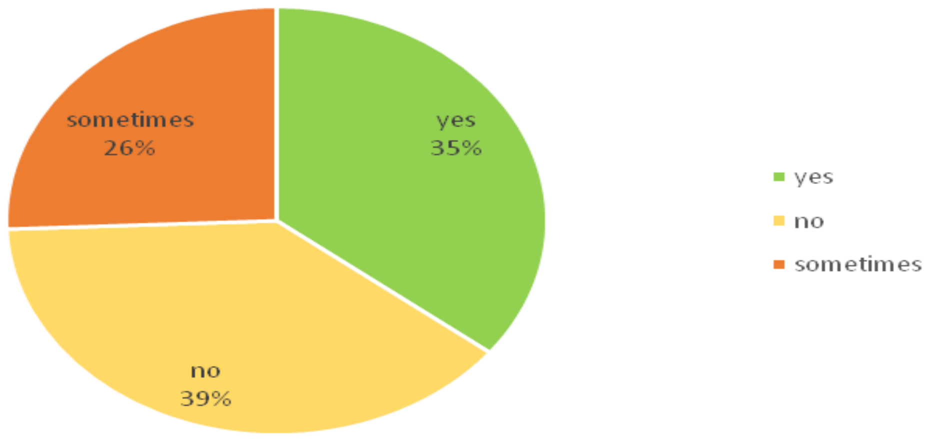


Figure V-27 Frequency Of Participants' Awareness Of Recyclability In Purchasing

V.1.5 Perceived Risks and Sustainability-Related Behaviors

V.1.5.1 Food Deterioration Due to Plastic

70% believe plastic can deteriorate food, confirming significant consumer distrust.

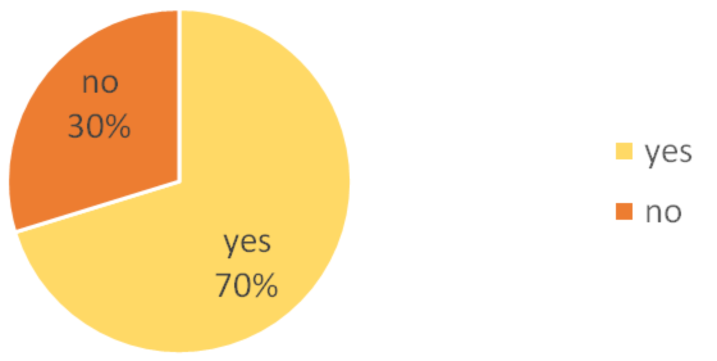


Figure V-28 Perception of food spoilage caused by plastic.

V.1.5.2 Willingness to Pay More for Sustainable Packaging

81% would accept paying more for sustainable packaging compared with 19%. This reveals potential for ecological transition policies.

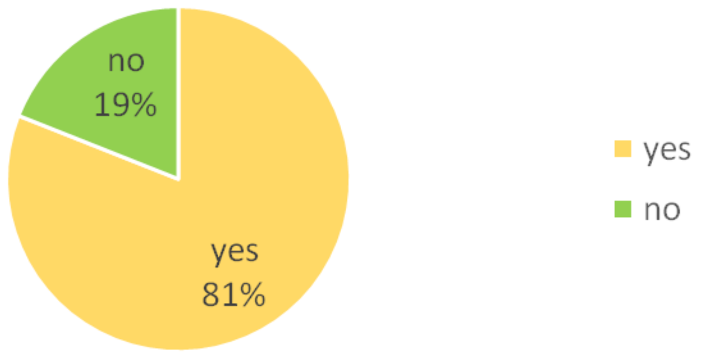


Figure V-29 Participants' willingness to pay more for sustainable plastic packaging.

V.1.5.3 Perception of the need for plastic packaging in food preservation :

Despite criticisms, 70% acknowledge that plastic provides better food preservation.

