# Analysis Of Efficiency And Sustainable Management Of Urban Solid Waste (Msw)

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## Abstract

The growth of the world population and consumption habits leads to an increase in waste generation. According to the World Bank (1), if no action is taken, urban solid waste will increase by 50% by 2050. Possible actions focus on two areas: changing consumption habits on one hand, and reusing waste for a second use to avoid using new resources on the other. In the first case, current consumption habits have existed for a long time and represent a structural situation that is difficult to change in the short term. This requires actions in education, public awareness, and legislation. Waste treatment has evolved in Europe over the years, moving from uncontrolled dumping to incineration, composting, or anaerobic digestion to produce biogas. The last two are inefficient solutions because they waste valuable components in the organic fraction of both municipal and industrial waste. In both cases, microplastics are present in biogas digestate (2) and in the compost from municipal organic waste (3). Also, the potential use of pyrolysis as a source of energy generation, gray and green hydrogen, and microplastic removal is not taken advantage of. According to European regulations, landfill disposal must be reduced to 10% by 2035. This is important because, in 2020, Spain had a landfill rate of over 50% (4). On the other hand, the energy crisis caused by the Russian invasion of Ukraine has led to a significant increase in biogas plants in Spain. In fact, by December 2023, there were only 10 biogas plants, but it is estimated that more than 2,300 plants could be built, covering 45% of the national demand (5). This will cause a high demand for waste and an excess of digestate, which is difficult to use in agriculture. The objective of this study is to provide an approach based on waste evaluation. Depending on its fat and carbohydrate content, it will determine the viability of its use and adopt a specific strategy before implementing solutions such as composting or anaerobic digestion. For the remaining organic matter, processes are proposed to prevent plastics from reaching the soil. Efficient waste characterization will help identify high-value products.

**Keywords:** Waste management, Pyrolysis, Hydrogen, Biogas, MSW.

# 1. Introduction

Optimization strategies for recycling and reuse have always been aimed at source separation, meaning that the waste generator separates waste into major categories—known as selective collection:

Paper and Cardboard: Blue container.

Packaging: Yellow container.

Glass: Green container.

Organic waste: Brown container.

In Spain, the selective collection of urban waste in 2021 amounted to 5.6 million tons, representing less than 25% of the total (6). Furthermore, this selective collection includes a high percentage of contaminants, which hinders recycling and/or recovery. The targets set by European regulations for 2035 are certainly ambitious, limiting landfill disposal to just 10%.

The Russian invasion of Ukraine led to an energy crisis due to the disruption in oil product supplies, highlighting the weakness of a strategy based on Europe's inexplicable geostrategic decision to rely on Russian gas as the foundation of its energy policy. Biogas had not been developed at all in Spain, mainly due to administrative barriers and the influence of the gas lobby that prevented its growth. In fact, by December 2023, there were only 10 biogas plants in Spain. This situation has since changed, and it is now estimated that Spain could support more than 2,300 biogas facilities, which would cover 45% of the national demand (5).

These would be biogas plants not intended for electricity generation but rather for injecting methane into the grid after undergoing an upgrading process. Biogas contains about 60% methane; to be injected into the gas network, this content must exceed 90%. With this regulatory framework and the high expectations, the biogas boom could lead to competition for waste, potentially resulting in fraudulent use of non-waste materials for methanization. The large number of biogas plants is also expected to result in an oversupply of compost and digestate.

4. Current Uses of Organic Matter from MSW and Industrial Sources

Traditionally, the primary use of the organic fraction of municipal solid waste (MSW) has been agricultural composting. In less developed societies, this is the main destination, accounting for 56% of waste, while in more developed countries this figure is around 32% (1). As development increases, the waste composition changes, with more non-compostable elements appearing. These must either be physically separated or sent to landfills.

Mechanical-Biological Treatment Plants

Mechanical-biological treatment (MBT) plants aim to separate the different fractions of MSW such as plastics, metals, or glass, as well as the organic fraction, which is composted, reducing weight and volume by approximately 40–50%. During this process, the organic matter decomposes, emitting $CO_2$ and generating water.

