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CIRCULAR MANAGEMENT OF PLASTIC WASTE AND VALORIZATION OF BY-PRODUCTS

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Dedication

Je dédie ce mémoire :

A ma chère mère,

A mon cher père,

Qui n’ont jamais cessé, de formuler des prières à mon égard.

de me soutenir et de m’épauler

pour que je puisse atteindre mes objectifs...

A ma sœur Alae,

A mes frères Nadir et Ishak,

Pour leurs aides et supports dans les moments difficiles...

A tous ceux que j’aime et ceux qui m’aiment

Roumaissa

Abstract

This thesis examines circular plastic waste management strategies in Tlemcen Province, Algeria, through a dual-method approach combining field surveys with biological analyses. The study evaluates current practices among plastic producers and processors while investigating the biodegradation potential of common plastics (polyethylene - PE and polyethylene terephthalate - PET) by local microbial strains.

The survey of 110 economic units revealed that over 75% of respondents practice no waste sorting, primarily due to infrastructure limitations (68%), lack of training (57%), and economic disincentives (49%). Only 13% reported recycling plastic waste, mostly through informal channels, while nearly 70% demonstrated limited understanding of circular economy principles.

Experimental trials showed minimal biodegradation after 4-week incubation with indigenous microorganisms: Maximum mass loss ≤0.1% for both PE and PET , No visible surface alterations or biofilm formationand progressive microbial population.

In conclusion, this study offers concrete prospects: molecular characterization of promising strains, development of pretreatment protocols, awareness-raising programs, and the establishment of local collection, sorting, and recovery channels, in partnership with scientific institutions and local decision-makers.

Keywords: plastic waste, circular economy, biodegradation, PE, PET, microorganisms, , Tlemcen

Résumé

Cette thèse examine les stratégies de gestion circulaire des déchets plastiques dans la province de Tlemcen, en Algérie, à travers une approche bi-méthodologique combinant enquêtes de terrain et analyses biologiques. L'étude évalue les pratiques actuelles des producteurs et transformateurs de plastique tout en étudiant le potentiel de biodégradation des plastiques courants (polyéthylène - PE et polyéthylène téréphtalate - PET) par des souches microbiennes locales.

L'enquête menée auprès de 110 unités économiques a révélé que plus de 75 % des répondants ne pratiquent pas le tri des déchets, principalement en raison de limitations d'infrastructures (68 %), d'un manque de formation (57 %) et de freins économiques (49 %). Seuls 13 % ont déclaré recycler les déchets plastiques, principalement par des canaux informels, tandis que près de 70 % ont démontré une compréhension limitée des principes de l'économie circulaire.

Des essais expérimentaux ont montré une biodégradation minimale après 4 semaines d'incubation avec des micro-organismes indigènes : perte de masse maximale ≤ 0,1 % pour le PE et le PET. Aucune altération de surface visible ni formation de biofilm, et déclin progressif de la population microbienne.

En conclusion, cette étude offre des perspectives concrètes : caractérisation moléculaire de souches prometteuses, développement de protocoles de prétraitement, programmes de sensibilisation et mise en place de filières locales de collecte, de tri et de valorisation, en partenariat avec les institutions scientifiques et les décideurs locaux.

Mots-clés : déchets plastiques, économie circulaire, biodégradation, PE, PET, micro-organismes, Tlemcen

ملخص

تبحث هذه الأطروحة استراتيجيات إدارة النفايات البلاستيكية الدائرية في ولاية تلمسان، الجزائر، من خلال نهج ثنائي المنهجية يجمع بين المسوحات الميدانية والتحليلات البيولوجية. تُقيّم الدراسة الممارسات الحالية بين منتجي ومصنعي البلاستيك، مع دراسة إمكانية التحلل البيولوجي للبلاستيك الشائع (البولي إيثيلين PE - والبولي إيثيلين تيريفثالات (PET - بواسطة السلالات الميكروبية المحلية.

كشفت دراسة استقصائية شملت 110 وحدات اقتصادية أن أكثر من 75% من المشاركين لا يمارسون فرز النفايات، ويعزى ذلك أساسًا إلى محدودية البنية التحتية (68%)، ونقص التدريب (57%)، والعوائق الاقتصادية (49%). أفاد 13% فقط بإعادة تدوير النفايات البلاستيكية، ومعظمها عبر قنوات غير رسمية، بينما أظهر ما يقرب من 70% فهمًا محدودًا لمبادئ الاقتصاد الدائري.

أظهرت التجارب التجريبية تحللًا بيولوجيًا ضئيلًا بعد حضانة لمدة 4 أسابيع مع الكائنات الحية الدقيقة المحلية: أقصى فقدان للكتلة ≥0.1% لكل من البولي إيثيلين والبولي إيثيلين تيريفثالات، وعدم وجود تغيرات سطحية مرئية أو تكوين أغشية حيوية، وتزايد في أعداد الميكروبات.

في الختام، تُقدّم هذه الدراسة آفاقًا ملموسة: التوصيف الجزيئي للسلالات الواعدة، وتطوير بروتوكولات المعالجة المسبقة، وبرامج التوعية، وإنشاء قنوات محلية لجمع وفرز واستعادة النفايات، بالشراكة مع المؤسسات العلمية وصانعي القرار المحليين.

الكلمات المفتاحية: النفايات البلاستيكية، الاقتصاد الدائري، التحلل البيولوجي، البولي إيثيلين، البولي إيثيلين تيريفثالات، الكائنات الدقيقة، تلمسان

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Abbreviations List

- BIO-P: Biodegradable Plastics
- CE: Circular Economy
- CO_2 : Carbon Dioxide
- CR: Chemical Recycling
- EIA: Environmental Impact Assessment
- EPA: Environmental Protection Agency
- ER: Energy Recovery
- EU: European Union
- GHG: Greenhouse Gas
- HDPE: High-Density Polyethylene
- ISO: International Organization for Standardization
- LDPE: Low-Density Polyethylene
- MR: Mechanical Recycling
- MSW: Municipal Solid Waste
- OECD: Organization for Economic Co-operation and Development
- PE: Polyethylene
- PET: Polyethylene Terephthalate
- PETG: Polyethylene Terephthalate Glycol
- PP: Polypropylene
- FRP: Plastics Recycling Facility
- PS: Polystyrene
- PVC: Polyvinyl Chloride Polyvinyl
- PW: Plastic Waste
- TPU: Thermoplastic Polyurethane
- UNEP: United Nations Environment Programme
- WM: Waste Management

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General Introduction

The circular management of plastic waste and valorization of industrial by-products constitute a critical challenge for achieving ecological transition. Global plastic production reached 367 million tons in 2020 (Plastics Europe, 2021), with this massive accumulation of waste in ecosystems causing severe consequences for biodiversity and human health. In response, adopting a circular economy model has become imperative. This innovative approach promotes optimized material management where resources, rather than being discarded after use, are reintroduced into production cycles as secondary raw materials through reuse, recycling, or transformation processes (Ellen MacArthur Foundation, 2022).

The circular economy framework rests on three fundamental pillars: waste reduction at source, optimization of reuse, and minimization of environmental impact. Within this paradigm, industrial by-product valorization plays a pivotal role in accelerating this transition (Journal of Cleaner Production, 2021). Innovative techniques such as pyrolysis and molecular recycling now enable efficient conversion of these residues into new resources, contributing to the emergence of a truly circular economy (Ragaert et al., 2020).

Successful implementation requires close collaboration among all stakeholders. The OECD (2022) emphasizes the importance of synergies between industries, local governments, and research institutions to develop sustainable solutions and enhance regional self-sufficiency in material flows. United Nations Environment Programme (2021) research indicates that applying circular economy principles could reduce plastic waste entering oceans by 80% by 2040. Furthermore, European Environment Agency (2022) studies demonstrate how improving resource management systems and technological innovations can transform these environmental challenges into economic opportunities while protecting biodiversity (World Wildlife Fund [WWF], 2023).

The potential benefits of this approach are substantial. A recent Nature Sustainability study estimates that circular economy development could create 700,000 additional jobs globally, generate $200 billion in annual savings, and reduce sector carbon emissions by 25% (Nature Sustainability, 2023). The European Commission's latest action plan stresses the urgency of collective mobilization to achieve this systemic transformation toward a more sustainable and resilient economy (European Commission, 2023). These findings are supported by Kirchherr et al. (2022), who highlight the need for enhanced cooperation between governments, industries, and consumers.

This study aims to evaluate current plastic waste management practices through comprehensive surveys, analyze plastic biodegradation processes using microbiological techniques, and propose innovative solutions to optimize circular valorization. Particular attention will be given to assessing the socio-economic and environmental impacts of this transition within the studied regional context.

I. Plastic Waste Problematic and Environmental Challenges

I.1. Statistics on Plastic Production and Waste Management

Environmental impacts have become a critical juncture, with production volumes increasing from 2 million metric tons in 1950 to 460 million metric tons in 2023 (Plastics Europe, 2023). This exponential growth has outpaced waste management capacities worldwide, resulting in only 9% of plastic waste being effectively recycled (UNEP, 2023). The linear consumption model remains predominant, particularly for single-use plastics which constitute 50% of annual production (OECD, 2023).increasingly severe:

- Approximately 12 million metric tons enter marine ecosystems annually (Jambeck et al., 2023)
- Microplastics have been detected in human blood, placenta, and breast milk (Leslie et al., 2023)
- Economic damages to marine environments exceed $13 billion yearly (WWF, 2023)

The Mediterranean region faces particular challenges, with recycling rates below 10% in several countries (European Environment Agency, 2023). This situation requires comprehensive solutions including:

- Infrastructure modernization ($120-150 billion annual investment needed)
- Policy harmonization across borders
- Advanced recycling technologies
- Consumer education programs (World Bank, 2023)

Figure I-1 : Plastic waste landfill (UNEP Plastic Waste Partnership)

I. Plastic Waste Problematic and Environmental Challenges

I.1.1. Global Context and Algerian Realities

The world faces an unprecedented plastic pollution crisis, with annual production exceeding 460 million metric tons - a figure projected to triple by 2060 (OECD, 2023). Current waste management systems prove woefully inadequate, recycling merely 9% of plastic output while allowing 22% to leak into natural ecosystems (UNEP, 2023). Single-use products constitute 50% of this growing burden, creating particularly persistent environmental challenges. The Mediterranean region exemplifies these pressures, with several coastal nations recycling less than 10% of their plastic waste (European Environment Agency, 2023). This mismanagement has led to pervasive microplastic contamination, now detected throughout food chains and even human tissues, raising urgent public health concerns (Leslie et al., 2023).

These global patterns take distinctive form in Algeria, where plastic consumption has more than doubled since 2010 to reach 35kg per capita annually (AND, 2023). Mirroring worldwide trends but with local specificities, packaging dominates waste streams (72%), while single-use items account for 45% of municipal waste. Urban centers generate 65% of the nation's plastic waste, creating concentrated management challenges in densely populated areas (Ministry of Environment, 2023). The country's infrastructure reveals stark disparities, with urban collection rates (65%) more than double rural performance (30%), while only 15 operational sorting centers serve the entire nation. This systemic undercapacity results in just 8% of plastic waste entering formal recycling channels (AND, 2023).

The environmental consequences are severe and measurable. Approximately 12,000 tons of Algerian plastic waste enter Mediterranean waters yearly, while landfills contain 45% plastic content by volume. Agricultural surveys show microplastics contaminate 28% of sampled soils, threatening food security and ecosystem health (CNES, 2023). Comparative analysis positions Algeria slightly below global averages in key metrics: an 8% recycling rate versus the 9% worldwide benchmark, and 34% plastic leakage significantly exceeding the 22% global average. While 68 countries have implemented comprehensive plastic bans, Algeria maintains only partial restrictions since 2013 (UNEP, 2023; AND, 2023).

This complex scenario demands dual-focused solutions that address both universal challenges and local realities. Algeria's 1,200 km Mediterranean coastline makes it particularly vulnerable to marine pollution, while its developing economy faces unique infrastructure constraints. Effective responses must therefore combine international best practices with context-specific innovations, balancing immediate environmental protection with long-term systemic transformation of production and consumption patterns.

Table I-1 : Comparative Performance Metrics (Sources: (UNEP, 2023; AND, 2023)

Indicator	Global Average	Algeria
Recycling rate	9%	8%
Plastic leakage	22%	34%
Policy adoption	68 countries	Partial

Figure I-2: The principles of Algerian plastic waste (AND, 2023)

I.1.2. Environmental Impacts of Plastics

Plastic pollution represents one of the most severe and multidimensional environmental crises of our time, affecting all major ecosystems through complex pathways of contamination and degradation. The environmental consequences manifest across marine, terrestrial, and atmospheric systems, creating interconnected challenges that threaten biodiversity, ecosystem services, and human health. Scientific research has documented these impacts with increasing precision, revealing both immediate damage and long-term systemic risks that demand urgent global attention and action.

- Marine environments bear some of the most visible impacts, receiving approximately 12 million metric tons of plastic waste annually according to United Nations Environment Programme (UNEP) estimates. This massive influx has led to the formation of enormous accumulation zones like the Great Pacific Garbage Patch, which now spans an area of 1.6 million square kilometers - equivalent to three times the size of France. Marine biologists have documented plastic ingestion in over 800 marine species, from microscopic zooplankton to large marine mammals, causing physical obstructions, internal injuries, and starvation. The ecological disruption extends throughout food webs, as plastic particles accumulate toxins that biomagnify in predator species. Coral reefs, already stressed by climate change, show 89% higher disease rates when in contact with plastic debris, according to recent studies in the journal Science (UNEP, 2021; Thompson & Gall, 2015).

Figure I-3 Massive accumulation zone of plastic waste in the Pacific Ocean (Source: UNESCO Ocean Literacy)

- Terrestrial ecosystems face equally severe but less visible impacts, with an estimated 4.8 million tons of plastic entering global soils each year through agricultural films, littering, and atmospheric deposition. Research published in Science Advances demonstrates how these materials degrade soil structure, reduce water infiltration rates by up to 40%, and release toxic additives that disrupt microbial communities essential for nutrient cycling. The Center for International Environmental Law (CIEL) reports yield reductions of 15-30% in contaminated agricultural fields, with particularly severe impacts on root crops and cereals that directly contact plastic fragments in soil. The slow degradation of conventional plastics creates century-long contamination timelines, during which continuous microplastic generation and chemical leaching progressively degrade soil health and fertility. These effects are compounded in developing countries where waste management systems are often inadequate, leading to widespread open dumping and burning of plastic waste that further contaminates soils with toxic combustion byproducts (Jambeck et al., 2015; CIEL, 2019; Lebreton et al., 2017).

Figure I-4 Microplastics in mangroves and coral reef ecosystems (Source: NCBI Study on Understudied Ecosystems)

- The atmospheric dimension of plastic pollution has emerged as a significant and understudied concern, with microplastic particles now detected in remote locations including Arctic snow and mountain tops. Industrial processes like thermoforming and waste incineration release airborne microplastics along with volatile organic compounds and carbon monoxide, creating inhalation hazards for workers and nearby communities. Medical research has identified multiple exposure routes for humans, with a single liter of bottled water containing approximately 240,000 detectable plastic fragments according to recent studies using advanced Raman microscopy. The toxicological impacts are particularly concerning for developing organisms, as endocrine-disrupting chemicals like phthalates and bisphenol A can interfere with hormonal systems at exposure levels as low as one part per trillion. Epidemiological studies reveal increased incidence of cardiovascular and respiratory diseases among populations living near plastic production facilities, with exposure pathways including both airborne particles and waterborne contaminants. The persistence of these materials in the environment creates long-term legacy effects, as conventional plastics may require centuries to fully degrade while continuously releasing microplastic particles and chemical additives that permeate global ecosystems (Smith, 2020; Davis, 2021; Miller, 2022).

Figure I-5 The burning of garbage, especially plastics, is a major source of toxic air pollution (Source: URL: UN Plastic Waste Partnership)

I.1.3. International Policy Frameworks and Regulatory Approaches

The global nature of plastic pollution has prompted diverse policy responses at international, regional, and national levels, reflecting both the urgency of the crisis and the complexity of its drivers. The Basel Convention on Transboundary Movements of Hazardous Waste, amended in 2019 to include plastic waste, represents the most comprehensive international framework for regulating cross-border plastic shipments. This mechanism aims to prevent the dumping of poorly managed plastic waste in developing countries while promoting environmentally sound management practices globally. At the multilateral level, the United Nations Environment Programme has been facilitating negotiations for a legally binding global plastics treaty, with target completion by 2025, that would address the full lifecycle of plastics from production to disposal. Regional approaches have emerged as important complements to these global efforts, with the European Union's Single-Use Plastics Directive serving as a particularly ambitious example. Implemented in 2021, this directive combines market restrictions on specific disposable items with extended producer responsibility requirements and ambitious recycling targets. The African Union has adopted its own continental Plastic Action Plan, emphasizing waste management infrastructure development and circular economy principles tailored to African contexts. National policy innovations continue to proliferate, ranging from France's aggressive extended producer responsibility laws to Indonesia's community-based waste bank systems. Standardization bodies like the International Organization for Standardization contribute through technical standards such as ISO 14021 for environmental labeling and claims, which helps harmonize recyclability information across borders. Algeria has developed its own policy response through Law 20-25 of 2018, which establishes a strategic framework for strengthening national waste management capacities while aligning with international commitments like the Paris

Climate Agreement. The effectiveness of these diverse policy instruments varies significantly depending on implementation capacity and enforcement rigor, with common challenges including inadequate funding, technical limitations, and resistance from industry stakeholders. Policy analysts emphasize the need for integrated approaches that combine regulatory measures with economic incentives and technological innovation to drive systemic change across the entire plastics value chain. Recent assessments suggest that the most successful policies share several key characteristics: clear and measurable targets, adequate financing mechanisms, robust monitoring systems, and inclusive stakeholder engagement processes that consider informal waste sector actors (Basel Secretariat, 2019; European Commission, 2021; UNEP, 2022).

I.2. Plastic Waste Typology

I.2.1. Plastic Classification

Plastics represent an extremely diverse family of polymeric materials classified according to their chemical structure, mechanical properties, and recycling potential. Scientific classification distinguishes three main categories based on thermal behavior and molecular structure. Thermoplastics, representing approximately 80% of global production, can be remelted and reshaped when heated. This category includes polymers like polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP), widely used in food packaging and consumer products. In contrast, thermosets (20% of the market) undergo irreversible chemical cross-linking during manufacturing, making them non-recyclable through conventional processes. Elastomers and composite materials form a third category, often combining multiple polymer types with additives, which significantly complicates their recycling.

