CHAPTER 4: Waste Management and Recycling

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4.1 Introduction

Industrial Ecology (IE) has adopted various methodologies, approaches, and analytical tools to develop industrial ecosystems with a high degree of closed-loop material exchanges and energy cascade efficiency. This chapter addresses life cycle thinking/analysis and design for the environment, which also contribute to achieving IE objectives.

The chapter explores the product life cycle, life cycle analysis (LCA) tools, and the methodology of design for the environment. From the perspective of operations management (OM), the product life cycle includes material acquisition, manufacturing, distribution, usage, and post-usage. It investigates eco-design options at each stage to proactively reduce the environmental impact of industrial activities.

4.2 Life Cycle Analysis

Two perspectives are associated with the product life cycle concept:

- **Marketing perspective**
- **Operations management (OM) perspective**, including supply chain management (SCM).

From a marketing perspective, the product life cycle comprises four main phases: introduction, growth, maturity, and decline. These phases relate to the overall sales performance of a product or product family in the market after development and launch. This perspective generates research and applications in product lifecycle management (PLM), which integrates new product development, project management, and product data management to achieve sustainable production and consumption models.

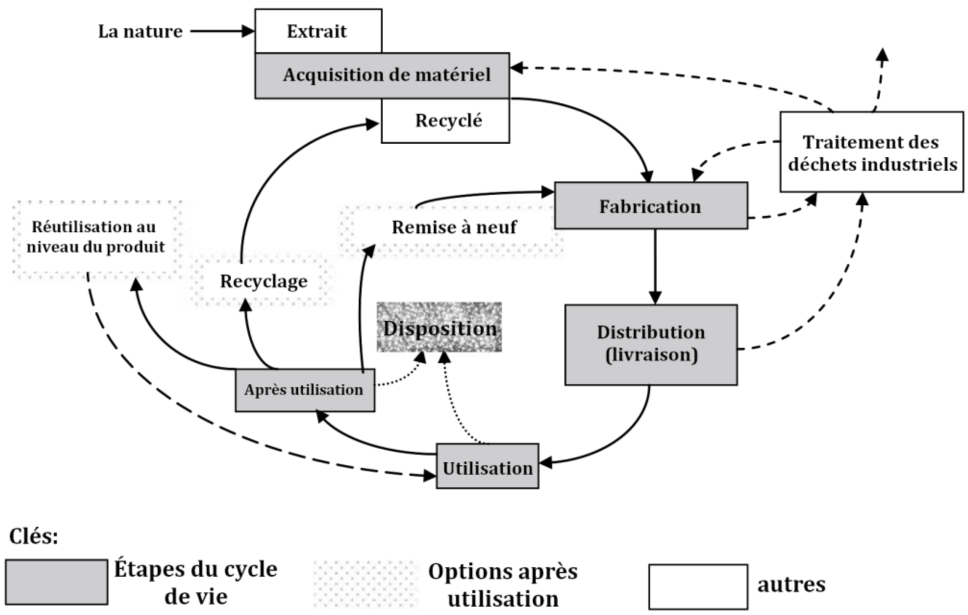

Figure 4.1: Product Life Cycle Considering Post-Usage Options

From an OM perspective, the product life cycle begins with resource acquisition and progresses through manufacturing, distribution, usage, and post-usage stages (see Figure 4.1). Inputs and outputs, decision-making options, strategies, policies, and environmental, economic, and societal impacts can be examined throughout this cycle.

Post-usage options such as reuse, refurbishment, and recycling play a crucial role in achieving closed-loop material exchanges and energy cascade efficiency. These options should be thoroughly explored before final disposal (see Figure 4.1). Additionally, "waste" is generated at other stages of the product life cycle, including industrial waste from manufacturing and distribution.

Industrial waste has been studied in the context of industrial symbiosis (IS) in previous chapters. Figure 4.1 focuses on the primary product life cycle and post-usage options and does not aim to encompass all possibilities associated with each stage.