Unfortunately, this compost often contains many contaminants, typically macro- and microplastics, making it unsuitable for agricultural use. At the very least, these plants avoid direct landfill disposal, reducing waste and preventing fermentation and leachate formation. However, they do not fully utilize the potential of the included compounds.

Biogas

Using the organic fraction of MSW to produce biogas is a clear example of resource recovery and reintegration into the economic cycle. Anaerobic digestion yields a mixture of $CO_2$ and methane, along with digestate that can be used as fertilizer.

Initially, biogas plants used cogeneration to convert the gas into thermal energy for internal use and electricity injected into the power grid. This model was supported by subsidies for each kWh generated. When the regulatory framework changed and subsidies decreased, the business model became unviable.

Following the crisis in Russian gas supply, biogas plants are now being developed to inject gas into the national grid. This involves upgrading the methane from about 60% to a commercial-quality natural gas of over 98%. It is estimated that up to 45% of national natural gas demand could be met from renewable sources.

This approach is better than biological treatment alone, as it yields two products that can be reintegrated into the production process—whereas before, the focus was only on reducing landfill. However, valuable components such as lipids and carbohydrates are still not utilized, and the problem of microplastics in the digestate remains.

From a commercial standpoint, while the produced methane is in demand and its price is set on international markets, digestate—used only as agricultural fertilizer—faces greater marketing challenges. The large number of biogas plants will create a high supply that the market may struggle to absorb, potentially threatening the viability of these plants.

Moreover, considering digestate as fertilizer is somewhat risky, as it often lacks a balanced NPK ratio, stabilized organic matter, or suitable soil microbiota. It may also contain high levels of metals, salts, or microplastics.

Composting

Materials suitable for direct composting may come from MSW, as long as selective collection is in place. Regulatory frameworks promote the selective collection of MSW, especially in industrial and hospitality settings. This waste can produce high-quality compost. However, in the medium to long term, the high volume of digestate from biogas plants—direct competitors—may hinder its commercialization due to market saturation.

At the same time, the difficulty in separating plastics from organic matter highlights the presence of macro- and microplastics in this application, which ultimately end up in the soil.

Uncontrolled Incineration

Although uncontrolled incineration of MSW is nearly nonexistent in Europe, it is common in underdeveloped and developing countries. This practice severely impacts soil, water, and air quality in affected areas and has negative health effects.

Incineration contaminates the soil with ash and by-products, including plastics and metals, reducing fertility and introducing toxins into the food chain. These pollutants can also leach into and harm groundwater. Volatile ash settles in the soil and washes into rivers with rainfall, affecting aquatic life. Additionally, the combustion emits toxic compounds like dioxins and furans, harming human and animal health.

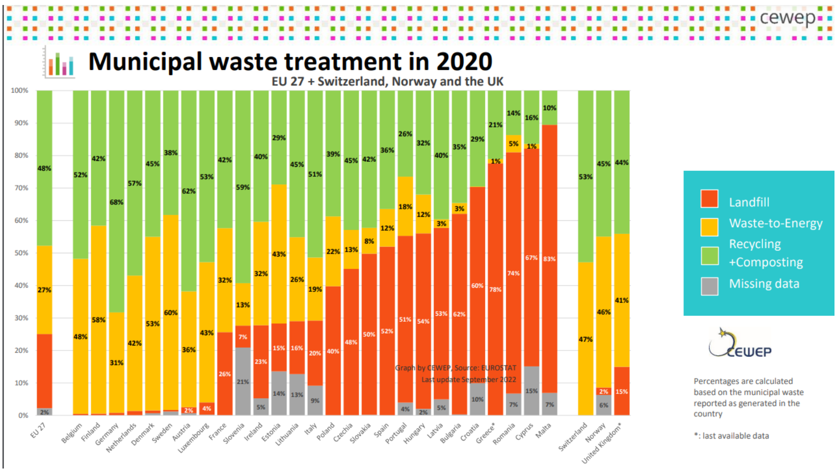
Incineration in Waste-to-Energy Plants

This involves controlled incineration in a specially designed facility, avoiding toxic emissions through bag filters or electrostatic precipitators. However, a suitable regulatory framework is essential to prevent potential emission risks (7).