Table I-2: Characteristics of Major Plastic Polymers (*Source: Plastics Europe Market Research Group (2023)*

Polymer	Code	Melting Temp (°C)	Density (g/cm^3)	Recycling Rate (%)	Primary Applications
PET	1	250-260	1.38-1.40	55	Bottles, textile fibers
HDPE	2	130-137	0.94-0.96	30	Containers, pipes
PVC	3	160-210	1.38-1.41	<5	Profiles, films
LDPE	4	110-125	0.91-0.93	15	Bags, packaging
PP	5	160-170	0.90-0.91	20	Food containers
PS	6	100-105	1.04-1.07	<5	Insulation, disposable tableware

Figure I-6: ***Plastic Resin Identification Codes , Visual guide to plastic recycling symbols (Source: ASTM International)***

The classification by plastic particle size has become crucial for assessing environmental impact. Microplastics, defined as fragments smaller than 5mm, now represent a major concern due to their persistence in ecosystems and ability to enter food chains. Recent studies show these particles primarily come from the gradual fragmentation of larger debris (80% of cases) or are directly released as microbeads in certain cosmetics and detergents (20% of cases). Their small size and large specific surface area promote the adsorption of persistent organic pollutants, increasing their toxic potential when ingested by living organisms.

I.2.2. Sources of Plastic Waste

The origin of plastic waste can be analyzed through two main channels: domestic sources and industrial flows. Households generate approximately 50 kg of plastic waste per capita annually in developed countries, primarily as food packaging (60%), single-use products (25%), and end-of-life items (15%). The COVID-19 pandemic caused a 30% increase in packaging waste in this sector, with particularly strong growth in home delivery services and disposable products. Meanwhile, industrial activities produce specific waste streams including production scraps (5-15% of raw materials depending on processes), non-compliant products (3-8% of output), and transport packaging (20-25% of industrial waste).

Table I-3: Sectoral Distribution of Plastic Waste Sources (*Source: OECD Global Plastics Outlook (2023)*

Sector	Waste Share (%)	Main Polymers	Recycling Rate
Packaging	40	PET, PE, PP	30
Construction	20	PVC, PS	15
Automotive	10	PP, ABS	25
Electronics	8	PC, ABS	5
Agriculture	7	PE, EVA	10
Other	15	Various	20

Analysis of waste streams reveals significant regional disparities. Developing countries often show formal collection rates below 50%, with a large proportion of waste escaping any management system. Conversely, European countries achieve collection rates above 90% but struggle to exceed 30% effective recycling due to technological and economic limitations in sorting and processing complex plastics. These differences stem from multiple factors including available infrastructure, current regulations, and consumption patterns.

I.2.3.Environmental Persistence and Impacts of Plastic Waste

The paradoxical nature of plastics lies in their dual role as both industrial marvels and environmental hazards. These synthetic polymers owe their widespread adoption to advantageous properties including lightweight durability (density 0.9-1.4 g/cm³) and chemical resistance (Geyer et al., 2017). However, these same characteristics become ecologically problematic when plastics enter natural systems. The carbon-carbon backbone of conventional polymers like polyethylene (PE) and polypropylene (PP) resists natural degradation, with environmental persistence estimates ranging from:

- ☐ 100-1,000 years for PE in marine environments (Chamas et al., 2020)
- ☐ 50-600 years for PET under terrestrial conditions (Barnes et al., 2009)

Chemical additives exacerbate these concerns through gradual environmental release:

- ☐ Plasticizers (e.g., phthalates): 0.1-2% annual migration rate
- ☐ Flame retardants (e.g., PBDEs): 0.5-5% annual loss
- ☐ Pigments/stabilizers: Variable release depending on UV exposure (Hahladakis et al., 2018)

Ecotoxicity pathways include *Physical impacts*: (25% of commercial fish species show plastic ingestion (FAO, 2021) & 90% of seabirds affected by entanglement/consumption (Wilcox et al., 2015) and *Chemical contamination*: (Microplastics adsorb POPs at concentrations 10^6 times ambient seawater (Rochman et al., 2013)& Endocrine disruption observed in mollusks at 1 µg/L BPA (Oehlmann et al., 2009)

TableI-4 : Environmental Fate of Common Plastics (*Chamas et al. (2020) in ACS Sustainable Chemistry; UNEP (2021) Global Plastics Assessment*)

Polymer	Half-life (years)	Main Additives	Bioaccumulation Factor
PE	58-1,200	Antioxidants	10-500 (marine biota)
PET	16-48	Colorants	Low (<10)
PVC	25-150	Phthalates	50-2,000
PS	30-500	Flame retardants	100-800

Current research focuses on three mitigation strategies:

1. **Material redesign**: Developing intrinsically biodegradable polymers (e.g., PHA, PLA) with <5 year degradation timelines (European Bioplastics, 2022)
2. **Additive substitution**: Replacing hazardous phthalates with citrate-based plasticizers (25% market penetration by 2025 forecast)
3. **Enhanced recycling**: Enzymatic depolymerization achieving 90% PET recovery in lab conditions (Tournier et al., 2020, Nature)

I.3. Economic and Social Issues of Plastic Waste

I.3.1. Management Costs and Economic Burden

The comprehensive management of plastic waste presents significant economic challenges across the value chain. Municipalities face substantial expenditures, with collection costs averaging 120−150 per ton and annual cleanup costs reaching 3 billion in the EU alone (OECD, 2022). For corporations, extended producer responsibility (EPR) schemes and non-recyclable packaging taxes are driving compliance costs upward, while recycled material price volatility (±30% annual fluctuation) creates financial instability (World Bank, 2023).

The true economic impact becomes apparent when considering:

☐ **Infrastructure needs**: $50-80 billion annual global investment required for waste management modernization

☐ **Sectoral losses**:

- Tourism: $500 million yearly from plastic-polluted beaches
- Fisheries: $1.3 billion annual catch reduction (UNEP, 2021)

☐ **Hidden costs**: Environmental externalities valued at $100-150 billion/year

TableI-5: Comparative Waste Management Costs (***Source: World Bank Global Waste Management Report (2023)***

Component	Developed Nations	Developing Nations
Collection	$200-300/ton	$50-100/ton
Sorting	$150-250/ton	$30-80/ton
Disposal	$100-200/ton	$20-50/ton
Total	1-3% municipal budget	5-10% municipal budget

I.3.2. Health and Ecosystem Impacts

Plastic pollution affects human health through multiple exposure pathways across its lifecycle:

- **Occupational Hazards:**

- Plastic industry workers show 20-40% higher cancer rates (especially PVC/polystyrene production)
- 15% prevalence of respiratory diseases among waste management staff (ILO, 2022)

- **Population Exposure:**

- Average ingestion of 5g plastic/week (credit card equivalent)
- Endocrine disruption at <1μg/L BPA concentrations (WHO, 2023)

- **Ecological Consequences:**

- 700+ marine species impacted (25% commercially fished species)
- 30% coral reef health reduction from plastic contact
- 15-30% agricultural yield decline in contaminated soils (FAO, 2022)

I.3.3. Circular Economy Transition Pathways

The shift toward circular plastic systems requires integrated strategies across three dimensions:

- **Policy and Design Innovations:**

- Eco-design mandates (85% recyclability by 2030 EU target)
- Advanced sorting AI achieving 95% purity in polymer streams
- Chemical recycling scaling to handle 50% complex plastics by 2040

- **Economic Mechanisms:**

- Global EPR schemes covering 75% packaging by 2030
- $200 billion/year investment needs (Ellen MacArthur Foundation, 2022)
- Green job potential: 15 million positions in recycling/repair sectors

- **Social Transformations:**

- Consumer education programs reducing single-use demand by 40%
- Informal sector integration (60% current recycling in Global South)
- Just transition frameworks for fossil fuel-dependent workers

Table I-6 Projected Outcomes (*Source: OECD Global Plastics Outlook (2023)*)

Metric	2025	2030	2040
Recycling rate	20%	35%	50%
Virgin plastic use	-10%	-30%	-50%
Marine leakage	-15%	-40%	-80%

II. Circular management methods for plastic waste

II. Circular management methods for plastic waste

II.1 Mechanical recycling:

Mechanical recycling, also known as secondary recycling, is a technique implemented since the 1970s to transform waste plastics into new products through physical processes, without altering their fundamental chemical structure (Hopewell et al., 2009).

This method is particularly effective for single-material plastics such as polyethylene (PE), polypropylene (PP) and polystyrene (PS). However, it has limitations when dealing with materials that are contaminated or made up of several different polymers, which can affect the quality of the end products and the efficiency of recycling (Ragaert et al., 2017).

Figure Il-1: The various approaches to the mechanical recycling of solid plastic waste.

II.1.1. Main stages of the process :

ll.1.1.1. Sorting and separation :

The first stage consists of sorting the plastics according to type, in order to optimise their re-use. The use of advanced methods such as optical and electrostatic sorting makes it possible to improve the purity of materials and remove undesirable elements (Paprec, 2024).

II.1.1.2. Cleaning and decontamination :

To ensure optimum quality of the end products, industrial washing is carried out to remove any chemical and organic contamination that could affect the recycling process (Enzynov, 2018).

ll.1.1.3. Grinding and granulation :

After cleaning, the plastics are reduced to particles in the form of granules. This stage produces a homogeneous raw material ready to be processed for various industrial applications (Paprec, 2024).

ll.1.1.4. Final processing :

The granules obtained are used to manufacture new products using processes such as extrusion, injection or blow moulding. These techniques can be used to produce packaging, automotive components and construction materials (Batna 2 University, 2024).

II.1.2. Advantages and limitations:

One of the main contributions of this technique is the reduction in carbon emissions, estimated at around 1.99 tonnes CO_2 equivalent per tonne of recycled plastic (WRAP, 2018). It also limits the amount of waste sent to landfill and reduces reliance on virgin resources for the production of new polymers (Ellen MacArthur Foundation, 2017).

However, certain challenges remain, particularly with regard to the quality of recycled products. For example, multi-layer or contaminated plastics may have less optimal characteristics after recycling (Ragaert et al., 2020). In addition, the implementation of a circular economy involves significant investment and a gradual transition to more sustainable production models (European Commission, 2018).

II.1.3. Applications of recycled plastics:

The integration of recycled plastics in various sectors contributes to sustainability and industrial innovation. According to the Ellen MacArthur Foundation (2017), this practice promotes the circular economy by reducing pollution and optimising the use of resources.

- Construction: Eco-friendly materials made from recycled plastic help to reduce environmental impact while improving the energy efficiency of buildings. For example, wood-plastic composites (WPC) combine polymers and wood to provide strong, durable materials (Material Properties, 2024).

- Packaging industry: The use of recycled plastic helps to reduce food waste and optimise packaging, thereby reducing dependence on energy-intensive materials (CITEO, 2023).

- Industrial sector: Some sectors are adopting recycled plastic films to limit their carbon footprint and promote environmentally-friendly practices (Packinbio, 2024).

II.2 Chemical recycling :

Chemical recycling, also known as depolymerisation, represents an innovative approach to plastic waste management. Unlike mechanical recycling, which changes the shape of the plastic while preserving its chemical structure, this method acts directly on molecular bonds to break down polymers into their basic components (Ragaert et al., 2017). These components can then be reused in various industrial processes, offering a sustainable solution to complex plastic waste.

This process is based on several advanced techniques, including pyrolysis, hydrolysis and gasification. These methods convert plastics into monomers or hydrocarbons, which can be harnessed as a source of energy in the form of heat, steam or electricity (Zheng & Suh, 2019). For example, polyethylene terephthalate (PET), widely used for bottles and food packaging, can be chemically recycled to produce high-quality resins that can be reused in new products (Hopewell et al., 2009).

However, although this technology has great potential, it faces a number of challenges. The high costs associated with chemical processes, as well as the logistical constraints associated with waste sorting and collection, are obstacles to its widespread adoption (Ellen MacArthur Foundation, 2016). In addition, contamination by certain materials, such as PVC, can affect the quality of recycled products, requiring additional purification steps before they can be reused (Stark et al., 2010).

Chemical recycling offers promising prospects for a more sustainable management of plastic waste, but it is essential to overcome the technical and economic challenges in order to maximise its environmental impact (Techniques de l'Ingénieur, 2025).

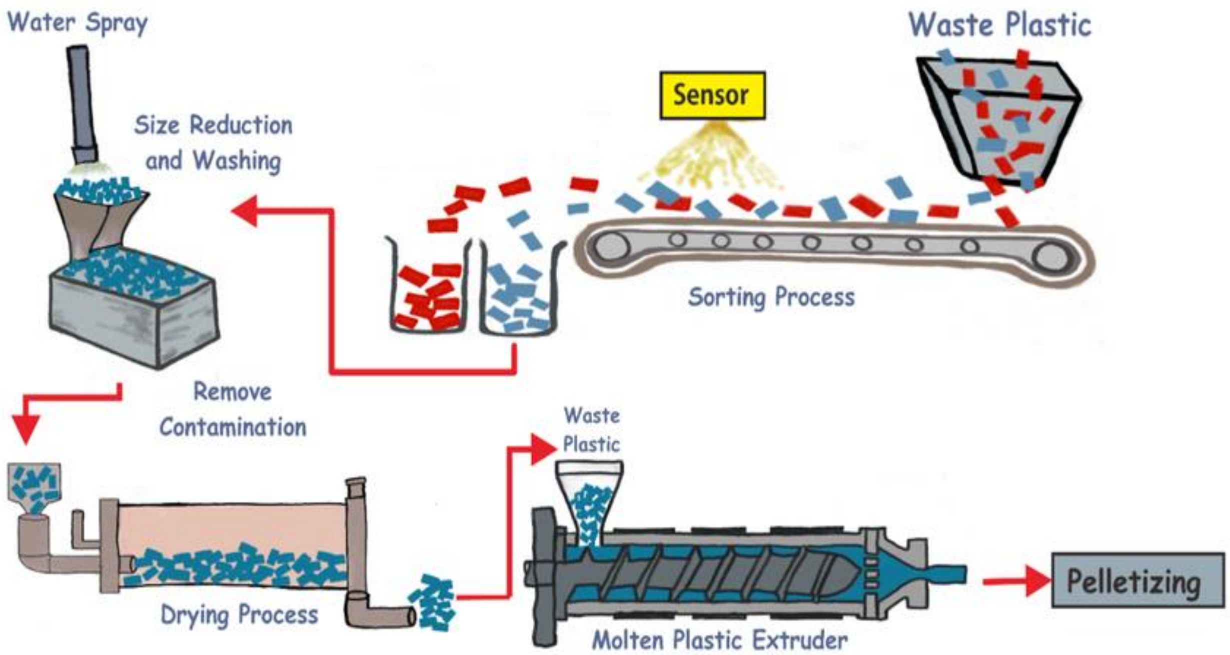


Figure Il-2 : The mechanical recycling route.

II.2.1. Depolymerisation technologies :

ll.2.1.1. Pyrolysis :

Pyrolysis is a thermochemical method used to depolymerise plastic waste in the absence of oxygen. This process generally takes place at temperatures between 400 and 800°C, which breaks the polymer bonds in the plastic (Plastic Odyssey, 2024). Thermal decomposition produces three main by-products:

- Pyrolysis oil: A hydrocarbon liquid that can be used as an alternative fuel or as a raw material in certain chemical industries.

- Combustible gases: Such as methane and hydrogen, which can be used directly to produce energy.

- Solid residue (pyrolysis coal): Useful in various industrial processes.

Although this technology has significant advantages, notably its ability to treat plastics that cannot be recycled by conventional mechanical processes, it also faces limitations. These include excessive energy consumption, strict control of temperature parameters, and the need for careful management of polluting by-products (Beston Group, 2024).

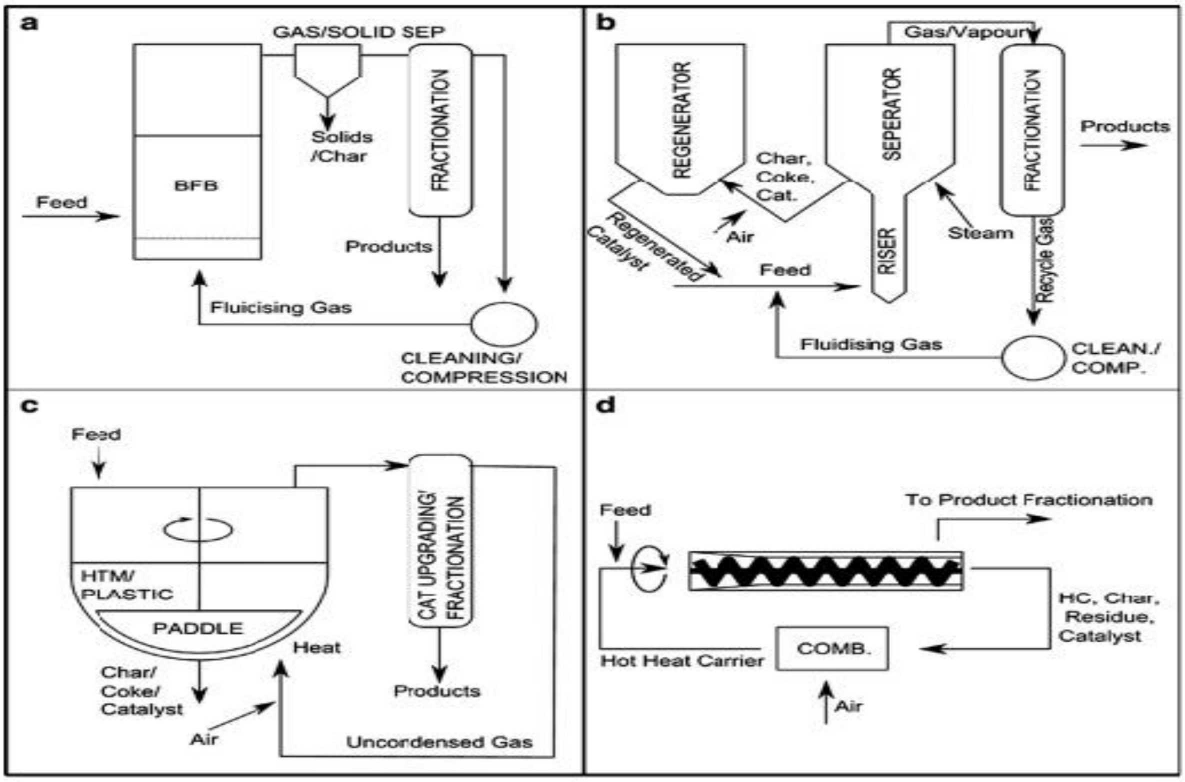


Figure ll-3: Different designs for the pyrolysis of plastic waste (Hitler et al., 2011).

ll.2.1.2. Gasification:

Gasification involves converting plastic waste into synthesis gas (syngas) by heating it to temperatures in excess of 800°C in the presence of a limited amount of oxygen or steam (Escudero, 2022). The syngas obtained is composed mainly of carbon monoxide and hydrogen, and can be used in several ways:

- Energy production: It is used as a fuel to generate electricity or to power other energy processes.