Life cycle thinking/analysis has formed the foundation for developing various LCA tools and applications in literature, exhibiting significant divergence. The terms for LCA tools and abbreviations often lack consistency and do not always accurately reflect their intended objectives. Table 4.1 summarizes several LCA tools from literature and proposes new terms and abbreviations for three sustainability-related LCA tools.

Application Aspect	Current LCA Tool Terms (Abbreviations)	Suggested LCA Tool Terms (Abbreviations)
Environmental	Life Cycle Analysis, Inventory Analysis, Impact Analysis	Environmental Life Cycle Analysis
Economic/Cost	Life Cycle Cost Analysis	Economic Life Cycle Analysis
Social	Social Life Cycle Analysis	Social Life Cycle Analysis
Sustainability	Sustainability Life Cycle Analysis	(Same)
Risk	Life Cycle Risk Analysis	(Same)

4.3 Waste Management

Human activity has always generated waste, with each era developing specific treatment methods and facing unique challenges. The industrial age has led to an increased volume of waste, introducing issues such as non-biodegradability, toxicity, lifespan, and environmental impact.

Landfilling initially appeared to be a practical solution, evolving from uncontrolled dumps to controlled landfills. However, these eventually posed their own environmental threats.
Today, pollution reduction, energy conservation, and natural resource management have turned waste treatment into an essential factor for the planet's survival.

4.3.1 Waste Treatment Challenges

Recognizing the environmental threat, legislators have long acted to regulate waste proliferation, encourage selective sorting, and impose restrictions on landfill use, allowing only ultimate waste. Despite progress, gaps persist, particularly at the local level, where collection, treatment, and market challenges remain significant.

Most waste can be valorized as secondary raw materials. For instance, the average household waste production is estimated at 450 kg per capita per year, creating a substantial market. Including industrial and agricultural waste amplifies this figure. A 2018 Algerian government study reported total waste production at 13 million tons, projected to exceed 20 million tons by 2035 due to population growth and economic development.

The **National Integrated Waste Management Strategy 2035 (SNGID 2035)** highlighted that municipal waste generation is expected to rise from 0.8 kg/capita/day in 2016 to over 1.23 kg/capita/day by 2035. Recycling and composting rates remain low at under 10% for municipal waste, necessitating new landfill sites and funding sources.

Valorization can support the transition to a circular economy, creating wealth and jobs while fostering sustainable links between the environment and economy. According to the National Waste Agency (AND), the potential market value of recyclable waste could exceed 90 billion DZD annually, with significant employment opportunities in recycling, particularly plastics.

4.3.2 Waste Management Pathways

Implementing waste management pathways involves:

- Addressing logistical, technical, industrial, legislative, and legal challenges.
- Balancing energy valorization and material valorization techniques.
- Overcoming interference among pathways.
- Achieving economies of scale through extensive collection and treatment.

Barriers include public opposition (NIMBY: "Not in My Backyard") and political hesitation (NIMEY: "Not in My Election Year"). Despite these challenges, the sector's growth is supported by increasing public and political attention.

4.3.3 Key Issues

Waste valorization provides benefits such as conserving natural materials, reducing imports, and achieving cost savings in some cases (e.g., glass and aluminum recycling). Strategic political choices enable shared funding responsibilities between local authorities and private sectors. While some pathways require public support, others offer significant profitability, provided they anticipate legislative and market trends.

The heightened awareness of climate change has driven policies and public interest in environmental and waste management. The Paris Climate Agreement, adopted in 2015, reinforces global efforts to mitigate and adapt to climate change, with waste management as a critical component of these strategies.

4.4. Different Types of Waste

Household Waste and Collection Modalities

Waste types include common household refuse, inert waste (e.g., DIY debris), bulky items, municipal waste (from green spaces, street cleaning, sewage treatment), automotive-related waste (tires, oils, metals), agricultural and industrial waste (both general and hazardous), among others. Waste collection and treatment vary greatly, ranging from simple food scraps to toxic chemical industry outputs.