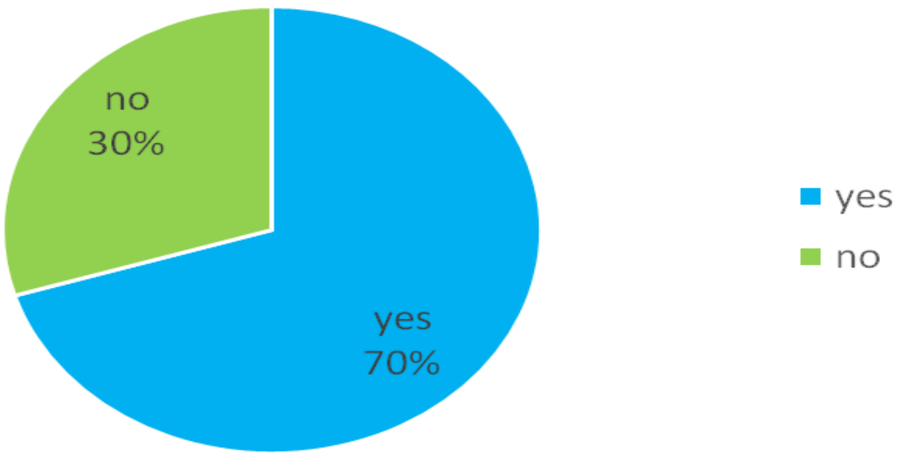


Figure V-30 Perception Of The Need For Plastic Packaging For Food Preservation

V.1.5.4 Plastic Reduction by Companies

Near-unanimous support (98%) exists for producers reducing plastic usage.

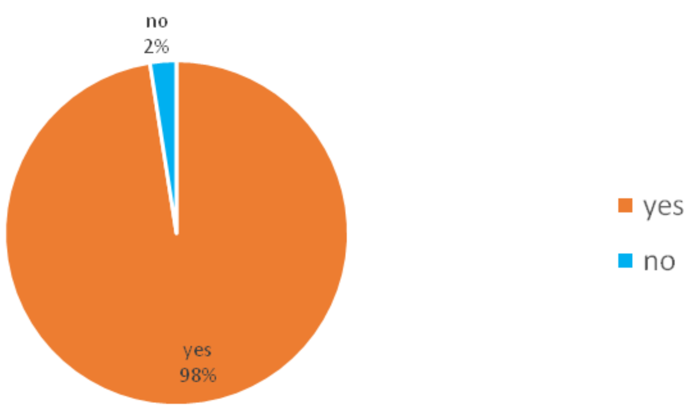


Figure V-31 Participants' views on the reduction of plastic packaging by companies

V.1.6 Cross-Analyses

V.1.6.1 Age × Recycling Frequency

Cross-tabulation 01: Age × recycling frequency

Despite a high proportion of young people, their recycling rate is very low (only 5.9% always recycle). Older individuals, although fewer in number, show more favorable behavior.

Table V-13 Recycling frequency by age group

âge	never	Rarely	sometimes	always	Total
Under 18 years	1	1	1	0	**3**
18-30 years	37	30	34	4	**68**
31-50 years	4	6	1	1	**6**
Total	**42**	**38**	**36**	**5**	**121**

18-30 year olds: 4/68 always recycle (5.9%)

31-40 year olds: 1/6 (16.7%) always recycle

According to the data, 31-40 year olds recycle slightly more regularly than younger people, although the sample is very small.

V.1.6.2 Education Level × Risk Awareness!

Cross-tabulation 02: Education Level × Risk Awareness

University graduates are better informed. However, a significant portion remains poorly aware, highlighting the value of targeted campaigns even among the more educated.

Table V-14 Awareness of the health risks associated with the use of plastic packaging for food by participants' level of education

Level Of Education	Yes	No	A Little	Total
Univesity	53	11	41	105
Secondary	8	2	6	16
Total	61	13	47	121

The table shows participants' awareness of the health risks associated with the use of plastic food packaging, according to their level of education. The majority of respondents with a university degree stated that they were aware of the risks (‘yes’ or ‘a little’).

50.5% of respondents said they were aware of the risks (‘yes’), the vast majority of whom were university graduates (around 87% of ‘yes’ respondents).

V.1.6.3 Gender × Preference for Alternatives

Cross-table n°3: Packaging Preference by Gender

Men are more decisive in their responses ("yes" or "no"), while women have more nuanced opinions. This could reflect differences in attitudes toward eco-friendly choices.