While this was the best available technique in the 1980s and 1990s, it is no longer the most efficient. In 2020, the European average for incineration was 27%, with 23% going to landfill and 48% to recycling and composting. Specifically, incineration rates in Northern Europe range from 30% to 60%, while Southern and Eastern European countries often exceed 50% landfill rates.

It can be considered a "necessary evil" since incineration has helped Northern European countries reduce landfill use to negligible levels. In contrast, countries like Spain still send about 50% of waste to landfills, as shown in the graph below. It is essential that these facilities have appropriate post-combustion treatment to prevent emissions of dioxins and furans.

## Figure 1.




(4)

Waste Exports

The European Union exports around 32 million tons of waste, the majority of which is ferrous metals and paper. Nearly 40% goes to Turkey, followed closely by India, the United Kingdom, Switzerland, and Norway (European Parliament, 2024).

## Figure 2.


(8)

Most of this waste was sent to countries with very permissive legislation regarding waste treatment and disposal. For example, ferrous waste is exported to Turkey or India, while at the same time new ferrous metals are imported from these same countries. On the other hand, there are countries with more advanced technology to transform waste into new resources.

A special mention should be made of obsolete electronic equipment. Basel Action Network tracked disused electronic devices and found that 19% of them—extrapolated to approximately 350,000 tons—are sent to developing countries, where they end up in landfills or are subjected to unsafe treatment processes, causing environmental damage (9).

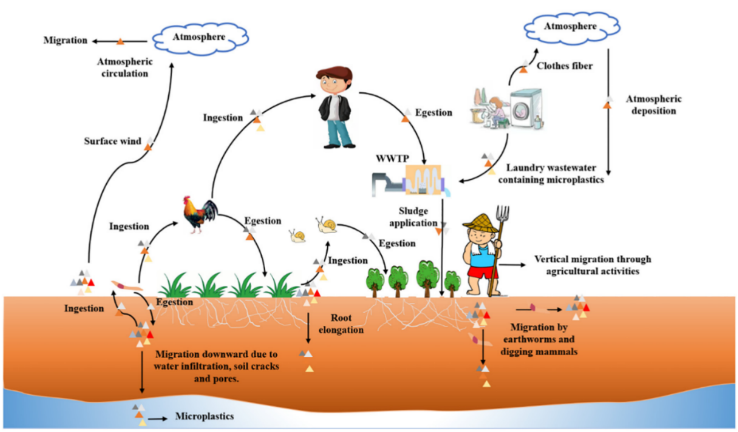
Plastics, Microplastics, and the Trophic Chain

Current uses of the organic fraction of municipal solid waste (MSW) are leading to an increasing presence of microplastics in the soil, air, and even the sea. The relevance and potential negative effects of these pollutants are still not fully understood. However, growing interest in this topic is evident, as reflected by the number of scientific publications on the subject. In fact, only 52 papers on microplastics were published worldwide in 2009, while in 2019 that number rose to 1,208 (10).

Microplastics in Soil

The following diagram shows the origins, destinations, and propagation vectors of microplastics from the soil.

**Figure 3.**



The graph below also includes the effects of microplastics in the soil.


(11)

To analyze the origin of microplastics in soil, several sources can be identified:

Composting. The fertilizer resulting from the composting of the organic fraction of organic waste contains between 5 and 20 particles smaller than 5mm in diameter per gram. Five polymers account for 94% of these, listed by abundance: polyethylene, polystyrene, polyester, polypropylene, polyvinyl chloride, and acrylic polymers (3).

Agricultural plastic use and misuse.

Sewage sludge used for compost.

Biogas digestate.

Treated water that returns to rivers and is reused in agriculture and human consumption.