Waste composition often varies depending on the location and time, e.g., urban versus rural or seasonal changes. Moreover, the concept of waste is subjective; what one discards as waste might be valuable to another, evidenced by scavengers collecting reusable items from bulky waste before collection trucks arrive.

Several classification systems exist, including one based on collection scope, which distinguishes municipal, industrial, and agricultural origins. However, overlap between these origins often complicates this approach.

4.4.1 Municipal Waste

In Algeria, the evolving consumption habits, particularly over the last decade, have made household and similar waste (DMA) characterization critical for integrated waste management. Such characterization provides insights into both quantitative aspects (volume, per capita ratios) and qualitative details (chemical composition, moisture).
Characterization campaigns track waste composition evolution, enabling optimized waste management systems. For instance, the **2018 DMA campaign**, conducted by the National

Waste Agency (AND), provided an updated waste composition assessment, improving on the 2014 campaign's findings. This effort supports strategic goals like recycling 30% of household waste, implementing sorting practices, and encouraging private-sector investment in treatment infrastructure.

This study identifies appropriate treatment methods over the next 5–10 years, including energy recovery, material recycling, composting, and landfilling. It covered four pilot provinces (wilayas), representing Algeria’s diverse climatic zones: Jijel (humid north), Constantine (semi-humid to semi-arid), M'Sila (semi-arid to arid), and Ouargla (arid to hyper-arid).

4.4.1.1 Household and Similar Waste

The waste characterization study focused on three climatic zones (humid, semi-arid, arid) represented by Jijel, Constantine, M'Sila, and Ouargla. The categories of waste assessed are outlined in **Table 4.2**, detailing organic (compostable and non-compostable), plastics, paper/cardboard, metals, glass, textiles, and hazardous waste.

Table 4.2: Average Composition of Household Waste in Four Wilayas of Algeria (2019)

Category	Subcategories
Organic	Compostable, Non-compostable, Bread, Wood
Paper and Cardboard	Cardboard, Coated Paper, Other Paper + Cardboard
Plastic	PET, HDPE, Plastic Bags, PVC, PS, PP, HDPE Film
Glass	Transparent, Colored, Flat Glass
Metals	Iron Packaging, Aluminum Packaging, Other Ferrous, Other Aluminum, Aluminum Films, Other Metals
Composite	
Complexes/Packaging	
Textiles	
Shoes	
Hazardous	WEEE, Medical Waste, Batteries, Chemicals
Inert Waste	
Disposable Diapers	
Other	Schoolbags, Umbrellas, etc.

Insights:

- Paper, Cardboard, Glass, and Plastics: These materials represent a significant proportion of the waste stream. Their distinct nature and ease of identification by the producer make them ideal candidates for selective collection.
- This selectivity aligns with waste management goals to improve recycling rates and reduce

4.4.1.2 Waste Composition across the Four Wilayas

- **Jijel:**
  Organic waste predominates (58.5%), followed by plastics (~14.4%) and disposable diapers (~11.6%). Seasonal variations were noted, with organic content peaking in spring (61.9%) and decreasing to 55.5% in autumn. Other notable fractions include paper/cardboard (~6.22%) and textiles (~2.62%).
- **Constantine:**
  Organic material constitutes 53.5%, with plastics (~15.41%) and disposable diapers (~8.34%). Seasonal changes were observed, such as a significant decrease in organics during summer (48.35%) and increased textile fractions in the same period (11.3%).
- **M'Sila:**
  Organics dominate at 53.9%, followed by plastics (~14.9%) and disposable diapers (~12.4%). Seasonal trends show a notable decrease in organics from spring (61.7%) to winter (~49.25%) and fluctuations in plastic fractions, peaking in winter (17.4%).
- **Ouargla:**
  Organic waste forms the largest share (48.53%) but is the lowest among the provinces studied. Plastics (16.57%) and disposable diapers (14.65%) are significant fractions. Seasonal trends reveal substantial drops in organics during summer and autumn.