Table V-15 Preference for alternatives to plastic packaging by sex of participants

Gender	Yes	No	It Depends	Total
Male	21	0	3	24
Female	83	3	11	97
Total	104	3	14	121

V.2 Identification of plastics and biodegradation test

V-2-1 Buoyancy and solubility test

These tests allow preliminary identification of plastic types in collected samples (bottles, bags, food films, and tumblers). Two criteria were used: behavior in salt water (buoyancy) and solubility in acetone.

Table V-16 Results of Flotation and Solubility Tests

Sample	Buoyancy in Salt Water	Solubility in Acetone	Identified Plastic Type
Bottles	Sink	Insoluble	Polyethylene terephthalate (PET)
Plastic bags	Float	Insoluble	Polyethylene (PE)
Food films	Float	Insoluble	Polyethylene/Polypropylene (PE/PP)
Tumblers	Float	Insoluble	Polystyrene (PS)

Buoyancy and insolubility in acetone are reliable indicators for guiding plastic type identification. These results were confirmed by literature (Andrady, 2015; ASTM D4330-04).

V.2.2 Plastic Biodegradation Test

The biodegradation test was conducted over 4 weeks, with weekly weighing of samples to assess mass loss related to biological degradation in standardized compost.

Table V-17 Percentage of Sample Biodegradation After 4 Weeks

Sample	Biodegradation Percentage (%)
Bottles (PET)	2%
Plastic bags (PE)	5%
Food films	9%
Tumblers (PS)	9%

Food films and tumblers show the highest biodegradation rates (9%), likely due to their thinner structure or plastic additives. PET (bottles) is the least degradable, consistent with previous studies (Hopewell et al., 2009). This highlights the persistence of rigid plastics in the environment.

According to Shah et al. (2008), biodegradation depends on polymer type, thickness, temperature, humidity, and microbial load of the environment.

V.3 Microbiological Analysis Results

This analysis aimed to evaluate contamination of certain plastic-packaged food products by testing for fecal coliforms after incubation at 37°C for 24 and 48 hours.

Table V-18 Results of Food Contamination by Fecal Coliforms

Analyzed Sample	After 24h Incubation	After 48h Incubation
Vacuum-packed meat	Absence	Absence
Fresh cheese	Absence	Absence
Water	Absence	Absence

5.3 Results of microbiological analysis:

Results after 24 and 48 hours incubation at 37°C:

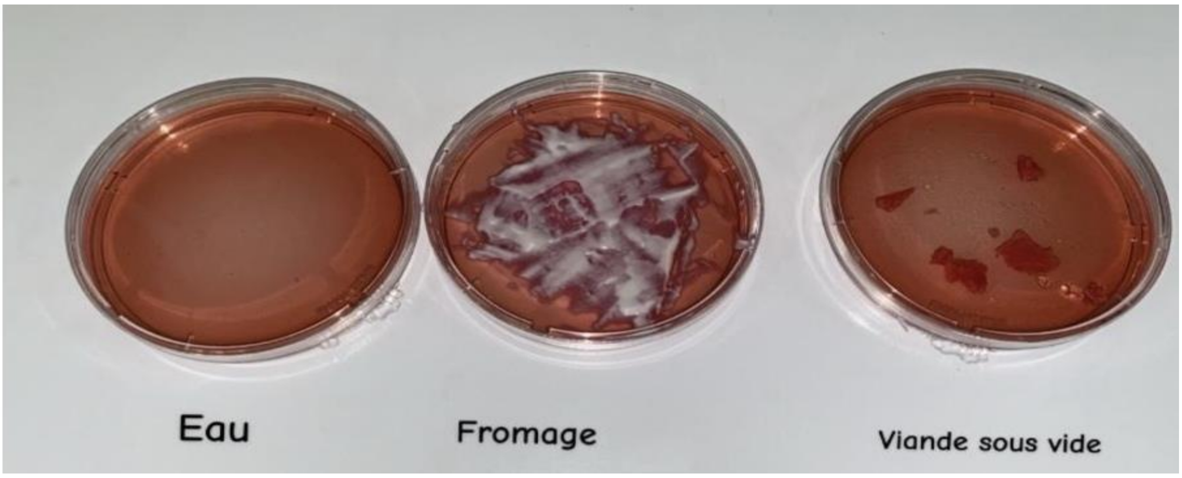


Figure V-31 Samples after 24h of Incubation

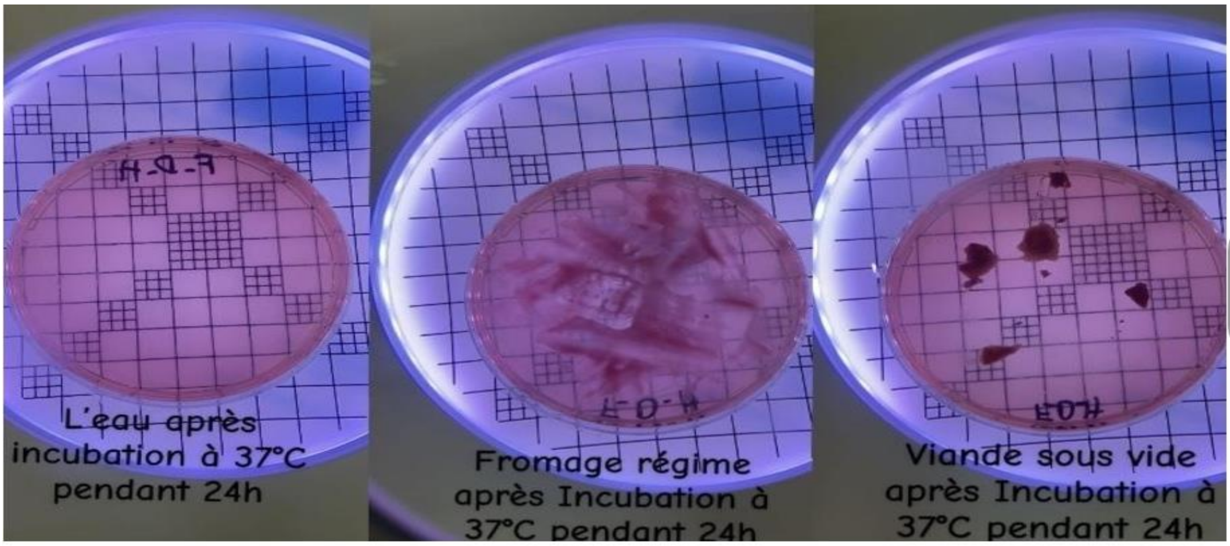


Figure V-32 Samples after 48h of Incubation

No fecal coliform growth was observed, suggesting good product hygiene and effective packaging. However, this doesn't guarantee absence of migrating substances like BPA or phthalates, which require additional chemical analysis.

☐ Questionnaire Survey

- ✓ The results show that 95% of respondents regularly purchase food items packaged in plastic. This confirms a strong reliance on plastic packaging in daily consumption.

  - ✓ These findings align with those reported by Stevens et al. (2020)**,** who indicated that over 90% of processed food products in North African supermarkets are packaged in plastic due to its low cost, availability, and excellent barrier properties**.**

- ✓ Approximately 60% of surveyed individuals lacked knowledge about the risks associated with bisphenol A (BPA), phthalates, and chemical migration.

  - ✓ This is in agreement with Groh et al. (2019)**,** who found that **c**onsumer awareness of endocrine-disrupting chemicals (EDCs) is generally low across Europe and North Africa. Similarly, Khalfaoui et al. (2021) reported that only 28% of Tunisian consumers were aware of the potential health risks linked to plastic packaging.

This lack of knowledge suggests a serious underestimation of the dangers posed by materials such as polycarbonate and expanded polystyrene, which are commonly used in films and trays for food contact.

- Only 22% of respondents in this study reported practicing plastic waste sorting, which reflects the marginal adoption of such practices.

  - ✓ In Algeria, the lack of structured sorting systems likely discourages environmentally responsible behavior.
  - ✓ A similar situation was described by Medhioub et al. (2017) in Tunisia, where fewer than 25% of households engaged in plastic waste sorting. In contrast, countries with well-established recycling systems (e.g., Germany, Canada, France) report sorting rates exceeding 50% (OECD, 2020).