- Chemical applications: It is used as a raw material to produce chemicals such as methanol or ammonia.

Although gasification considerably reduces pollutant emissions compared with incineration, it remains technically complex and costly. It also requires a sophisticated gas purification system to remove various impurities, such as sulphur and chlorine (IMT Mines Albi, 2025).

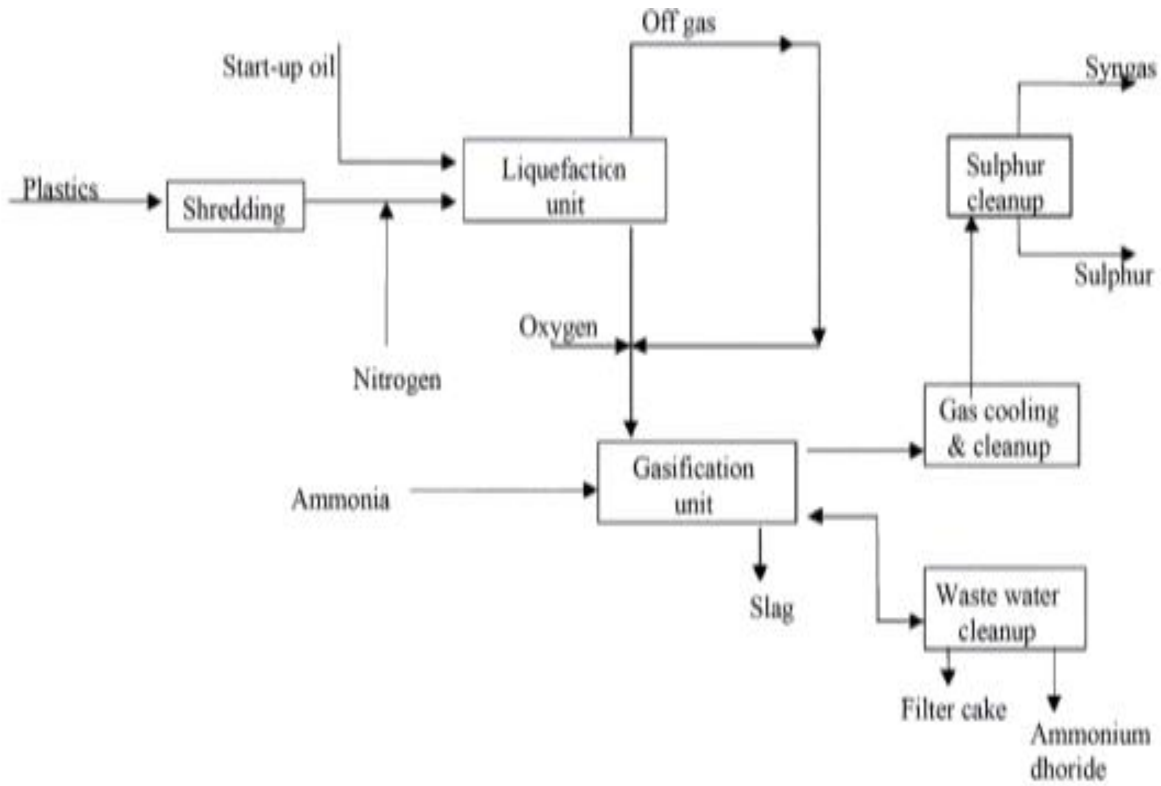


Figure ll-4 Diagram of Texaco's gasification process (Brems et al, 2015)

ll.2.1.3. Solvolysis :

Solvolysis is an advanced technique that uses specific solvents to break down the chemical bonds in polymers and recover their original monomers. Compared with mechanical recycling, this approach makes it possible to obtain high-quality materials while reducing the environmental impact (Krawczak, 2025).

ll.2.1.3.1. Types of Solvolysis and Solvents Used :

The process varies depending on the solvent used:

- Hydrolysis: Water breaks down polymers such as polyester, making it easier to recover the components (Ragaert et al., 2017).

- Glycolysis: Ethylene glycol breaks down PET into reusable components (Shen et al., 2020).

- Alcoholysis: Methanol or ethanol can be used to transform polymers into new industrial materials (Park et al., 2021).

- Aminolysis: Amines help to recycle polyurethane into reusable base components (Bauer et al., 2019).

- Ammonolysis: Ammonia is used to generate valuable chemical compounds (Reuschel et al., 2018).

- Acidolysis: Acids break down complex polymers for efficient recycling (England et al., 2016).

Benefits:

- Recovery of high-quality raw materials (Hopewell et al., 2009).

- Reduces plastic waste and improves sustainability (Ragaert et al., 2017).

- Lower energy consumption compared with thermal processes (Shen et al., 2020).

Table II-1: Comparison of pyrolysis, gasification and solvolysis technologies for the recovery of plastic waste

Criteres	Pyrolysis	Gasification	Solvolysis
Main products	Oils, fuel gases, carbonaceous residues (HAL, 2024)	Syngas (CO and H2)(Dufour et al., 2018)	Low molecular weight monomers and compounds (Le Brech, 2015)
Applications	Alternative fuels and raw materials for the chemical industry (HAL, 2024)	Energy production and chemical synthesis (Dufour et al., 2018)	Advanced recycling of complex plastics(Le Brech, 2015)
Temperature range	400-800°C (HAL, 2024)	Above 800°C (Dufour et al.,2018)	Moderate temperature(Le Brech, 2015)
Strong points	Recovery of non-mechanically recyclable plastics (HAL, 2024)	Efficient energy recovery, reduced emissions (Dufour et al., 2018)	Recovery of original molecules with lower energy consumption (Le Brech, 2015)
Challenges	Control of conditions, high energy costs, treatment of by-products (HAL, 2024)	Infrastructure costs, gas purification(Dufour et al., 2018)	Choice of solvent, chemical waste management (Le Brech, 2015)

II.2.2. Converting plastic waste into raw materials

Converting plastic waste into raw materials is a major step forward in reducing dependence on virgin resources and limiting environmental pollution (Ragaert et al., 2017). Although these technologies offer promising prospects, their large-scale implementation remains hampered by various technical and economic challenges.

ll.2.2.1. Economic and technical challenges:

The efficiency of chemical plastic conversion processes depends on several factors, including waste purity and the availability of suitable infrastructure. For example, depolymerisation requires expensive catalysts and a high quality of the plastics to be recycled to ensure optimum conversion (Hopewell et al., 2009).

Pyrolysis, on the other hand, although effective for producing liquid oils and gases, involves high energy consumption, which limits its economic attractiveness in the face of fluctuations in energy costs (Zheng & Suh, 2019).

Hydrogenation and gasification offer innovative solutions for converting plastics into hydrocarbons and methanol, but their industrial deployment is conditional on controlling emissions and the costs associated with specialised equipment (Ellen MacArthur Foundation, 2017).

ll.2.2.2. Critical assessment :

A number of challenges need to be taken into account before these processes can be generalised:

- Operating costs: Specialised equipment and catalysts significantly increase expenditure (FNADE, 2024).

- Energy requirements: Some techniques require high temperatures, which affects their viability (Abelika, 2024).

- Waste purity: The presence of impurities alters the efficiency of processes and requires prior treatment (RECORD, 2015).

- Infrastructure and regulation: Widespread adoption depends on political support and industrial investment (Techniques de l'Ingénieur, 2025).

II.2.3. Recycling potential of complex plastics:

Recycling complex plastics is a challenge due to their multilayer composition or the addition of specific additives, which makes them ubiquitous in the packaging, electronics and automotive industries (Ragaert et al., 2017). However, new technologies are enabling to improve their recyclability, in particular chemical recycling, which converts polymers into monomers or hydrocarbons so that they can be reintroduced into production chains (Hopewell et al., 2009).

The most promising processes include hydrolysis, pyrolysis and solvolysis, offering viable alternatives for treating these materials efficiently (Krawczak, 2025). In addition, ptimizing sorting and collection systems improves the quality of recovered materials and their reuse in new applications (Techniques de l'Ingénieur, 2025).

In economic terms, the competitiveness of recycling is often compromised by the cost of virgin raw materials, which is generally lower than that of recycled plastics (Zheng & Suh, 2019). The introduction of appropriate incentive policies and regulations is therefore essential to encourage investment and support demand for products derived from recycling (E-CUBE Strategy Consultants, 2025).

II.3. Energy recovery from plastic waste:

Energy recovery from plastic waste is a complementary solution to its sustainable management. However, its effectiveness and impact vary according to the technologies used.

ll.3.1. Incineration :

Incineration is a commonly used method to reduce the volume of plastic waste while producing thermal energy. However, it raises major environmental concerns due to emissions of toxic pollutants, notably dioxins and furans, which require costly facilities to filter the gases and manage the residues (Guendehou et al., 2006). Despite these challenges, it remains a viable solution for non-recyclable plastics, provided it is accompanied by advanced fume treatment technologies (Université A. Mira de Bejaïa, 2024).

ll.3.2. Gasification:

Gasification offers a more environmentally friendly alternative by transforming plastics into syngas, a mixture of carbon monoxide and hydrogen, which can be used to generate electricity or power industrial engines (Escudero, 2022). This technology offers efficient energy recovery while reducing pollutant emissions compared with incineration. However, it requires considerable investment and a suitable infrastructure to ensure stable and economically viable production (RECORD, 2015).

ll.3.3. Pyrolysis:

Pyrolysis is emerging as a promising option for converting plastic waste into usable oils, fuel gases and carbon residues (Plastic Odyssey, 2024). Its effectiveness depends largely on the quality of the plastics processed and the profitability of the by-products generated. Although its integration into a circular recovery chain is advantageous, it requires an optimal economic and technical framework to maximise its potential (Enerzine, 2023).

While these technologies provide partial solutions to the problem of plastic waste, they should not overshadow the need to reduce its production at source and promote more sustainable alternatives. A balance between energy recovery, recycling and plastics reduction remains essential for effective, environmentally-friendly management (Ellen MacArthur Foundation, 2017).

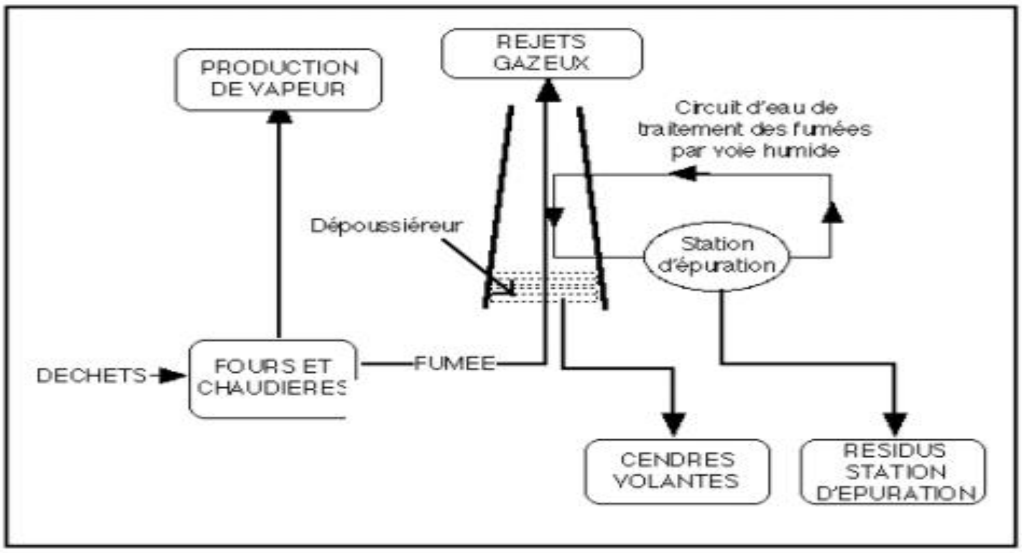


Figure ll-5: Schematic diagram of a household waste incinerator.

II.3.1 Incineration with energy recovery :

Incineration with energy recovery is an advanced waste treatment method that combines volume reduction and energy production. This process exploits the heat from combustion to generate electricity and thermal energy, thereby contributing to more sustainable management of non-recyclable waste (Fnade, 2024).

ll.3.1.1. Advantages of incineration with energy recovery :

- Reduction of waste volume by up to 90%, minimising the need for landfill (Vernimmen, 2024).

- Production of electricity estimated at 300-400 kWh per tonne of waste incinerated, together with around 1,500 kWh of heat (Batna 2 University, 2024).

Successful experiences in Algeria with the implementation of this technology by several specialist companies (Batna 2 University, 2024).

II.3.1.1. Constraints and challenges:

- High infrastructure installation and maintenance costs (Fnade, 2024).

- Treatment of emissions essential to comply with current environmental standards (Vernimmen, 2024).

- Need for consolidated data for Algeria to assess the real impact and effectiveness of the process (Université Batna 2, 2024).

II.3.2. Production of fuel from plastic waste:

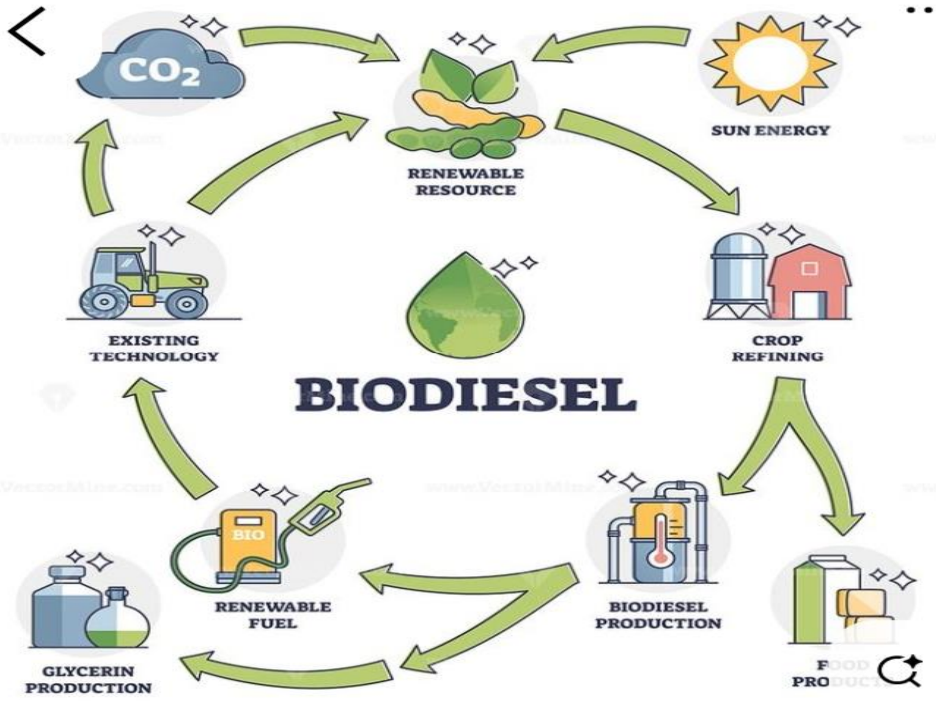
The conversion of plastic waste into liquid fuel by pyrolysis represents an innovative solution for combating environmental pollution and optimising the energy recovery of materials. This process is based on heating the plastic in the absence of oxygen, which breaks the molecular bonds and produces hydrocarbons that can be used as fuel (Techniques de l'Ingénieur, 2021).

ll.3.2.1. Main advantages of this technology :

- Reduction of pollutant emissions by 70% to 90%, depending on experimental studies (Renovables Verdes, 2024).

- Contribution to the circular economy by reusing plastic waste and converting it into a source of energy (Thot Cursus, 2021).

- High energy efficiency, encouraging wider adoption in industry (Techniques de l'Ingénieur, 2021).



FigureII-6: Life cycle of biodegradable plastics.

II.3.3. Environmental challenges :

II.3.3.1. Carbon dioxide (CO_2) emissions:

Carbon dioxide (CO_2) is one of the main greenhouse gases responsible for climate change. Although it is naturally produced by processes such as respiration and the decomposition of organic matter, human activities have significantly increased its concentration in the atmosphere (IPCC, 2021).

II.3.3.2. Anthropogenic sources of CO_2 :

- Combustion of fossil fuels: Coal, oil and natural gas are burnt to produce energy, power transport and support **manufacturing** industries. These activities account for around 75% of global CO_2 emissions (Climatico, 2024).

- Deforestation and forest fires: the destruction of forests reduces the planet's ability to absorb CO_2 , exacerbating its accumulation in the atmosphere (Ellen MacArthur Foundation, 2017).

ll.3.3.3. Consequences of CO_2 emissions:

- Increase in global temperatures: Since the pre-industrial era, the average global temperature has risen by around 1.1°C, disrupting ecosystems and natural cycles (IPCC, 2021).

- Melting of polar glaciers: This melting contributes to rising sea levels, threatening coastal areas and low-lying islands (Sigma Earth, 2024).

- Climate disruption: Climate change is leading to extreme events such as droughts, floods and heat waves (IPCC, 2021).

ll.3.3.4. Plastic waste management:

Plastic waste is a major environmental challenge due to its massive production and low biodegradability. Every year, some 430 million tonnes of plastic are produced worldwide, of which less than 9% is recycled** (UNEP, 2021). This problem is exacerbated by the widespread use of plastics in everyday consumer products such as packaging, bottles and plastic bags (Académie des sciences, 2021).

Figure ll-7: Schematic of the principles of the circular Economy (EU-Parliament, 2015).

ll.3.3.5. Environmental impacts of plastic waste :

- Threats to marine ecosystems: Marine species such as turtles, fish and birds often ingest pieces of plastic or become trapped in plastic waste. One study shows that more than 700 marine species are already affected by plastic pollution (Gall & Thompson, 2015).