4.4.1.2.1. Jijel: Household and Similar Waste

The average composition of household and similar waste (HSW) over four seasonal campaigns in Jijel revealed the following:

1. A dominance of organic matter (~58.5%),
2. Significant fractions of plastics (all types) (~14.4%),
3. A notable proportion of disposable diapers (~11.6%),
4. Paper/cardboard (~6.22%) and textiles (~2.62%),
5. Other waste streams ("other") varying between 0.46% and 1.37%.

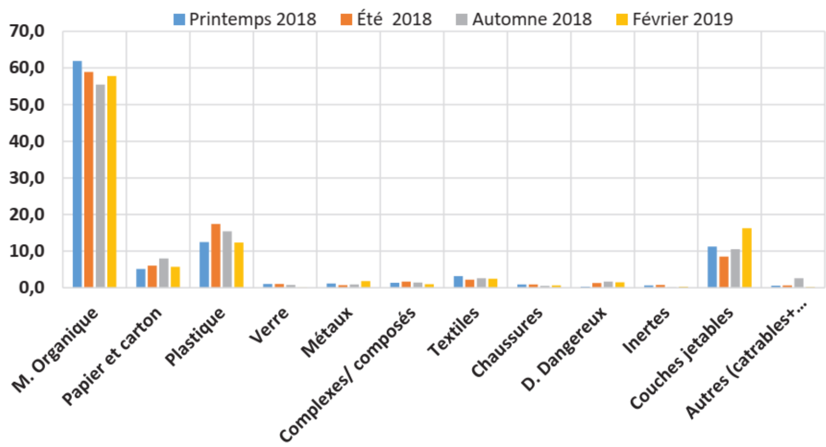

Figure 4.2: Seasonal Evolution of HSW Composition – Jijel 2018–2019

- Organic matter consistently dominated, peaking in spring (61.9%) before decreasing to 55.5% in autumn and slightly rising to 57.8% in winter.
- Paper/cardboard ranged between 5% (spring) and 8% (autumn).
- Disposable diapers showed significant seasonal variation: 8.5% in summer and 16.2% in winter.
- Plastics peaked at 17.4% in summer and 15.4% in autumn, with stable rates (~12.5%) in other seasons.

4.4.1.2.2. Constantine: Household and Similar Waste

The average HSW composition across four seasonal campaigns in Constantine revealed:

1. A prevalence of organic matter (>53.5%), slightly lower than Jijel,
2. A significant plastic fraction (~15.41%),
3. Lower proportions of disposable diapers (~8.34%), paper/cardboard (~8.05%), and textiles (~6.78%),
4. "Other" waste ranging from 0.93% to 1.30%, representing less than 7.91% of HSW.