- Using buoyancy in saltwater and acetone solubility tests, we identified the following:

  - ▪ Bottles**:** sank in saltwater and insoluble in acetone → Polyethylene terephthalate (PET)**.**

- Plastic bags: floated and insoluble → Polyethylene (PE).
- Food-grade films: floated and insoluble → Polyethylene/Polypropylene (PE/PP).
- Cups: floated and insoluble → Polystyrene (PS).

- Over a 4-week period, weight loss was observed in all plastic samples:

  - PET (bottles): 2% biodegradation
  - PE (bags): 5%
  - PP/PE films: 9%
  - PS cups: 9%

  ✓ These results reflect the extremely low biodegradability of conventional plastics under ambient aerobic conditions. According to Shah et al. (2008) and Narancic et al. (2018), the natural biodegradation of PE and PET in soil or water is less than 5% after six months, unless enhanced by specialized enzymes such as PETase.

  ✓ In contrast, bioplastics (e.g., polylactic acid - PLA, polyhydroxyalkanoates - PHA) have shown biodegradation rates between 40% and 60% in controlled environments, indicating the need to shift toward more sustainable materials.

- The microbiological analysis revealed: No presence of faecal coliforms in vacuum-packed meat, fresh cheese, or drinking water after 24h and 48h incubation at 37°C.

  ✓ These results confirm a satisfactory hygienic level in food processing and suggest that plastic packaging provides effective microbial protection. This is consistent with Tian et al. (2020), who demonstrated the antimicrobial effectiveness of sealed plastic packaging in reducing microbial load in meat and dairy products.

  ✓ However, absence of microbial contamination does not imply chemical safety, as emphasized by Geueke et al. (2018). Harmful substances such as BPA, phthalates, and styrenes may migrate into food without altering its appearance or microbial profile.

General Conclusion

This study provided a comprehensive assessment of plastic packaging’s role in food safety and environmental health, combining consumer perception surveys with laboratory-based material testing. The dual-method approach integrating structured questionnaires with empirical biodegradation and microbiological analyses yielded critical insights into the pervasive use of plastics and their limited environmental compatibility.

Key findings revealed that consumers in the study region heavily depend on plastic-packaged food products, yet demonstrate low awareness of associated health risks and minimal engagement in plastic waste sorting. Laboratory tests identified polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), and polystyrene (PS) as the most common packaging materials, confirming their poor biodegradability (≤9% degradation after four weeks). While microbiological analyses indicated short-term microbial protection from plastic packaging, this benefit does not offset long-term environmental and toxicological hazards.

These results align with existing scientific literature, reinforcing that conventional plastic food packaging presents significant challenges to public health and sustainable development.

- Proposed Solutions
  - Transition to Biodegradable Materials : Promote bioplastics such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), which exhibit superior biodegradability in composting environments.
  - Public Awareness Campaigns : Implement targeted educational programs to inform consumers about health risks (e.g., BPA, phthalates) and the ecological consequences of improper plastic disposal.
  - Regulatory Strengthening : Reform national food safety and environmental policies to restrict high-risk plastics and incentivize eco-certified packaging alternatives.
  - Enhanced Waste Management Infrastructure ; Develop decentralized collection and recycling systems, particularly in urban and semi-urban areas, supported by economic incentives and community participation.

This study underscores the urgency of transforming plastic use in food systems. By bridging scientific research, policy reform, and public engagement, stakeholders can mitigate health risks, reduce environmental harm, and accelerate the transition toward a circular, sustainable packaging paradigm.