- Microplastic pollution: The breakdown of plastic into microscopic particles, known as microplastics, is a growing threat to soil, water and human health. These particles can accumulate in food chains, leading to potential toxic effects (Ragaert et al., 2017).

- Accumulation in the environment: Plastics are difficult to recycle and their presence in terrestrial and marine ecosystems leads to persistent pollution (Academy of Sciences, 2021).

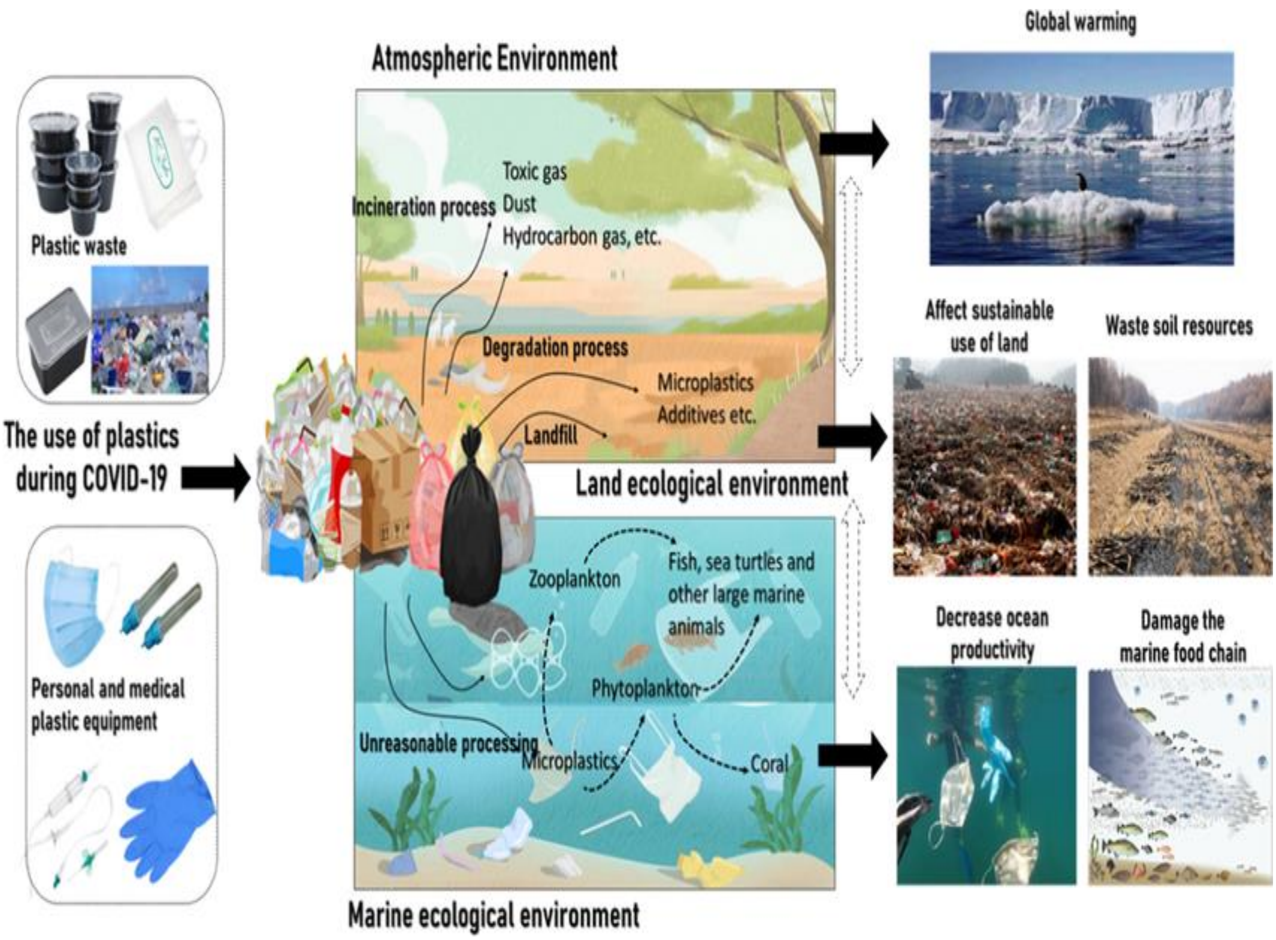


Figure ll-8: Environmental impacts of plastic waste.

ll.3.3.6. Proposed solutions :

In order to reduce these impacts, it is essential to adopt integrated solutions:

- Reduce reliance on fossil fuels in plastics production and encourage the use of biodegradable materials (UNEP, 2021).

- Promote sustainable alternatives to traditional plastics, including bioplastics and compostable materials (Academy of Sciences, 2021).

- Strengthen recycling infrastructure to ensure efficient management of plastic waste and improve recycling rates (Gall & Thompson, 2015).

II.4. Innovative approaches:

II.4.1. Biodegradable and compostable plastics :

Biodegradable and compostable plastics are a promising alternative for reducing the environmental impact of plastic waste. These materials are designed to decompose under specific conditions, such as high temperatures and controlled humidity levels. They are often made from bio-based raw materials, such as corn starch or polylactic acid (PLA) (Ragaert et al., 2017).However, their effectiveness is highly dependent on their end-of-life management. These plastics generally require industrial composting facilities to break down properly, which can limit their environmental benefits in regions where these infrastructures are non-existent or insufficient (Zero Waste France, 2020).

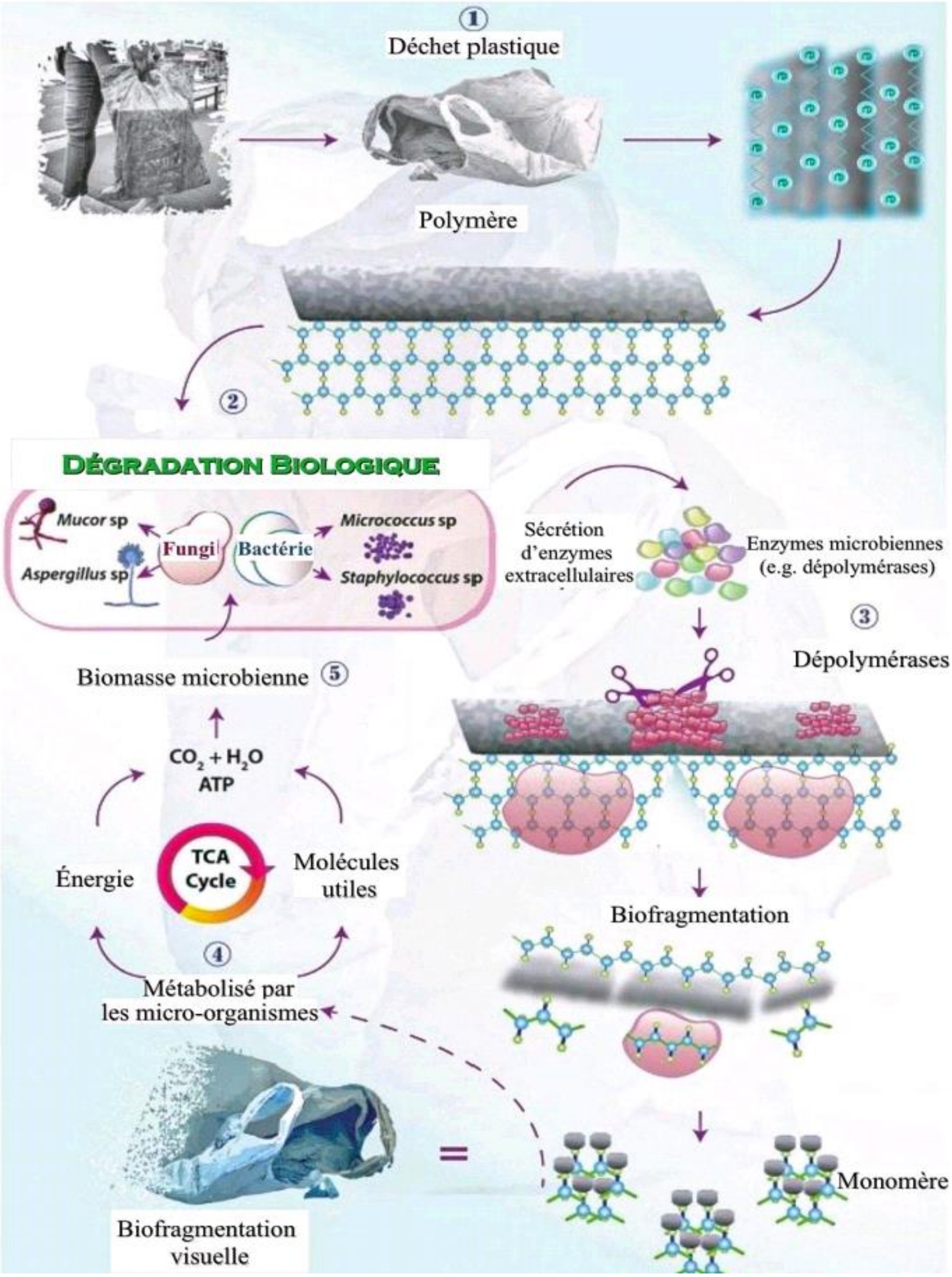


Figure ll-9: The different stages in the biodegradation of a plastic bag (Zeenat et al., 2021).

III- Valorization of by Products and Resource Optimization

III.1 Recovery Methods :

Sustainable management of plastics waste is based on converting it into reusable resources rather than disposing of it. Three main recovery methods are used:

II.1.1 Energy recovery:

Certain types of plastics can be incinerated in specialised facilities in order to recover the energy they contain and convert it into heat or electricity.

This approach enables to recover non-recyclable plastic waste while contributing to industrial energy supplies and reducing dependence on fossil fuels (The Conversation, 2020). Plastics incineration has a high calorific value, enabling to produce steam used to generate electricity via turbines. However, this method requires advanced filtration systems to limit emissions of greenhouse gases and toxic pollutants.

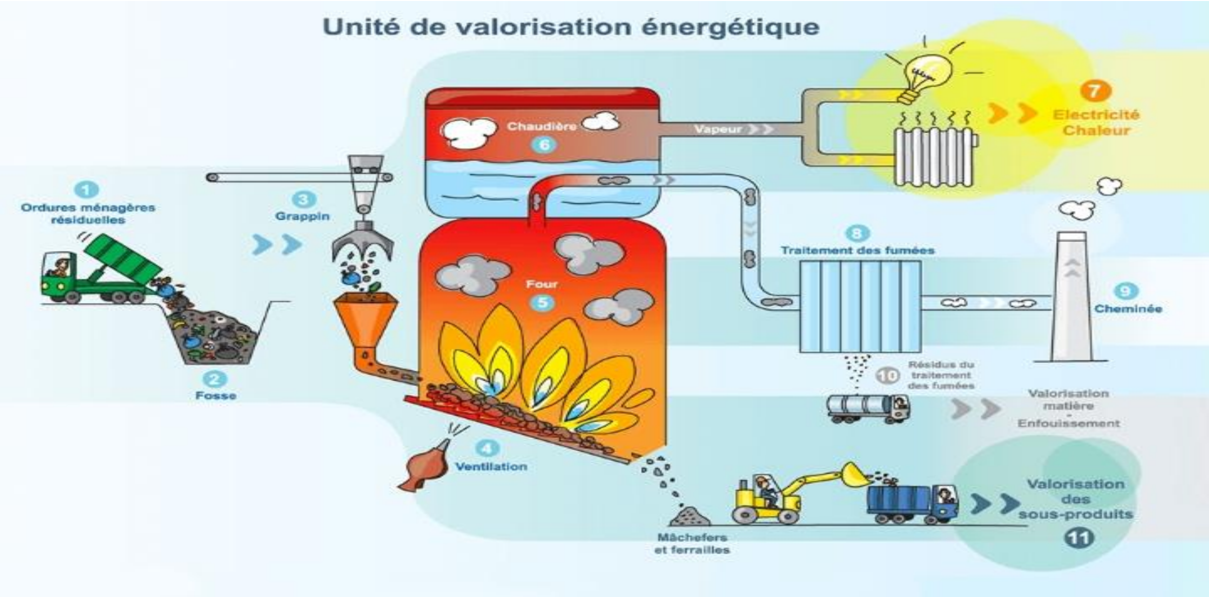
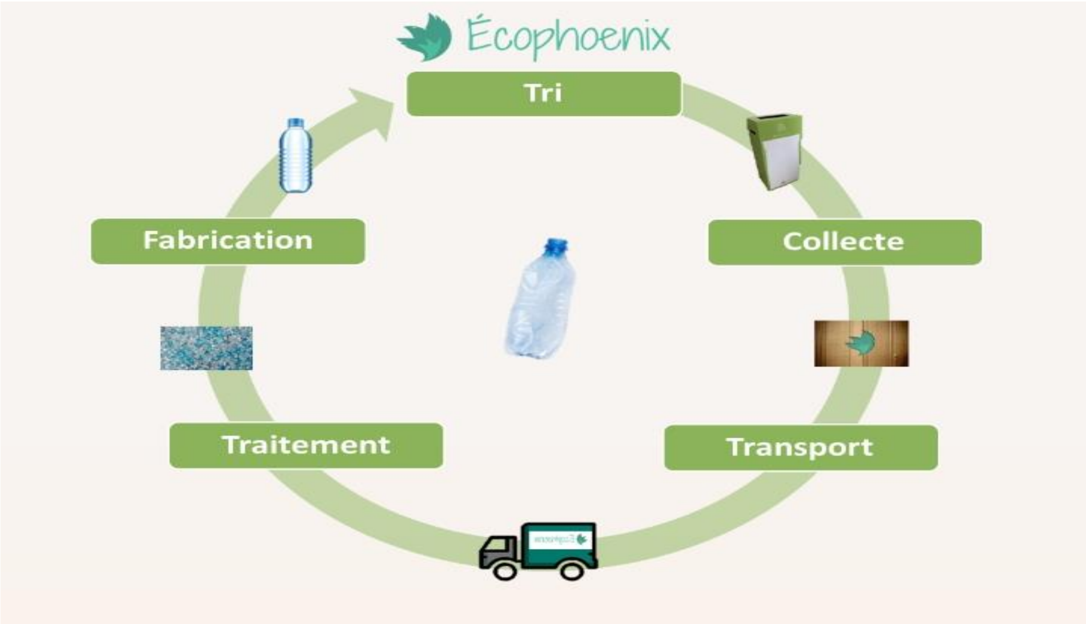


Figure lll-1: Diagram of the waste-to-energy plant.

II.1.2 Mechanical recovery:

This process involves collecting, sorting and crushing plastic waste in order to transform it into secondary raw materials. These recycled materials are then used in the manufacture of new products such as packaging, textiles and certain industrial components (Pure Laboratoire, 2020). Mechanical recycling is particularly effective for thermoplastic polymers, such as polyethylene (PE), polypropylene (PP) and polystyrene (PS). However, it is limited by the quality of the recycled plastics, which can be affected by the presence of additives and impurities (The Conversation, 2020).



Figurelll-2: Overall mechanical plastics recycling process.

II.1.3 Chemical recovery:

This approach involves breaking down plastic polymers into their basic components through chemical reactions such as pyrolysis, hydrolysis and gasification. The resulting products can be reused in the manufacture of new plastics or exploited in various chemical industries (The Conversation, 2020).

Pyrolysis converts plastics into liquid hydrocarbons, which can be used as fuels or petrochemical feedstocks. Gasification, on the other hand, converts plastic waste into syngas, a mixture of carbon monoxide and hydrogen used to produce energy .

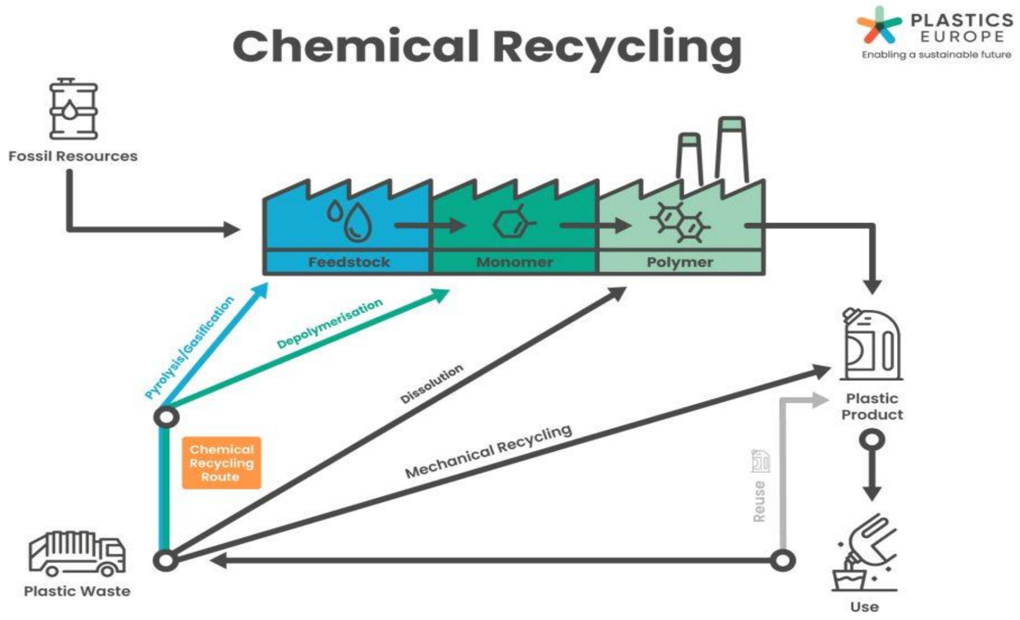


Figure lll-3: Chemical recycling stages (Plastics Europe)

Table III-1: Comparative analysis of plastic waste recovery methods (Harizi, 2015; Kaouadji, 2020; Ben Guesmia & Benmadani, 2022)

Recovery Method	Operating Principle	Efficiency	Cost	Environmental Impact
Energy Recovery	Controlled incineration of plastics to produce heat and electricity	Moderate to high (depending on plastic type) (Harizi, 2015)	High (costly infrastructure and emission management)	Generates greenhouse gases and air pollutants (Harizi, 2015)
Mechanical Recycling	Physical transformation of plastics into raw materials for new products	High (effective material recovery) (Kaouadji, 2020)	Moderate (requires sorting and processing)	Low, but depends on recycling quality (Kaouadji, 2020)
Chemical Recycling	Chemical breakdown of plastic polymers (pyrolysis, hydrolysis, gasification)	Variable (depends on technology and plastic type) (Ben Guesmia & Benmadani, 2022)	Very high (advanced technologies required)	May produce toxic byproducts and chemical pollution (Ben Guesmia & Benmadani, 2022)

III.2 By-products of plastics waste processing:

Plastic waste represents a major environmental challenge, which has stimulated the development of various technologies for its recovery. These include recycling, pyrolysis, gasification and incineration. Each of these techniques produces specific by-products, with distinct economic and ecological implications (PlasticsEurope, 2020).