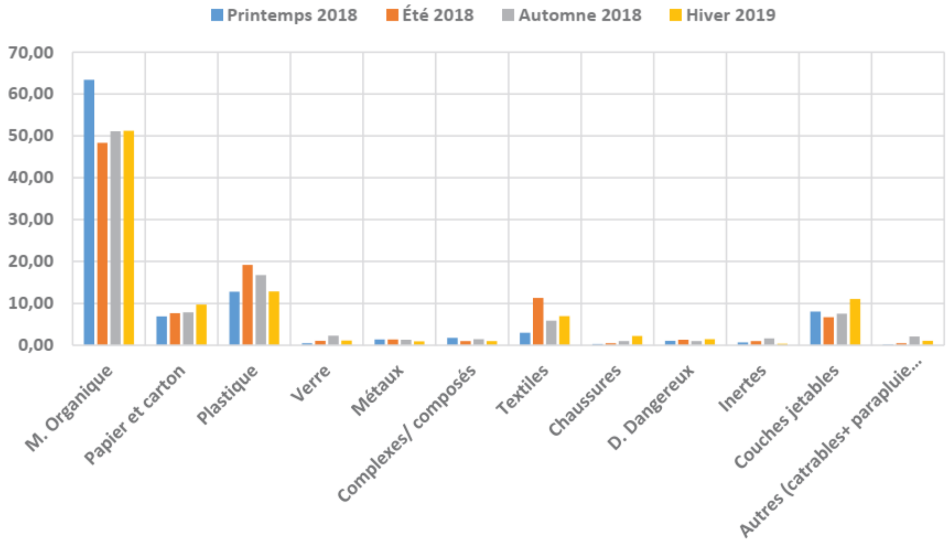

Figure 4.3: Seasonal Evolution of HSW Composition – Constantine 2018–2019

- Organic matter dropped sharply from 63.42% in spring to 48.35% in summer, followed by slight increases in autumn (51.1%) and stabilization in winter (51.2%).
- The textile fraction rose from ~3% in spring to 11.3% in summer, then fell to 5.87% in autumn, rising slightly to 6.98% in winter.
- Plastics increased sharply from 12.8% (spring) to 19.2% (summer) before declining slowly to 12.87% (winter).
- Disposable diaper and paper/cardboard fractions remained stable across three seasons, but rose significantly in winter (~4% for diapers, ~2% for paper/cardboard).

4.4.1.2.3. M'Sila: Household and Similar Waste

The average HSW composition across four seasonal campaigns in M'Sila revealed:

1. A predominance of organic matter (~53.9%),
2. Significant fractions of plastics (~14.9%) and disposable diapers (~12.4%),
3. Low paper/cardboard (~5.94%) and textile (~5.32%) proportions,
4. "Other" waste ranging from 0.6% to 1.7%, comprising ~7.6% of HSW.

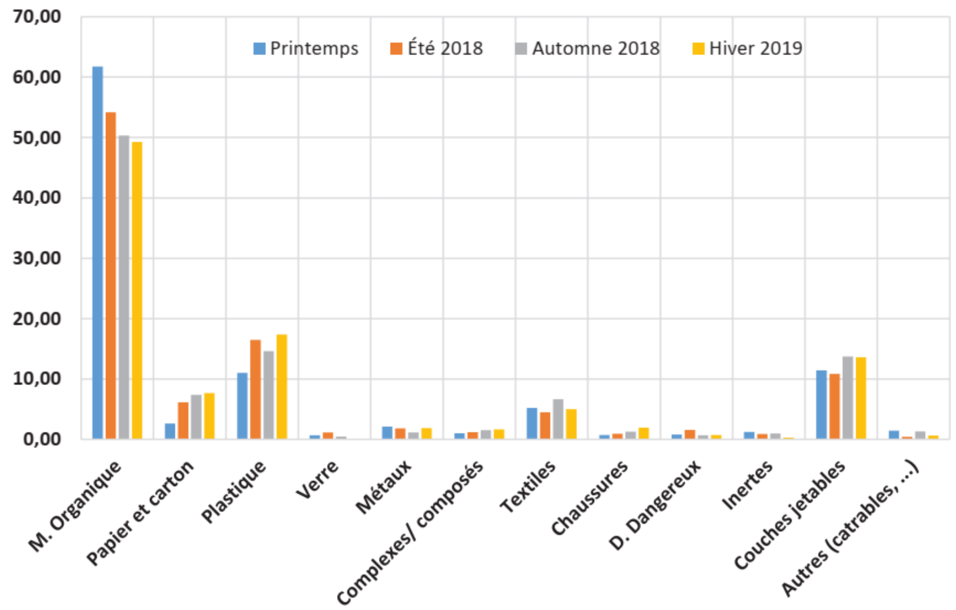

Figure 4.4: Seasonal Evolution of HSW Composition – M'Sila 2018–2019

- Organic matter decreased from 61.7% (spring) to 54.2% (summer), stabilizing around 49.25% in winter.
- Paper/cardboard showed a steady rise: 2.6% (spring), 6.12% (summer), 7.4% (autumn), and 7.7% (winter).
- Plastics fluctuated significantly, increasing from 11% (spring) to 16.5% (summer), decreasing to 14.6% (autumn), and rising again to 17.4% (winter).
- Textiles and disposable diapers decreased from spring to summer (5.19% and 11.43%, respectively) before increasing in autumn (6.6% and 13.7%). Winter saw textile fractions fall (~5%), while diaper proportions remained stable (~13.6%).