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ANNEX

I.1.5 (Questionnaire pour les consommateurs)

1. **Achetez-vous des produits alimentaires emballés dans du plastique ?**
   هل تشتري منتجات غذائية معبأة في البلاستيك؟
   - ☐ Oui / نعم
   - ☐ Non / لا

2. **À quelle fréquence achetez-vous des produits emballés dans du plastique ?**
   ما هي تكرارية شرائك للمنتجات المعبأة في البلاستيك؟
   - ☐ Très souvent / كثيرًا
   - ☐ Parfois / أحيانًا
   - ☐ Rarement / نادرًا

3. **Pensez-vous que les emballages plastiques affectent la qualité des produits alimentaires ?**
   هل تعتقد أن العبوات البلاستيكية تؤثر على جودة المنتجات الغذائية؟
   - ☐ Oui / نعم
   - ☐ Non / لا
   - ☐ Je ne sais pas / لا أعرف

4. **Faites-vous attention à la recyclabilité des emballages plastiques lors de vos achats ?**
   هل تنتبه لإمكانية إعادة تدوير العبوات البلاستيكية عند الشراء؟
   - ☐ Oui / نعم
   - ☐ Non / لا
   - ☐ Parfois / أحيانًا

5. **Selon vous, quel est l'impact des emballages plastiques sur l'environnement ?**
   برأيك، ما هو تأثير العبوات البلاستيكية على البيئة؟
   - ☐ Très négatif / سلبي جدًا
   - ☐ Négatif / سلبي
   - ☐ Neutre / محايد
   - ☐ Positif / إيجابي

6. **Préférez-vous des alternatives aux emballages plastiques (ex : verre, papier, etc.) ?**
   هل تفضل بدائل للعبوات البلاستيكية (مثل الزجاج، الورق، إلخ)؟
   - ☐ Oui / نعم
   - ☐ Non / لا
   - ☐ Cela dépend / يعتمد على المنتج

7. **Connaissez-vous les risques sanitaires liés à l'utilisation des emballages plastiques pour les aliments ?**
   هل تعرف المخاطر الصحية المرتبطة باستخدام العبوات البلاستيكية للأغذية؟
   - ☐ Oui / نعم
   - ☐ Non / لا
   - ☐ Un peu / قليلاً

8. **Recyclez-vous les emballages plastiques après utilisation ?**
   هل تقوم بإعادة تدوير العبوات البلاستيكية بعد الاستخدام؟

- ☐ Toujours / دائمًا
- ☐ Parfois / أحيانًا
- ☐ Rarement / نادرًا
- ☐ Jamais / أبدًا

9. **Avez-vous déjà remarqué une altération du goût ou de l'odeur des aliments due à l'emballage plastique ?**
   هل لاحظت من قبل تغيرًا في طعم أو رائحة الطعام بسبب العبوة البلاستيكية؟
   - ☐ Oui / نعم
   - ☐ Non / لا

10. **Seriez-vous prêt à payer plus cher pour des produits avec des emballages écologiques ?**
    هل أنت مستعد لدفع المزيد مقابل منتجات ذات عبوات صديقة للبيئة؟
    - ☐ Oui / نعم
    - ☐ Non / لا

11. **Pensez-vous que les emballages plastiques sont nécessaires pour préserver la fraîcheur des aliments ?**
    هل تعتقد أن العبوات البلاستيكية ضرورية للحفاظ على نضارة الطعام؟
    - ☐ Oui / نعم
    - ☐ Non / لا

12. **Connaissez-vous les symboles de recyclage sur les emballages plastiques ?**
    هل تعرف رموز إعادة التدوير على العبوات البلاستيكية؟
    - ☐ Oui / نعم
    - ☐ Non / لا

13. **Avez-vous déjà évité d'acheter un produit en raison de son emballage plastique excessif ?**
    هل تجنبت شراء منتج بسبب الإفراط في استخدام العبوة البلاستيكية؟
    - ☐ Oui / نعم
    - ☐ Non / لا

14. **Selon vous, les entreprises devraient-elles réduire leur utilisation d'emballages plastiques ?**
    برأيك، هل يجب على الشركات تقليل استخدامها للعبوات البلاستيكية؟
    - ☐ Oui / نعم
    - ☐ Non / لا

15. **Quelle est votre principale préoccupation concernant les emballages plastiques ?**
    ما هو همك الرئيسي فيما يتعلق بالعبوات البلاستيكية؟
    - ☐ Impact sur la santé / التأثير على الصحة
    - ☐ Impact sur l'environnement / التأثير على البيئة
    - ☐ Coût supplémentaire / التكلفة الإضافية
    - ☐ Autre / أخرى