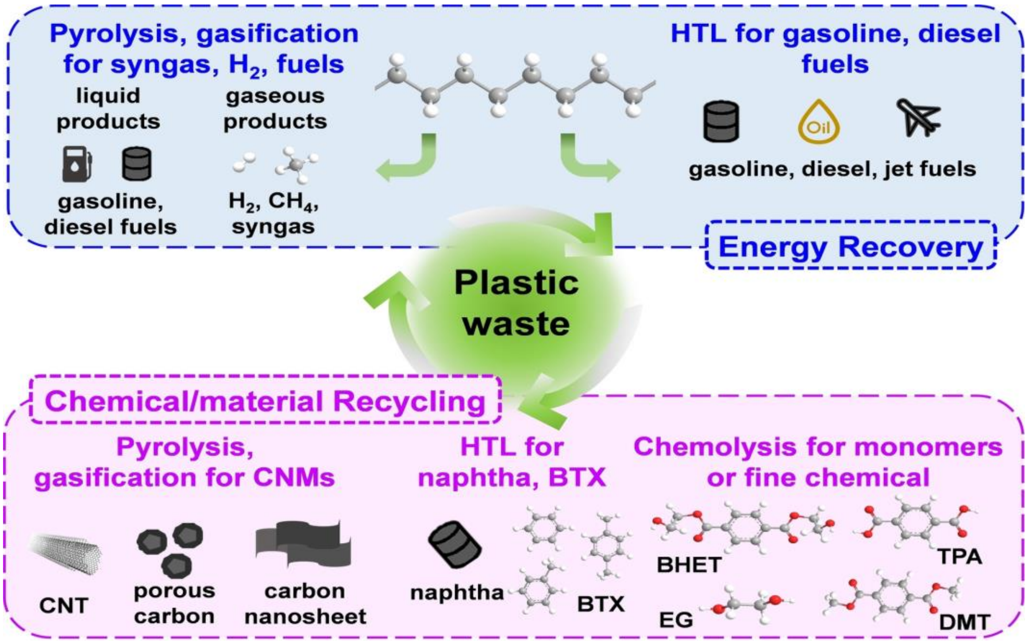


Figure lll-4: Transformation of plastic waste into sustainable materials.

III.2.1. Recycling residues :

Recycling residues mainly come from the plastic sorting and separation stages. According to a study carried out by PlasticsEurope (2020), around 25 to 30% of sorted plastics cannot be recycled and are often sent for other treatments, such as pyrolysis or incineration. These residues include fibres, powders and reprocessed granules.

Fibres and powders:

Recycled plastics can be transformed into fibres or powders, which have applications in various sectors. For example, recycled polyethylene fibres are used in the manufacture of textiles, offering a sustainable alternative to virgin materials (Recycling Today, 2021). Recycling not only reduces waste, but also minimises the consumption of natural resources.

III.2.2. Gases and oils produced by pyrolysis and gasification:

Pyrolysis and gasification processes are advanced thermochemical methods for breaking down plastic waste into recoverable products such as oils, gases and solid residues. These technologies offer an alternative to conventional plastic waste management methods and contribute to a more sustainable circular economy (Plastic Odyssey, 2024).

- Pyrolysis:

Pyrolysis is a process of thermal decomposition of plastics in the absence of oxygen, typically at temperatures between 400 and 800°C (Plastic Odyssey, 2024). This process breaks down the long polymer chains and produces three main by-products:

- Pyrolysis oils: These bio-oils are liquid hydrocarbons that can be refined and used as fuels or raw materials for the chemical industry (Hassibi, 2021).

- Combustible gases: Containing methane, hydrogen and carbon monoxide, these gases can be used to produce energy (NREL, 2019).

- Solid residues (pyrolysis coal): Used as additives in the manufacture of composite materials or as a source of carbon in certain industries (Connaissance des Énergies, 2024).

- Gasification:

Gasification is a thermochemical process that transforms plastics into synthesis gas (syngas) in the presence of a limited amount of oxygen or steam, at temperatures above 800°C (Techniques de l'Ingénieur, 2025). This syngas is composed mainly of carbon monoxide (CO) and hydrogen (H_2), and can be used for:

- Electricity production using gas turbines (Connaissance des Énergies, 2024).

- Manufacture of synthetic fuels using the Fischer-Tropsch process (Techniques de l'Ingénieur, 2025).

- Synthesis of chemicals such as methanol and ammonia (ULB, 2007).

- Incineration:

Incineration is a method of treating plastic waste that cannot be recycled. It considerably reduces the volume of waste while producing thermal energy (Université Batna 2, 2024). However, it generates by-products such as :

- Ash and bottom ash: Solid residues requiring specific treatment to avoid environmental contamination (IPCC, 2021).

- Gaseous pollutants : Emissions of CO_2 and dioxins that must be filtered before release into the atmosphere (Polytechnique Madagascar, 2023).

III.2.3. Ash and bottom ash from incineration:

Ash and bottom ash from waste incineration are solid residues containing heavy metals and other potentially toxic compounds. Their management is essential to avoid soil and water contamination.

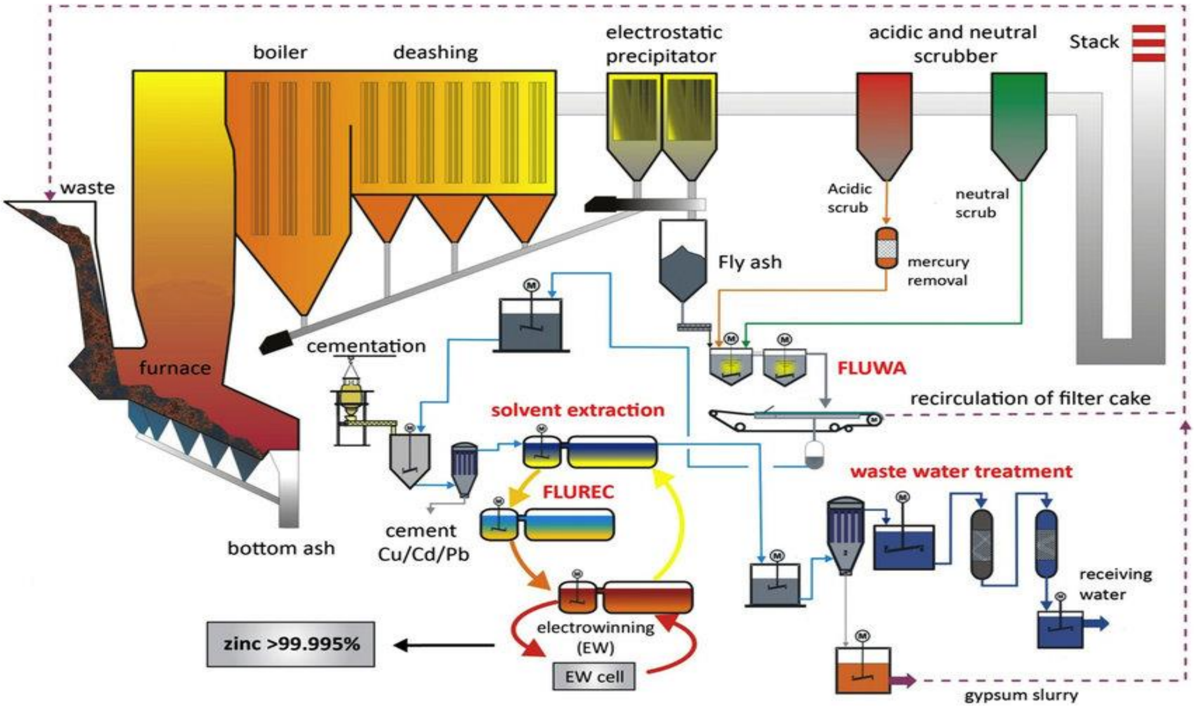


Figure lll-5 : Processus diagram of waste incineration, Fly ash leaching (FLUWA) and recovery of recyclable materiels (FLUREC).

lll.2.3.1. Composition and environmental risks :

Bottom ash consists mainly of silicates, metal oxides and carbonaceous residues. It contains heavy metals such as lead (Pb), cadmium (Cd), copper (Cu) and zinc (Zn), which can leach under certain conditions and contaminate the environment (Fendeleur et al., 2021).

lll.2.3.2. Recovery of bottom ash in road construction :

A study carried out by SMÉDAR (2024) has shown that bottom ash can be used as road base material after specific treatment. This process reduces the need to bury waste and limits the extraction of natural aggregates (SMÉDAR, 2024).

lll.2.3.3. Closed loops and sustainable management :

The concept of closed loops in the management of plastic waste and bottom ash is based on reintegrating recycled materials into the production cycle without generating new waste. This involves :

- Treatment of bottom ash to stabilise heavy metals and prevent leaching.

- Reuse in civil engineering to replace natural aggregates.

- Strict control of emissions and environmental impacts associated with their use (AIDA, 2024).

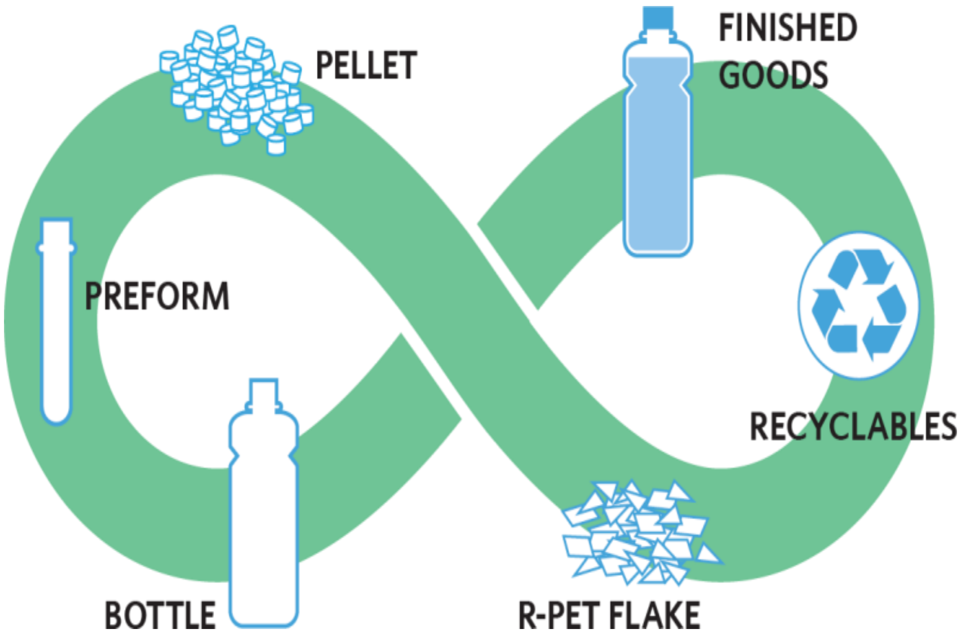


Figure lll-6: Plastic recycling life cycle (Bausano. (nd.). Usos y beneficios económicos del reciclaje de PET Bausano.

III.3 By-products and applications :

III.3.1. Types of by-products :

By-products from the processing of plastic waste can be classified into three main categories:

- Solid residues :

- Fly ash and bottom ash from incineration, which often contain heavy metals and other toxic components (Fendeleur, Trouvé, & Delfosse, 2021).

- Recycled fibres from the mechanical shredding of plastics (GéoLittoral, 2025).

- Liquid by-products :

- Pyrolysis oils obtained from the thermal decomposition of plastics (EPO, 2025).

- Organic solvents from gasification or pyrolysis (ULB, 2007).

- Gaseous by-products :

- Syngas, mainly composed of carbon monoxide and hydrogen, used in various energy processes (Connaissance des Énergies, 2024).

- Volatile organic compounds (VOCs) used in the chemical industry (Techniques de l'Ingénieur, 2025).

III.3.2. Industrial applications :

III.3.2.1. Conversion into construction materials:

By-products from the processing of plastic waste have applications in the construction sector. For example :

- Lightweight bricks made from recycled plastics offer a sustainable alternative to traditional materials (Mehta & Monteiro, 2014).

- Incorporating recycled plastic fibres into insulation panels improves the energy efficiency of buildings (GéoLittoral, 2025).

llI.3.2.2 Production of alternative fuels

Synthetic oils produced by pyrolysis can be refined to produce alternative fuels such as :

- Diesel and paraffin, reducing dependence on fossil fuels (EPO, 2025).

- Other fuels derived from co-products, used in certain industries (ULB, 2007).

Figure lll-7: The life cycle of plastic bottles (Spiegato, n.d.).

III.2.2.3. Use in the chemical industry :

Gaseous by-products from pyrolysis or gasification can be transformed into :

- Industrial solvents used in the manufacture of paints and adhesives (Techniques de l'Ingénieur, 2025).

- Recycled polymers, reducing the use of virgin raw materials (Connaissance des Énergies, 2024).

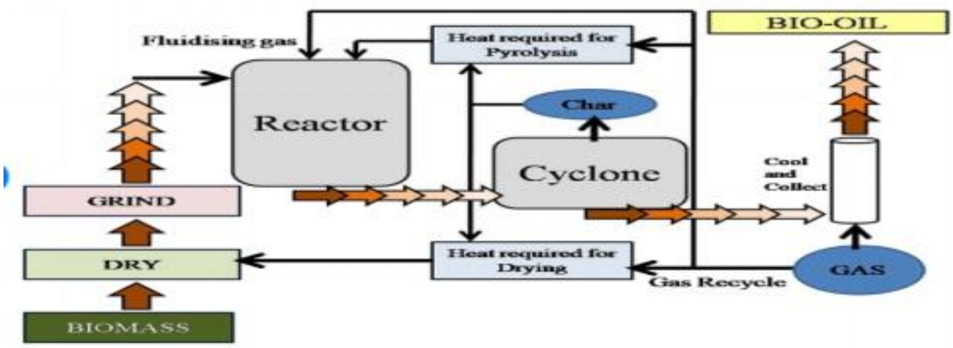


Figure lll-8: Biomass pyrolysis process (Institut National de l'Énergie et du Développement Durable, 2024).

III.4 Optimising resources and minimising environmental impact :

III.4.1. Closed-loop design :

The implementation of closed-loop recycling systems aims to maximise the reuse of resources while minimising waste.

- The "Cradle-to-Cradle" model (McDonough & Braungart, 2002) illustrates the continuous reintegration of materials into the production cycle.

- Recent initiatives in certain countries, notably Algeria, show the integration of closed loops in advanced recycling systems (Upcyclea, 2024).

lll.4.2. Life cycle assessment (LCA) to evaluate environmental impacts :

Life Cycle Assessment (LCA) is an essential tool for assessing the environmental impacts of by-products over their entire life cycle.

- The ISO 14040 standard (ISO, 2006) provides the methodological framework for LCA.

- Recent studies provide a quantitative comparison of the impacts of different recycling and recovery methods (Climate Selectra, 2023).

lll.4.3. Strategies for reducing the carbon footprint and minimising residual waste

To reduce the carbon footprint and minimise residual waste, several strategies are recommended:

- Eco-design and optimisation of industrial processes (Sigma Earth, 2024).
- The use of renewable energies in recycling and treatment processes (Climate Selectra, 2023).
- The promotion of sustainable management and industrial recycling policies, supported by strict regulatory frameworks (Ecotoxicologie, 2024).

III.5 Case studies and best practices:

III.5.1. Examples of successful circular plastic waste management projects:

The Ocean Cleanup project, initiated by Boyan Slat, illustrates how marine plastic waste can be collected and recycled into useful products, such as clothing or accessories. Since its inception in 2013, the project has removed more than 100 tonnes of plastic from the oceans using a system of floating barriers that capture waste in the North Pacific vortex (Futura Sciences, 2024) (Slat et al., 2019).

Figure lll-9: Collection of plastic waste from rivers by The Ocean Cleanup project (The Ocean Cleanup, 2025).

III.4.2. Partnerships between public, private and academic players:

Multi-stakeholder partnerships play a key role in promoting circular solutions. For example, collaboration between the Dutch government, Philips and the Eindhoven University of Technology has led to the development of innovative technologies for recycling electronic waste. Through its Solving the E-Waste Problem (STEP) programme, Philips is working with academic and industrial partners to improve the collection and recycling of electronic equipment, thereby reducing its environmental impact (Philips, 2024) (Porter & Kramer, 2011).

III.4.3 Local and community initiatives :

Local initiatives, such as the Zero Waste initiative in San Francisco, demonstrate the importance of community involvement in waste management. Thanks to ambitious municipal policies and the commitment of citizens, the city has achieved an 80% recycling rate and is aiming for zero waste. This programme is based on efficient selective collection, financial incentives and increased awareness among residents (C40 Cities, 2024) (Pretty, 2003).

IV.Materials And Methods

IV.1 Study Objective

The overarching objective of this study is to assess current plastic waste management practices through a questionnaire-based survey targeting a diverse population (municipalities, businesses, recyclers, and households). Additionally, it aims to investigate the biodegradation capacity of various plastics by environmental microorganisms (bacteria, fungi) via microbiological experiments, and to propose practical and sustainable solutions for optimizing circular management and the valorization of plastic byproducts within the framework of a local circular economy.

IV.2 Description of the study area

The study was carried out in the wilaya of Tlemcen, located in north-west Algeria. This region has a high level of agri-food activity, with frequent use of locally produced plastic packaging. The area was chosen in order to obtain results specific to the regional context. The samples studied come mainly from local production units. This enables to assess the real impact of plastic packaging used in Tlemcen's agri-food circuits.collected, in particular its ability to produce biogas or to be recovered as compost or recyclable material.

IV.3. Target Population and Sampling Criteria

The surveyed population (n = 110) included representatives from key stakeholder groups: municipal employees, businesses, households, and recyclers. A purposive (non-probabilistic) sampling method was employed, ensuring the selection of participants most relevant to the study's objectives.