4.4.1.2.4. Ouargla: Household and Similar Waste

The average HSW composition across four seasonal campaigns in Ouargla showed:

1. A dominance of organic matter (~48.53%), the lowest among the four wilayas,
2. Significant fractions of plastics (~16.57%) and disposable diapers (~14.65%),
3. Relatively low proportions of paper/cardboard (~6.82%), textiles (~3.34%), metals (~2.76%), and composites (~2.02%),
4. "Other" waste ranging from 0.53% to 1.58%, making up ~5.29% of HSW.

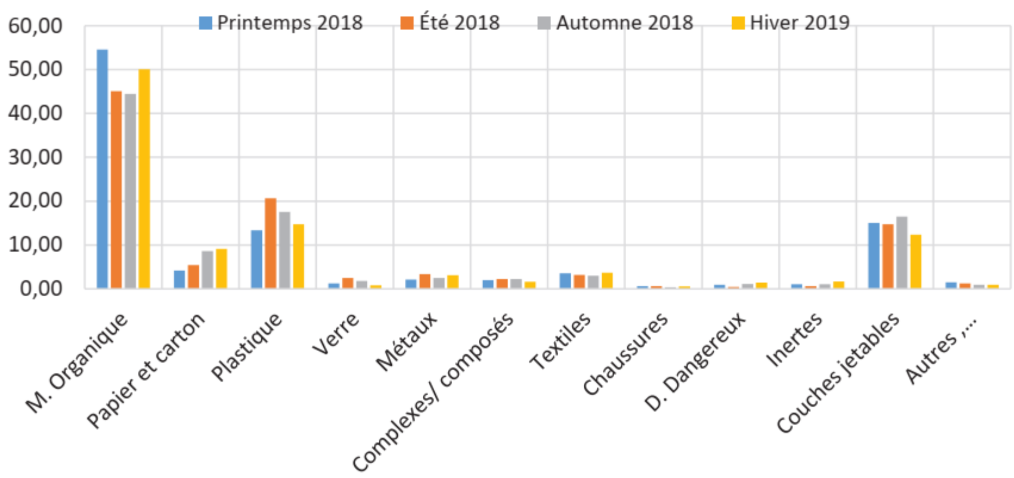

Figure 4.5: Seasonal Evolution of HSW Composition – Ouargla 2018–2019

- Organic matter peaked in spring (54.57%) and winter (50.05%), decreasing sharply in summer (45%) and autumn (44.5%).
- Plastics rose from 13.33% (spring) to 20.67% (summer) before gradually decreasing to 14.74% in winter.
- Disposable diaper fractions remained consistent in spring (15.03%) and summer (14.75%), increased slightly in autumn (16.49%), then fell sharply in winter (12.35%).
- Paper/cardboard fractions rose progressively from 4.14% (spring) to 9.11% (winter).
- Other fractions showed minimal variation, staying below 1.7%.

4.4.3 Average DMA Composition in Algeria (2018–2019)

Household and similar waste represents the bulk of solid waste in Algeria, with a 2018 estimate of over **13.1 million tonnes**, based on a per capita production rate of 0.8 kg/day. Recent decades have seen both qualitative and quantitative increases in waste generation, with limited treatment and recycling capacity intensifying environmental and public health risks. The 2018–2019 campaign yielded the following national average DMA composition:

- **Organics:** ~53.6%
- **Plastics:** ~15.2%
- **Disposable Diapers:** ~11.5%
- **Paper/Cardboard:** ~7.07%
- **Textiles:** ~4.5%
- **Others:** ~8% (including metals, glass, inert waste, etc.)