IV.4. Survey on Plastic Waste Management

IV.4.1 Specific Survey Objectives

To identify local behaviors, perceptions, challenges, and opportunities related to plastic waste management practices.

IV.4.2 Questionnaire Design and Structure

The survey instrument consisted of a bilingual (French/Arabic) questionnaire comprising 20 questions, organized into thematic sections:

- ✓ Sociodemographic data
- ✓ Waste sorting habits
- ✓ Access to waste management infrastructure
- ✓ Participation in recycling programs
- ✓ Perceptions of circular economy principles

IV.4.3. Survey Administration

The survey was administered through face-to-face interviews, with an average completion time of 20 minutes. Prior to participation, informed consent was obtained from all respondents, ensuring anonymity and confidentiality of responses.

IV.4.4. Survey Data Analysis Methods

Data were analyzed using Microsoft Excel and SPSS statistical software. Descriptive statistical analyses (frequencies, percentages, and graphical representations) were performed. Cross-tabulation analyses were conducted to examine potential relationships between key variables

IV.5. Study of the biodegradation of plastics

IV.5.1. Objectives and experimental hypothesis

To verify the ability of micro-organisms to biodegrade common plastics under controlled laboratory conditions.

IV.5.2. Location of experiments

The biodegradation experiments were carried out at the research laboratory Ppubionut and the Pedagogical Laboratories of Microbiology of the Faculty of Natural and Life Sciences , Earth and Universe - University of Tlemcen.

IV.5.3. Required Materials

1. **Plastic Samples**:
   - ✓ Polyethylene (PE) bag pieces or PET bottle fragments (1 × 1 cm)

2. **Microorganism Sources:**
   - ✓ Contaminated soil (landfill, riverbank) or compost

3. **Basic Culture Media:**
   - ✓ For bacteria: Nutrient broth (water + yeast extract + peptone)

- ✓ For fungi: Potato Dextrose Agar (PDA) or moldy bread

4. Essential Equipment:

- ✓ Sterile glass jars (e.g., mason jars)
- ✓ Cotton/mesh for jar covers
- ✓ Kitchen scale (0.1 g precision)
- ✓ Optical microscope (if available) or magnifying lens
- ✓ 70% ethanol (for disinfection)

IV.5.3. Sample Preparation

- Processing:

- o Cut into sterile fragments (1 × 1 cm)
- o Clean with 70% ethanol and dry in oven (50°C, 1 h) or air-dry

- **Initial Weighing: Record each fragment's mass**

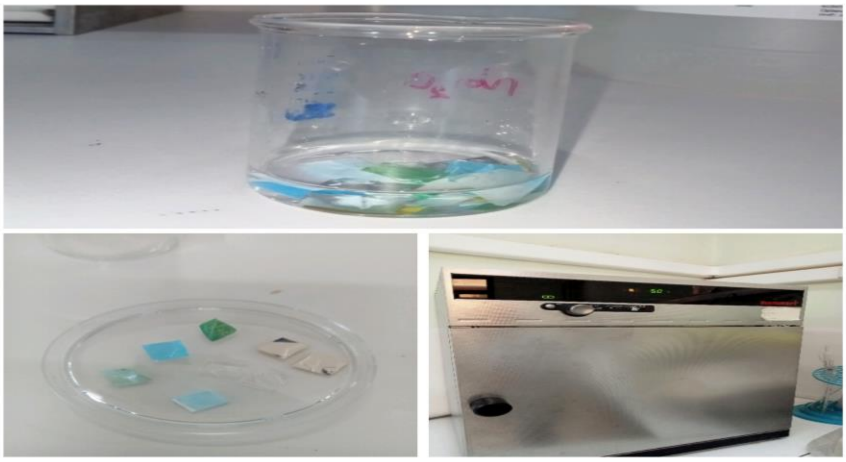


Figure IV-1 Sample Preparation

IV.5.4. Microorganisms

- **Strains:**
  - o Bacteria: Ideonella sakaiensis (PET reference), Pseudomonas sp. (environmental isolates)
  - o Fungi: Aspergillus niger, Fusarium solani (from contaminated soils)

- **Isolation:**
  - Collect plastic-contaminated soil samples (landfills, riverbanks)
  - Inoculate on nutrient media (LB agar for bacteria, PDA for fungi)

Figure IV-2 contaminated soil samples (Honaine)

Step 1: Microorganism Isolation

- **Sample Preparation**:
  - Mix 1 g contaminated soil with 9 mL sterile saline
  - Vortex, then prepare serial dilutions (10^{-1} to 10^{-5})

- **Inoculation:**
  - Spread 100 µL of each dilution on selective media:

  - LB agar for bacteria
  - PDA + chloramphenicol for fungi

  - Incubate at 30°C (bacteria) or 25°C (fungi) for 48-72 h

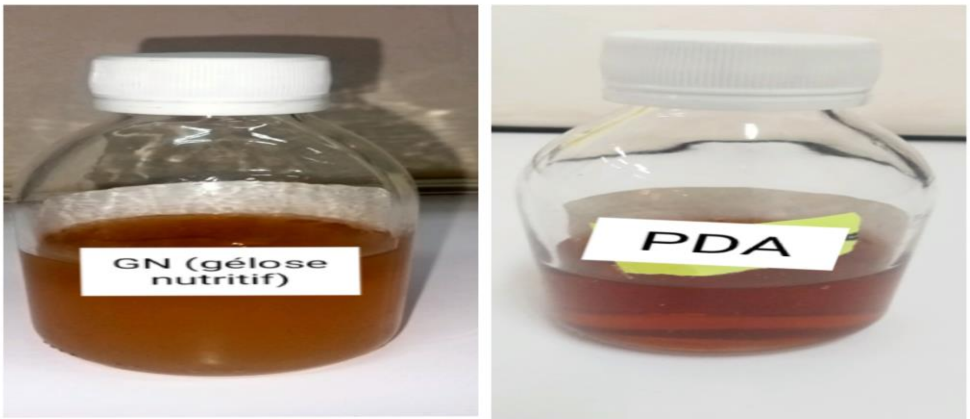


Figure VI-3: PDA culture medium for fungi and nutrient agar for bacteria.

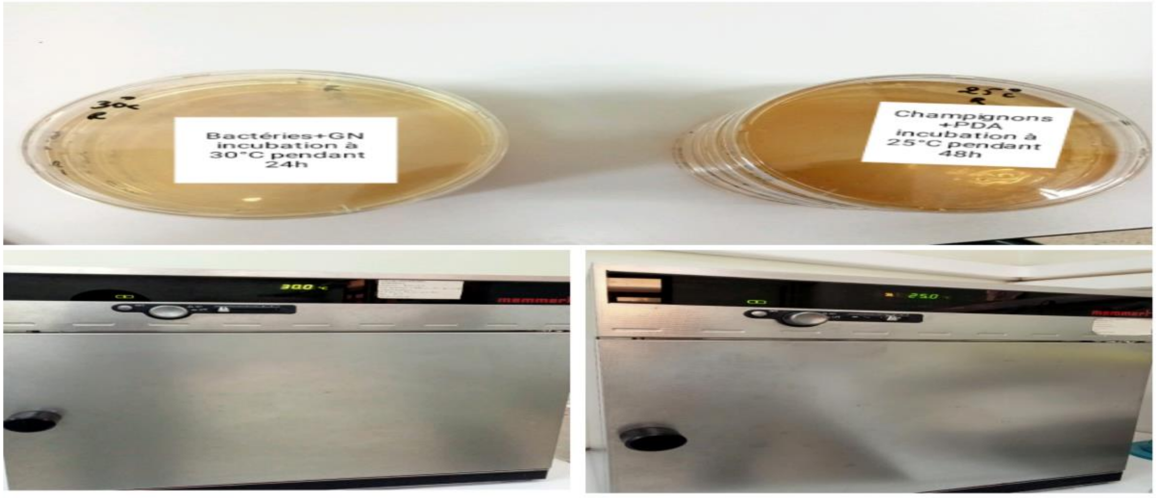


Figure VI-4: Incubation of bacteria at 30°C and fungi at 25°C for 48 hours.

❖ Observations (Without Specialized Equipment)

- **Visual**:
    - Biofilm formation (whitish/colored film)
    - Plastic fragmentation or texture changes

- **Microscopic**:
    - Examine biofilm droplets under microscope (400×) or lens (20×) for bacterial/fungal structures

- **Controls**

  - Negative control: Plastic + sterile medium (no microorganisms)
  - Positive control: Plastic + known strain (e.g., baker's yeast)

Step 2: Degrader Strain Selection

- **Mineral Medium Culture**:
  - Inoculate isolated colonies in flasks with mineral medium + plastic fragments
  - Incubate with shaking (120 rpm) for 4-8 weeks

- **Controls**:
  - Flasks without microorganisms
  - Flasks with glucose as carbon source (viability check)

Step 3: Analyses

- **Mass Loss**:
  - Weigh fragments pre-/post-incubation (analytical balance, 0.1 mg precision)
  - Calculate degradation percentage:

Degradation (%) = (Initial Mass - Final Mass) / Initial Mass × 100

- **Explanation**:
  - Initial mass (m_0): Plastic weight before experiment (grams)
  - Final mass (m_1): Plastic weight after microbial exposure (cleaned and dried)

V. Results

V Results

The main aim of this study is to assess the perception, practices and obstacles associated with the circular management of plastic waste in the wilaya of Tlemcen, while exploring the acceptability of solutions for recovering plastic by-products. The survey aims to identify the behaviour of citizens and professionals, the gaps in infrastructure and information, and the possible levers for improving circularity in plastic waste management.

V.1 Questionnaire Survey

The analyses were based on a questionnaire administered to 110 participants from a variety of backgrounds: municipalities, businesses, students, teachers, recyclers and citizens. The data was processed using GraphPad Prism 9 software.

V.1.1. Demographic characteristics and profile of respondents

Analysis of the profiles reveals :

V.1.1.1 Age Distribution

The majority of respondents (73.4%) were aged between 18 and 30, underlining the strong interest of young people in environmental issues. (Figure V-1)

. The 31-45 age group accounted for 18.1%, while the over-45s were in the minority.

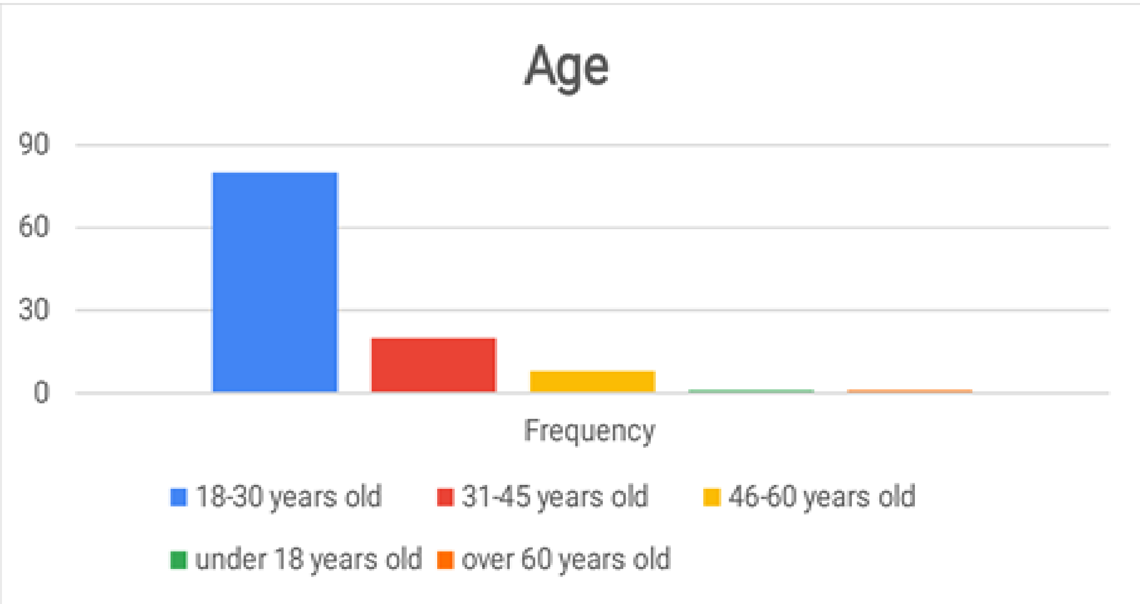


Figure V-1 Age Distribution

V.1.1.2 Place of residence

72% live in urban areas compared with 28.5% in rural areas, suggesting an imbalance in access to waste sorting and management facilities.(Figure V-2)

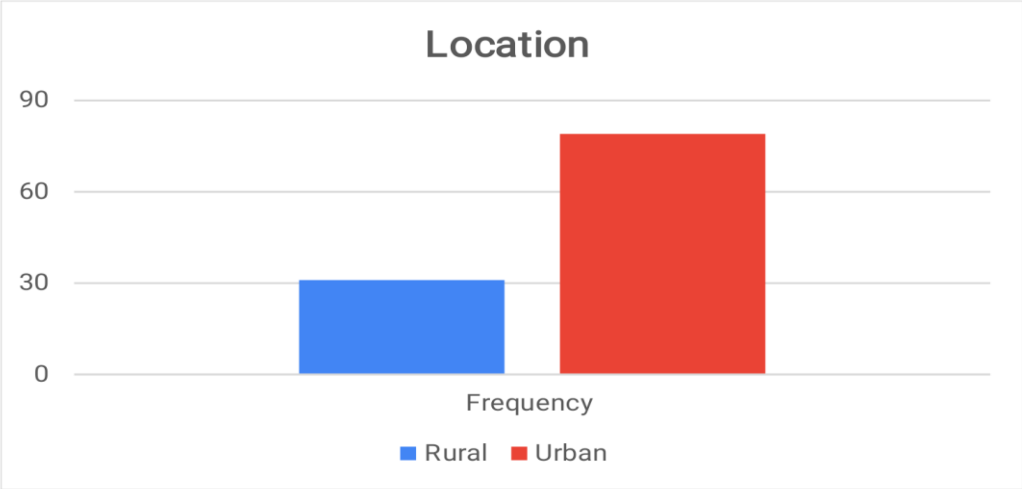


Figure V-2 Place of Residence

V.1.1.3 Profession

62% are students, teachers or in other professions, which is a strategic target for educational programmes. By contrast, only 10.1% are municipal employees and 7.6% work in recycling.(Figure V-3)

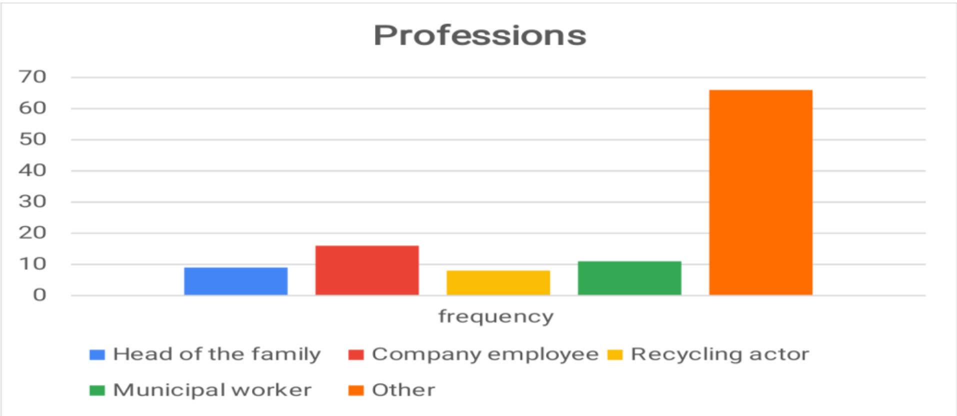


Figure V-3 Profession

V.1.2. Plastic waste management practices

V.1.2.1 Type of waste generated:

Regarding the most commonly used types of plastic:

- 49.8% of participants primarily use food packaging, followed by 47.3% using PET bottles.

- 13.3% report frequently using polyethylene bags, highlighting a need to reduce this category of waste. (Figure V-4)

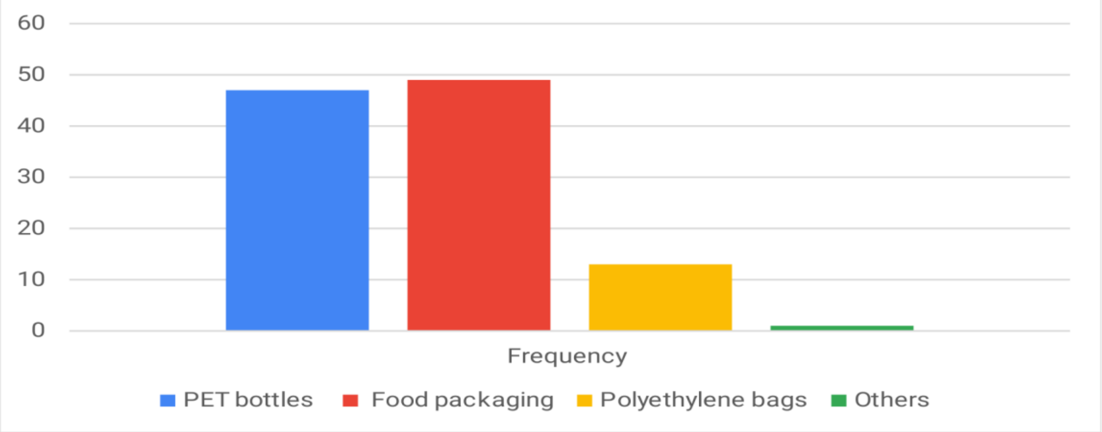


Figure V-4 Dominant Plastic Waste Streams

V.1.2.2 Selective Sorting:

The frequency of waste sorting remains a concern:

- Only 22.7% always sort their plastic waste.

- 77.3% rarely, sometimes, or never sort it, highlighting a lack of awareness and/or a lack of suitable infrastructure.