Seasonal trends indicate significant fluctuations in organic and plastic fractions, emphasizing the importance of tailored waste management strategies to address these dynamics.

Data Limitations and Further Research

Due to insufficient comprehensive national data on Algerian waste, this analysis relies on existing literature, including *Gestion des Déchets* (Dunod, 2006) and *Sustainable Solid Waste Management* (Wiley, 2015).

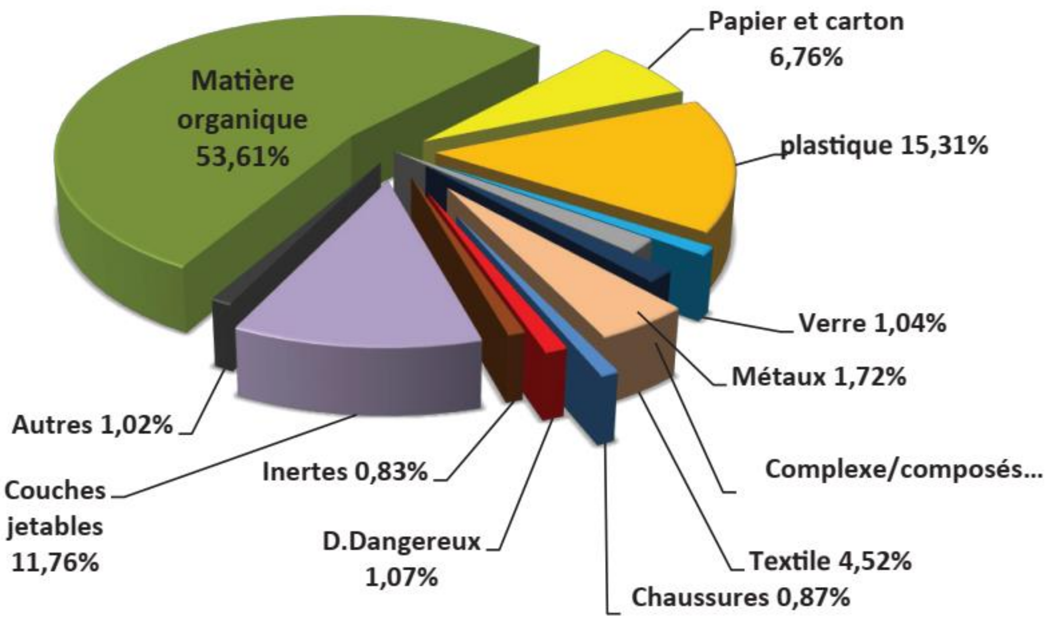

Figure 4.6: Average MSW Composition in Algeria, 2018/2019

- **Spring-Summer Period:**
  - Significant decrease in organic fraction from 60.1% to 51.6%.
  - Sharp increase in the plastic fraction from 12% to 18.4%.
  - Paper and cardboard fraction remains relatively stable at ~6%.
  - Slight decrease in disposable diaper fraction from 11.4% to 10% and a small increase in textiles from 3.8% to 4.2%.

- **Summer-Autumn Period:**
  - Slight decrease in organic fraction from 51.6% to 50.34% and plastic from 18.44% to 16.08%.
  - Small increase in paper/cardboard fraction from 6.32% to 7.96% and in disposable diapers from 10.21% to 12.07%.
  - Variations in other fractions are negligible.

- **Autumn-Winter Period:**
  - Increase in organic fraction from 50.34% to 52.08% and disposable diapers from 12.07% to 13.31%.
  - Decrease in plastic fraction from 16.08% to 14.32%.
  - Paper and cardboard fraction stabilize around 8%.