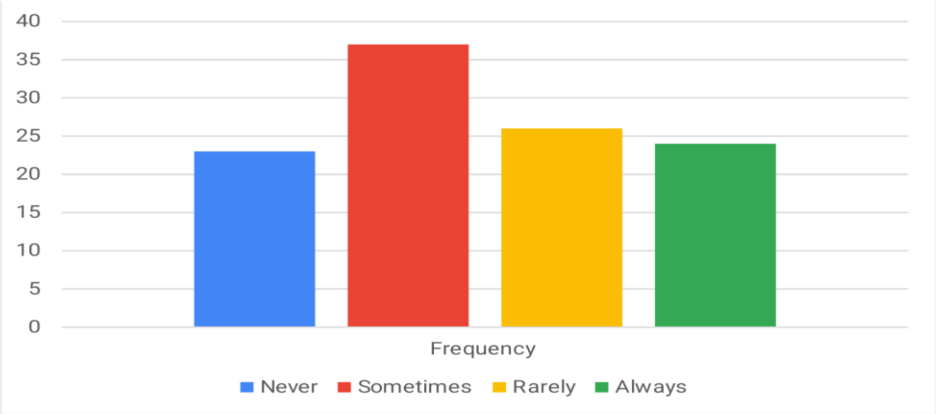


Figure V-5 Selective Sorting of Plastic Wasting

V.1.2.3 Available infrastructure:

63% report a lack of recycling bins in their neighbourhood or workplace. This could explain the low rate of sorting of plastic waste.

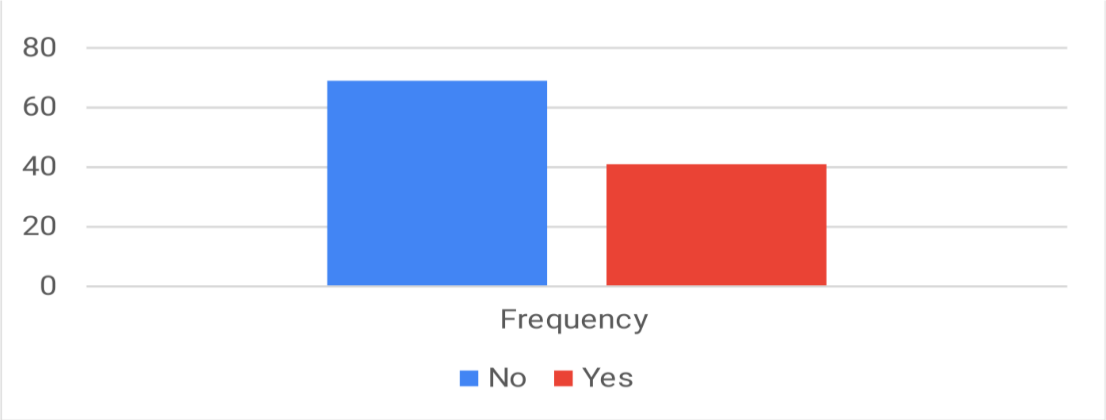


Figure V-6 Frequency of available Recycling bins

V.1.2.4 Participation in retraining programmes:

Participation in recycling programmes is also low:

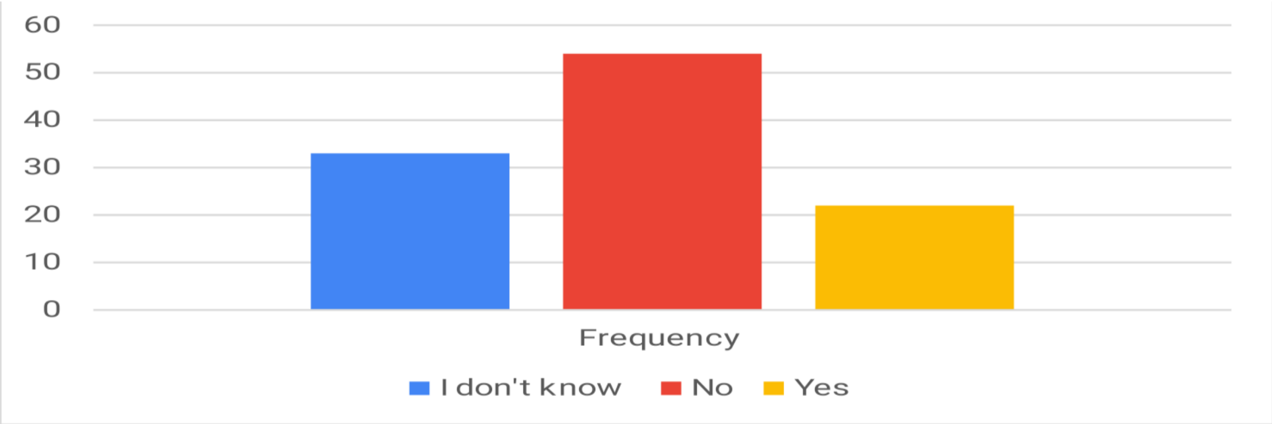
- 81% of respondents have never taken part in recycling or selective collection programmes.

This suggests a lack of awareness of existing initiatives or a lack of incentive to get involved.

V.1.3 Awareness and Perceptions of Circular Solutions

- **Knowledge of local recycling channels:** 50% have no knowledge at all; only 20% know exactly where to recycle.

- **Environmental concerns:** 40% say they are very concerned about plastic pollution, 44% say they are moderately concerned.
- **Known initiatives:** 64% are unaware of local waste recovery projects or companies.



V.1.4 Perception of responsibilities

- **Vision of the circular economy:** 76% believe it is an effective solution to plastic pollution.
- **Perceived responsibilities:**
  - **Municipalities:** 71% think their main role is collection and sorting; 21% favour awareness-raising.
  - **Businesses:** 91% believe they should take responsibility for the waste they generate.

V.1.5. Market Potential for Valorized By-Products

V.1.5.1 Purchasing behaviour and acceptability of recycled products

- 63% have used recycled plastic products: Signals growing demand for valorized materials (e.g., textiles, 3D-printing filaments).
- But 66% unwilling to pay premiums: Indicates need for cost-competitive circular products.

V.1.5.2 Preferred Valorization Strategies

- Mechanical recycling (53%)**:** Favored for simplicity, but limited by degradation.
- Chemical recycling (22%)**:** Emerging interest in advanced upcycling (e.g., pyrolysis for fuel).
- Reuse (25%)**:** Support for refill systems **or** second-life applications**.**

V.1.5. Barriers to Circularity and Proposed Solutions

V.1.5.1 Main Obstacles

The main obstacles identified are

- Infrastructure gaps (37%)**:** Lack of facilities for sorting/processing.

- Low awareness (48%)**:** Poor understanding of by-product value (e.g., plastic waste as raw material).
- Economic hurdles (13%)**:** High costs of circular technologies.

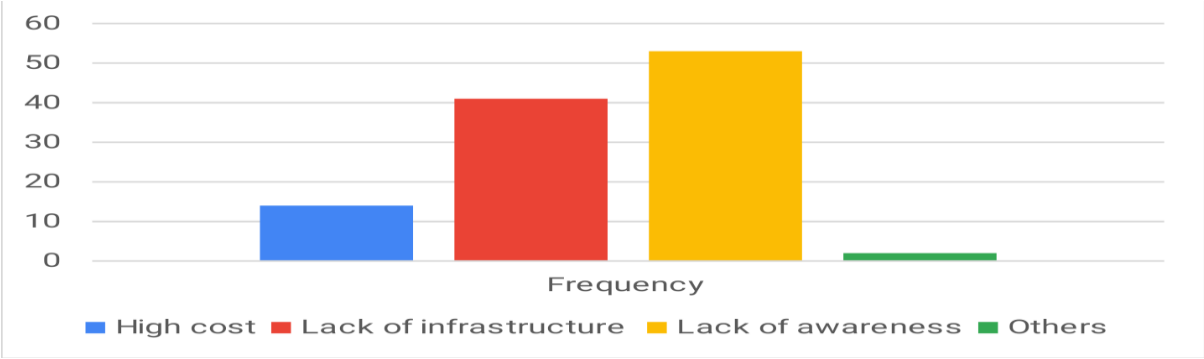


Figure V-8 Main Obstacle of Plastic Waste Management

The main sources of pollution cited are

- Unauthorised landfill (53%)
- Poorly sorted household waste (40%)

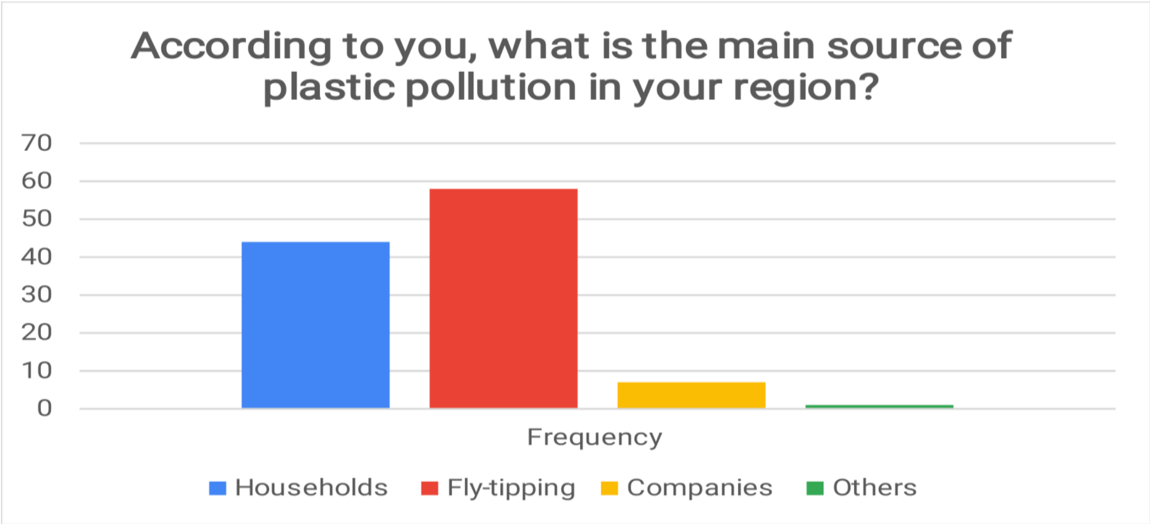


Figure V-9 Mains sources of Plastic Pollution

V.1.5.2 Solutions proposed by participants

The most frequently cited proposals include :

- Mass awareness campaigns (76%)
- Creation of collection points (15%)
- Support for recycling companies (9%)

V.2 Biodegradation of Plastics

V.2.1. Experimental Culture

Two types of set-up were implemented to assess the degradation capacity of plastic fragments (PE and PET) by environmental microorganisms:

- Negative control: plastic + sterile medium (without microbial inoculum)
- Positive control: plastic + microbial strains known for their biodegradation potential (bacteria or fungi)

These conditions made it possible to compare the potential effects of the tested microorganisms against a non-biodegradable background.

V.2.2. Controlled incubation conditions

Culture parameters were adjusted according to the type of micro-organism:

Table V.1: Experimental parameters

Parameter	Bacteria	Fungi
Temperature	30 °C	25 °C
Humidity	70 %	80 %
Duration	3 weeks	3 weeks
Culture medium	PDA nutrient agar	PDA Potato Dextrose Agar

V.2.2. Biodegradation Assessment

V.2.2.1. Mass Loss of Plastic Fragments

Biodegradation was measured by comparing initial and final weights of plastic fragments. The degradation percentage was calculated using the formula:

Degradation (%) = (m_initial - m_final)/m_initial × 100

Table V.2: Initial and final mass of plastic fragments

Fragment	Initial Weight (g)	Final Weight (g)	Degradation (%)
Piece 1	0.005	0.004	0.1
Piece 2	0.006	0.005	0.1
Piece 3	0.008	0.008	0
Piece 4	0.010	0.009	0.1
Piece 5	0.011	0.011	0
Piece 6	0.014	0.014	0
Piece 7	0.046	0.046	0
Piece 8	0.049	0.049	0
Piece 9	0.054	0.053	0.1
Piece 10	0.057	0.057	0
Piece 11	0.063	0.063	0
Piece 12	0.068	0.068	0

The mass loss remains very minimal (0-0.1%), suggesting no significant measurable biodegradation occurred.

V.2.2.2 Macroscopic Visual Observations

Visual monitoring was conducted at different incubation times (48h, 1 week, 2 weeks, 3 weeks) on plates containing bacteria and fungi:

Weekly photographs were taken to document culture evolution. (Table IV-3 ,4,5 & 6)

Based on systematic visual observations and documented photographic evidence:

- **Plastic Fragment Integrity**

  No detectable physical alterations:

  - Color stability: Absence of discoloration or pigment leaching
  - Structural integrity: No fragmentation, cracking, or surface erosion
  - Biofilm formation: No observable microbial mats or extracellular polymeric substances (EPS) coating

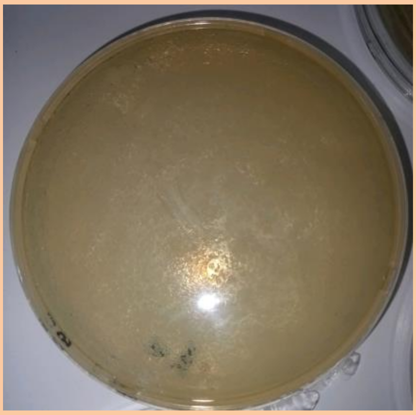
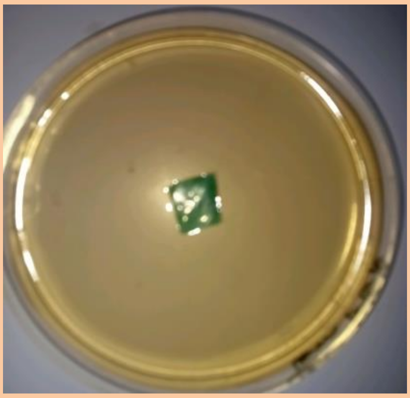
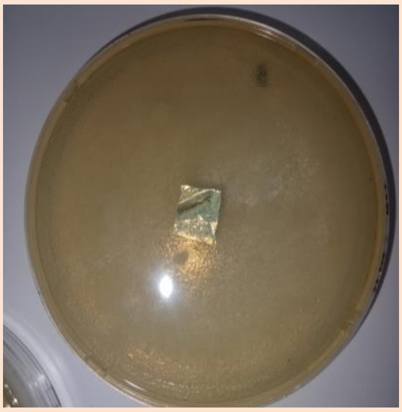
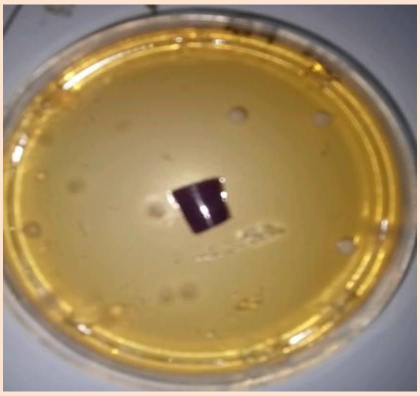
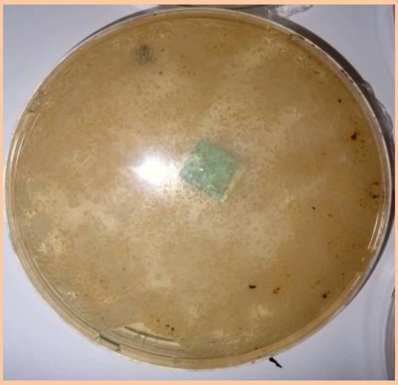
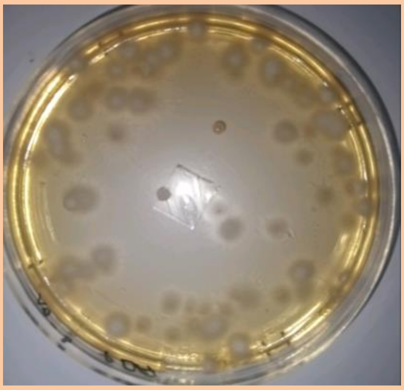
- **Microbial Dynamics**

  - Progressive decline in culturable cell counts:
  - Bacterial density decreased by 65-80% between weeks 1-3
  - Fungal hyphal networks showed reduced branching and sporulation
  - Nutrient agar controls confirmed this was not an artifact of medium depletion

- **Comparative Analysis**

  - Negative controls (sterile plastic) showed identical surface characteristics
  - Positive controls (known degradative strains) displayed expected:

Table IV-3: Observations of plates (bacteria in nutrient agar at 30°C and fungi in PDA at 25°C) for 48h.

Solution	Bacteria	Fungi
Control		
10^{-4}		
10^{-3}		

V Results

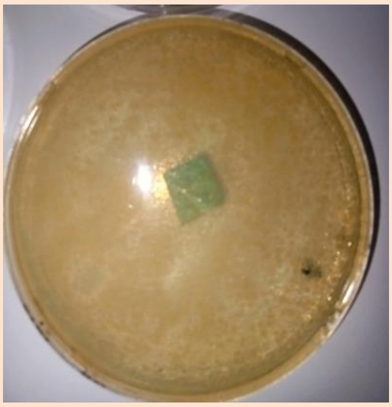
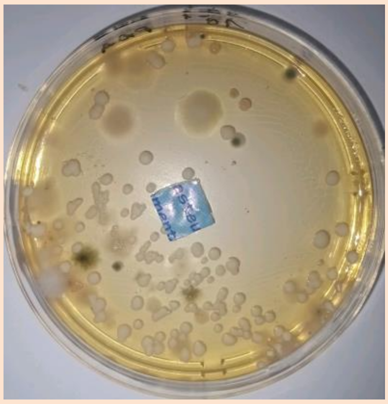
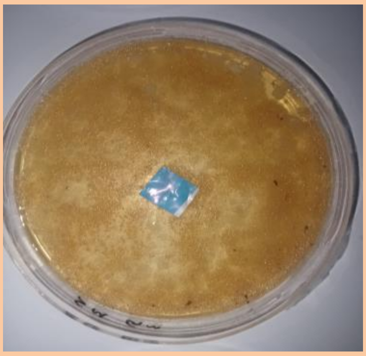
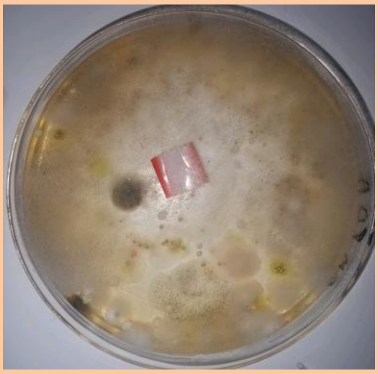
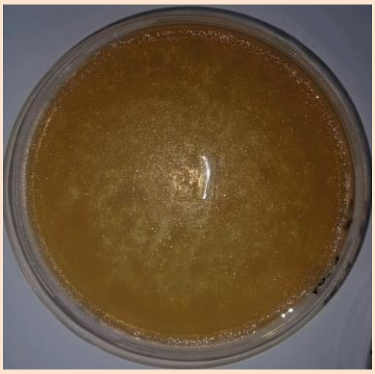
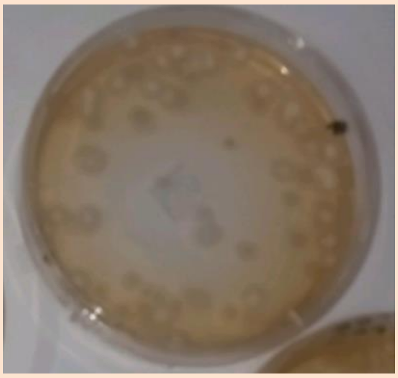
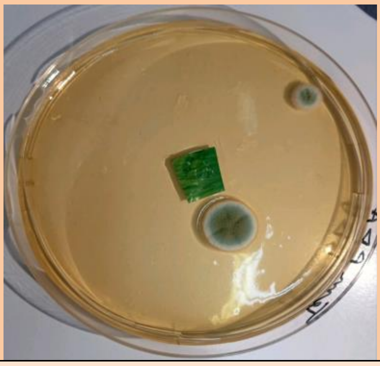
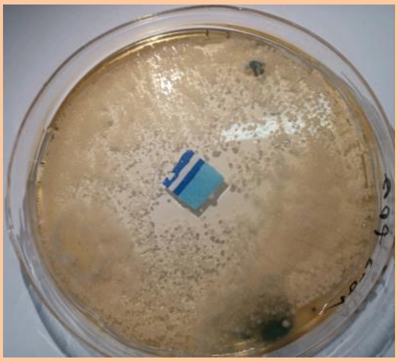
10^{-2}		
10^{-1}		
Stock solution		

Table IV-3: Observations of plates (bacteria in nutrient agar at 30°C and fungi in PDA at 25°C) for 1 Week

Solution	Bacteria	Fungi
Control		
10^{-4}		
10^{-3}		

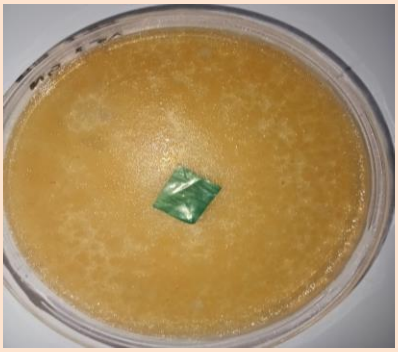
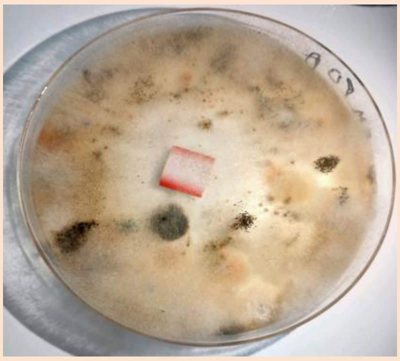
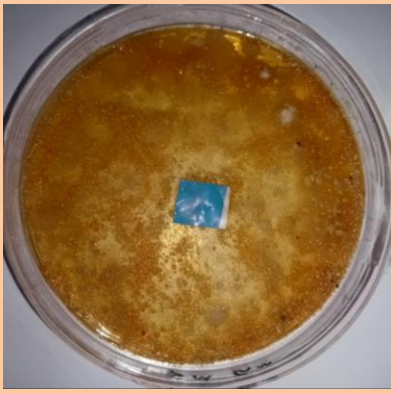
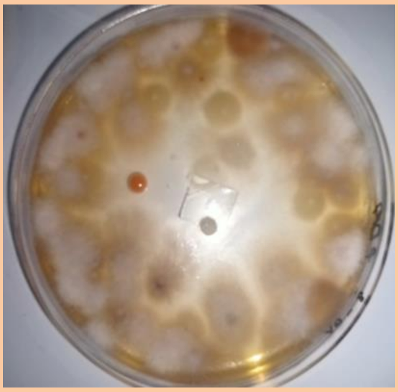
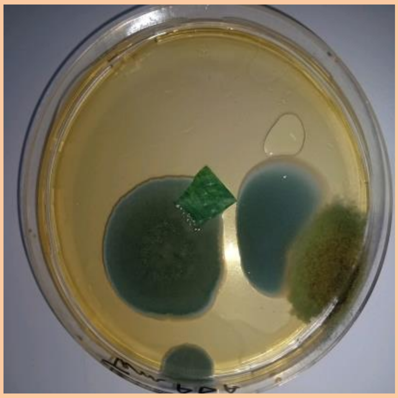
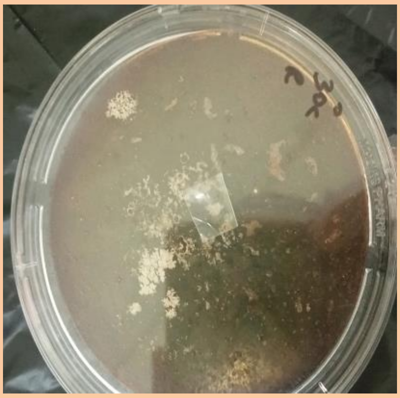
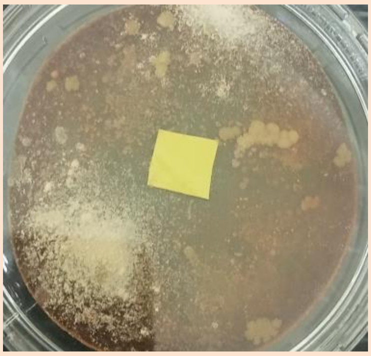
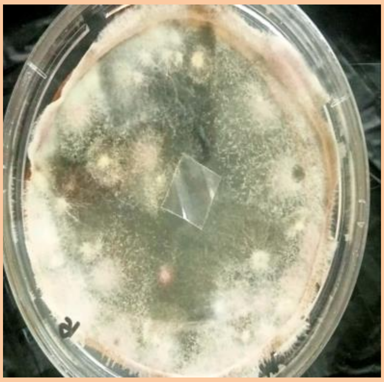
10^{-2}		
10^{-1}		
Stock solution		

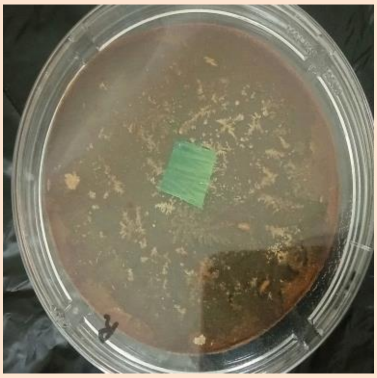
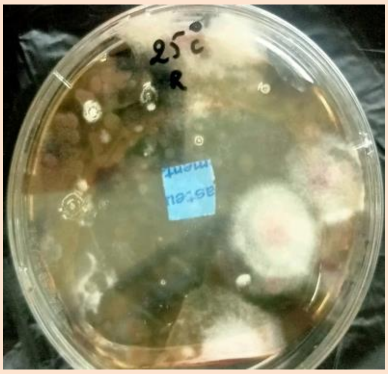
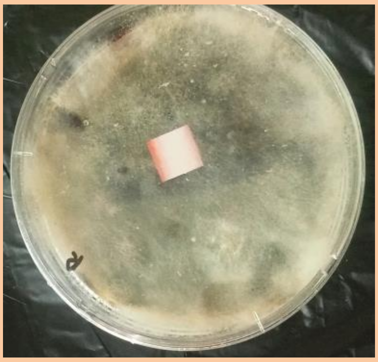
Table IV-3: Observations of plates (bacteria in nutrient agar at 30°C and fungi in PDA at 25°C) for 2 Weeks

Solution	Bacteria	Fungi
Control		
10^{-4}		
10^{-3}		

10^{-2}		
10^{-1}		
Stock solution		

Table IV-3: Observations of plates (bacteria in nutrient agar at 30°C and fungi in PDA at 25°C) for 3Week.

Solution	Bacteria	Fungi
Control		
10^{-4}		
10^{-3}		

10^{-2}		
10^{-1}		
Stock solution		

VI. Discussion

This study aimed to assess the feasibility of circular plastic waste management in the province of Tlemcen through two complementary approaches:

- A field survey conducted with 110 economic stakeholders (producers and processors), and

- Experimental laboratory analyses focusing on the biodegradation of plastic polymers (polyethylene (PE) and polyethylene terephthalate (PET)) by microorganisms isolated from contaminated soil.

The cross-analysis of the collected data provides a clear picture of the technical, economic, and biological obstacles to the sustainable recovery of plastic waste from a circular perspective.

Field Survey

- A vast majority of the units surveyed do not sort plastic waste, citing a lack of resources, awareness, and economic incentives.

This reality corroborates the observations of Bouguerra et al. (2020), who emphasize that selective sorting remains in its infancy in Algeria, often limited to unregulated informal activities. Less than 15% of respondents report recycling or recovering their plastic waste, mainly through informal channels.

The lack of structured recycling industries in the region reflects the weakness of the local circular economy, a situation also reported by Souilah et al. (2021).

- The concepts of bioplastics, bioremediation, and chemical recovery remain largely unknown.

This gap hinders the adoption of sustainable practices and highlights the need for widespread dissemination of knowledge around technological innovations in waste management.

Producers express potential support for the adoption of biological or circular solutions, provided they are simple, economical, and supported by incentive-based regulations.

- Experimental Analyses

VI. Discussion

The objective of the experiments was to assess the ability of microbial strains (bacteria and fungi), isolated from contaminated soil, to biodegrade PE and PET under controlled conditions over 4 weeks.

- No physical or chemical changes were observed in the plastic fragments after incubation. The maximum mass loss did not exceed 0.1%, which remains negligible.

This result is explained by:

• The high molecular stability of PE and PET;

• The short incubation time, insufficient to initiate significant degradation (the literature often indicates ≥ 6–8 weeks);

- A progressive decline in colony counts was observed in all media, reflecting:

• the depletion of available nutrients;

• the inability of the strains to use plastic as a carbon source;

• the possible presence of inhibitory compounds in the plastics (industrial additives).

- No biofilm formation was detected on plastic surfaces. This step is crucial in the biodegradation process, as it allows the adhesion of microorganisms.

Several hypotheses have been put forward:

• hydrophobic properties of plastics limiting adhesion;

• absence of anchoring factors (exopolysaccharides, surface proteins);

• insufficient enzymatic potential of the isolated strains.

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General Conclusion

General Conclusion

This study addressed the issue of circular plastic waste management in the province of Tlemcen through a dual approach: a field survey of industrial stakeholders (producers and processors) and a series of experimental laboratory analyses aimed at assessing the biodegradation of plastic polymers (PE and PET) by local microorganisms.

The survey results highlighted the structural limitations of the plastic waste management system in the region, characterized by a lack of source sorting, almost no material recovery, and a poor understanding of circular economy concepts. Local manufacturers expressed a conditional openness to sustainable solutions, provided they are simple, inexpensive, and supported by a clear regulatory framework.

The biodegradation tests conducted with indigenous microbial strains demonstrated negligible efficacy under the experimental conditions applied. The absence of measurable degradation, the reduction in microbial growth, and the lack of biofilm formation highlight the complexity of the plastic bioremediation process and the necessity for parameter optimization, strain selection, and pretreatment protocols.
The combined findings of the study highlights a wofold challenges, both technical and social that is impeding the transition to effective circular management of plastic waste. However, this study also opens up interesting perspectives: the biological recovery of plastics remains a promising area of research, provided it is supported by a regional collaboration framework involving institutions, businesses, research centers, and civil society.

In conclusion, this research confirms that the sustainable management of plastic waste cannot rely solely on technological solutions; it requires a systemic transformation, combining scientific innovations, political commitments, and changes in professional practices. The establishment of local circular sectors, supported by applied research and awareness-raising among stakeholders, constitutes a viable strategy to respond to the environmental, economic and social challenges associated with plastic waste in the Tlemcen region and similar contexts

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Annex

Questionnaire sur la gestion circulaire des déchets plastiques
استبيان حول الإدارة الدائرية للنفايات البلاستيكية

1. **Âge / العمر**
   - ☐ Moins de 18 ans / أقل من 18 سنة
   - ☐ 18-30 ans / 18-30 سنة
   - ☐ 31-45 ans / 31-45 سنة
   - ☐ 46-60 ans / 46-60 سنة
   - ☐ Plus de 60 ans / أكثر من 60 سنة
2. **Profession / المهنة**
   - ☐ Ménage / رب أسرة
   - ☐ Employé(e) d'entreprise / موظف في شركة
   - ☐ Travailleur municipal / عامل في البلدية
   - ☐ Acteur du recyclage / فاعل في مجال إعادة التدوير
   - ☐ Autre (précisez) / أخرى (حدد)
3. **Localisation / الموقع**
   - ☐ Urbain / حضري
   - ☐ Rural / ريفي
4. **Quels types de plastiques utilisez-vous le plus souvent ? / ما هي أنواع البلاستيك التي تستخدمها غالبًا؟**
   - ☐ Bouteilles en PET / زجاجات (PET)
   - ☐ Sacs en polyéthylène / أكياس البولي إيثيلين
   - ☐ Emballages alimentaires / عبوات غذائية
   - ☐ Autre (précisez) / أخرى (حدد)
5. **À quelle fréquence triez-vous vos déchets plastiques ? / ما هي وتيرة فرز النفايات البلاستيكية؟**
   - ☐ Toujours / دائمًا
   - ☐ Parfois / أحيانًا
   - ☐ Rarement / نادرًا
   - ☐ Jamais / أبدًا
6. **Disposez-vous de poubelles de tri sélectif à domicile ou au travail ? / هل لديك حاويات فرز نفايات في المنزل أو العمل؟**
   - ☐ Oui / نعم
   - ☐ Non / لا
7. **Connaissez-vous les filières de recyclage disponibles dans votre région ? / هل تعرف قنوات إعادة التدوير المتاحة في منطقتك؟**
   - ☐ Oui / نعم
   - ☐ Non / لا
   - ☐ Je ne sais pas / لا أعرف
8. **Participez-vous à des programmes de collecte ou de recyclage des déchets plastiques ? / هل تشارك في برامج جمع أو إعادة تدوير النفايات البلاستيكية؟**
   - ☐ Oui / نعم
   - ☐ Non / لا
9. **À quel point êtes-vous préoccupé(e) par l'impact des déchets plastiques sur l'environnement ? / إلى أي مدى أنت قلق بشأن تأثير النفايات البلاستيكية على البيئة؟**
   - ☐ Très préoccupé(e) / قلقة جدًا
   - ☐ Modérément préoccupé(e) / قلقة بشكل معتدل
   - ☐ Peu préoccupé(e) / قلقة قليلاً
   - ☐ Pas du tout préoccupé(e) / لست قلقة على الإطلاق
10. **Pensez-vous que la gestion circulaire des déchets plastiques est une solution efficace ? / هل تعتقد أن الإدارة الدائرية للنفايات البلاستيكية هي حل فعال؟**
   - ☐ Oui / نعم
   - ☐ Non / لا
   - ☐ Je ne sais pas / لا أعرف
11. **Connaissez-vous des initiatives locales de valorisation des déchets plastiques ? / هل تعرف مبادرات محلية لإعادة تدوير النفايات البلاستيكية؟**
   - ☐ Oui / نعم
   - ☐ Non / لا
   - ☐ Je ne sais pas / لا أعرف
12. **Selon vous, quelle est la principale source de pollution plastique dans votre région ? / في رأيك، ما هو المصدر الرئيسي للتلوث البلاستيكي في منطقتك؟**
   - ☐ Ménages / الأسر
   - ☐ Entreprises / الشركات

- ☐ Décharges sauvages / المكبات العشوائية
- ☐ Autre (précisez) / أخرى (حدد)

13. Quelles solutions proposez-vous pour améliorer la gestion des déchets plastiques dans votre région ? / ما هي الحلول التي تقترحها لتحسين إدارة النفايات البلاستيكية في منطقتك؟

- ☐ Sensibilisation du public / توعية الجمهور
- ☐ Mise en place de points de collecte / إنشاء نقاط تجميع
- ☐ Soutien aux entreprises de recyclage / دعم شركات إعادة التدوير
- ☐ Autre (précisez) / أخرى (حدد)

14. Seriez-vous prêt(e) à participer à des programmes de collecte ou de recyclage des déchets plastiques ? / هل أنت مستعد للمشاركة في برامج جمع أو إعادة تدوير النفايات البلاستيكية؟

- ☐ Oui / نعم
- ☐ Non / لا
- ☐ Peut-être / ربما

15. Pensez-vous que les entreprises devraient être responsables de la gestion des déchets plastiques qu'elles produisent ? / هل تعتقد أن الشركات يجب أن تتحمل مسؤولية إدارة النفايات البلاستيكية التي تنتجها؟

- ☐ Oui / نعم
- ☐ Non / لا
- ☐ Je ne sais pas / لا أعرف

16. Avez-vous déjà utilisé des produits fabriqués à partir de plastique recyclé ? / هل سبق لك أن استخدمت منتجات مصنوعة من البلاستيك المعاد تدويره؟

- Oui / نعم
- Non / لا

17. Seriez-vous prêt(e) à payer plus pour des produits fabriqués à partir de plastique recyclé ? / هل أنت مستعد لدفع المزيد مقابل المنتجات المصنوعة من البلاستيك المعاد تدويره؟

- ☐ Oui / نعم
- ☐ Non / لا

18. Selon vous, quel est le rôle des municipalités dans la gestion des déchets plastiques ? / في رأيك، ما هو دور البلديات في إدارة النفايات البلاستيكية؟

- ☐ Collecte et tri / الجمع والفرز
- ☐ Sensibilisation / التوعية
- ☐ Soutien aux initiatives locales / دعم المبادرات المحلية
- ☐ Autre (précisez) / أخرى (حدد)

19. Pensez-vous que les déchets plastiques peuvent être une ressource valorisable ? / هل تعتقد أن النفايات البلاستيكية يمكن أن تكون موردًا قابلاً للتثمين؟

- ☐ Oui / نعم
- ☐ Non / لا
- ☐ Je ne sais pas / لا أعرف

20. Quels sont les principaux obstacles à une meilleure gestion des déchets plastiques selon vous ? / ما هي العقبات الرئيسية أمام تحسين إدارة النفايات البلاستيكية في رأيك؟

- ☐ Manque de sensibilisation / نقص التوعية
- ☐ Manque d'infrastructures / نقص البنية التحتية
- ☐ Coût élevé / التكلفة العالية
- ☐ Autre (précisez) / أخرى (حدد)