4.5. Other Municipal Waste

This category encompasses all other waste collected by local authorities. Definitions vary by municipality, depending on what they choose to collect. These may include industrial waste comparable to the following:

In general, this includes:

- Household waste not suitable for regular collection:
    - Due to volume or weight: bulky waste or construction/demolition debris (often abandoned in nature).
    - Due to potential pollution: special household waste (e.g., batteries, used oil).
- Green waste (~1 Mt/year).
- Street cleaning waste.
- Automotive-related waste (tires, oils, car bodies).
- Waste from collective sanitation (e.g., sewage sludge).

Total annual volume: ~14 million tons.

Table 4.4: Estimated Annual Waste Production in France

(Sources: ADEME 2006: Les déchets en chiffres; IFEN Les enquêtes 2006)

Category	Type of Waste	Annual Production
Municipal Waste	Household Waste	21.9 Mt
	Assimilated Waste	4.5 Mt
	Other Municipal Waste	24.5 Mt
Industrial Waste	Non-Hazardous (Banal) Waste	44 Mt
	Hazardous (Special) Waste	6 Mt
	Inert Waste	343 Mt
Agricultural Waste	Agro-Food Industry	40 Mt
	Livestock	> 280 Mt
	Crops	> 65 Mt

Notes:

- Municipal waste includes household waste, waste assimilated to household waste, and other types of waste collected by local authorities.
- Industrial waste is categorized into banal (non-hazardous), special (hazardous), and inert waste, with inert materials dominating the total volume.
- Agricultural waste mainly consists of organic matter, with the livestock sector producing the largest share.

4.6. Industrial Waste

In 2004, economic activities (excluding agriculture) produced 393 million tons of waste, about 90% of which were inert materials (rubble and debris) from construction and public works. The remaining waste includes:

- **Industrial solid waste** (non-hazardous): comparable to household waste.
- **Hazardous industrial waste** (6 Mt): pollutants requiring special treatment.

4.7. Agricultural Waste

With an estimated production of 374 Mt/year, agriculture generates significant quantities of biodegradable waste, much of which is reused (e.g., manure spreading). Agro-industrial waste (~40 Mt) is often considered alongside industrial waste. The main producers are livestock farms (~280 Mt/year).

4.8. Total Annual Production and International Comparison (2004)

France produced ~849 Mt of waste annually, though this may be underestimated due to unrecorded waste. Internationally, richer countries tend to produce more waste, with the U.S. generating 755 kg/person/year, compared to much lower rates in developing nations. France is at an average level among wealthy nations.

4.9. Conclusion

The 2019 characterization study of Algerian waste highlights the importance of sustainable development to reduce waste, conserve resources, and minimize pollution. Waste is now considered a valuable resource for secondary raw materials and energy. Key strategic goals under the *National Integrated Waste Management Strategy 2035 (SNGID-2035)* include:

- Reducing waste production to under 1.1 kg/person/day by 2035.
- Implementing selective sorting and achieving 50% recycling or composting rates for all waste streams.
- Eliminating illegal dumps and ensuring 100% of landfill facilities are equipped for effective air and water emissions treatment by 2035.
- Introducing the "polluter pays" principle to cover 100% of public waste management costs through financial contributions by waste generators.
- Promoting the circular economy and creating 100,000 jobs in waste management and secondary resources by 2035.

Key findings from the characterization campaign include:

- MSW has a low density (230–300 kg/m^3) due to high packaging waste content.
- Most waste (>40%) is over 100 mm in size, with 25% in the 35–60 mm range.
- MSW is relatively moist (humidity >50%).

Recommandations

- **Organic fraction (~53.55%):** Biological recovery (composting, methanization) or stabilization before disposal could be a sustainable solution.
- **Recyclable fraction (>25%):** Materials such as plastics, paper/cardboard, glass, and metals could be prioritized for recycling.
- **Textiles and sanitary waste (~16%):** Energy recovery or alternative disposal methods could be explored. Campaigns promoting reusable diapers could also help mitigate the growing waste volume.