Although the effect of microplastics on crop development is a topic that requires further study, empirical trials have shown negative impacts on plant growth (12). According to several authors, impacts on soil are linked to changes in its physicochemical properties, including a reduction of 8% in organic matter, 13.10% in total nitrogen, 17% in phosphorus, 6.7% in potassium, 5.4% in porosity, 8.9% in moisture, and a 23% reduction in surface water infiltration. These changes directly affect soil fertility and, consequently, agricultural yields.

Microplastics can release chemical additives that may affect soil microorganisms. This type of pollution can also act as a vector for new microorganisms that alter the microbiota and its processes (13).

Soil characteristics, along with human activities, directly influence microplastic migration. Irrigation or rainfall infiltration is the main cause of vertical migration. Microplastics may also migrate due to external forces like wind and can remain suspended in the atmosphere. Earthworms also play a key role in this migration, facilitating their entry into the food chain. Additionally, due to their high hydrophobicity, microplastics can concentrate pollutants in the soil such as fungicides, pesticides, and even heavy metals (11).

Microplastics in Water

Microplastics in rivers, seas, and oceans enter the food chain with evident negative consequences. The best way to prevent this pollution is by tackling it at the source—improving selective waste collection and recycling, and reducing landfill disposal (14).

6. Alternative Energy Recovery

Depending on the composition of the organic fraction of municipal solid waste (MSW)—specifically its moisture, fat, carbohydrate content, and residue—various strategies can be applied: fat extraction, carbohydrate fermentation, or pyrolysis of residual waste, which generates energy for the process and possibly an energy surplus.

The final outcome can be one or all of the following by-products:

Fats for biodiesel, HVO, or HEFA-type SAF.

Crude ethanol for bioethanol or Alcohol-to-Jet SAF.

Energy for thermal use or conversion into electricity.

### Alcoholic Fermentation of Carbohydrates

If the carbohydrate content exceeds 15%, it makes industrial sense to ferment this organic matter to obtain crude ethanol for various uses.

### Ethanol

Ethanol is currently used as a biofuel blend in gasoline, with labeled blends such as E10 or E85 (10% or 85% ethanol respectively), suitable for gasoline or flex-fuel vehicles per manufacturer specifications. It can also be used to produce the gasoline additive ETBE (ethyl tert-butyl ether).

### Sustainable Aviation Fuel (SAF)

Ethanol can serve as a precursor for aviation biofuel, known by its acronym SAF (Sustainable Aviation Fuel), through a chemical transformation of the ethanol produced.

### Lipid Extraction

Lipid extraction is determined by industrial feasibility. The OFMSW + PLASTIC mix must have a moisture content below 1% for fat extraction to be efficient. Therefore, lipid extraction should occur after carbohydrate fermentation, as that process happens in aqueous media.

Solvent-based lipid extraction is the standard industrial practice, with a minimum fat content threshold of 15%. The resulting lipids can be raw materials for biofuels like biodiesel, HVO, or aviation biofuels.

There is high demand for these lipids, especially in Europe and the USA, as they are derived from sources that do not compete with animal or human food or land use—recycled from the economic cycle.

### Biodiesel

Biodiesel is a fatty acid methyl ester. In a basic medium, a reaction known as transesterification occurs in which oil reacts with methanol to generate biodiesel and glycerin. This biodiesel is typically blended up to 7% with mineral diesel and remains compliant with the EN590 diesel fuel standard. Higher concentrations must be labeled blends (e.g., B15 or B30).

Hydrobiodiesel (HVO)

Hydrobiodiesel or HVO (Hydrotreated Vegetable Oil) is a biofuel made from lipids through a hydrogenation process using heterogeneous catalysts. To protect the catalysts, the oil must be highly refined, with phosphorus content below 3 ppm and metal content below 10 ppm.

As oil from waste is not particularly clean, it must undergo strong refining, including degumming to reduce phosphorus and bleaching with activated clays to capture heavy metals.

HVO production involves refined lipids and hydrogen to produce fully saturated fatty acids (paraffins or HVO) and biopropane as a by-product.

HEFA/SAF Aviation Biofuels

HEFA (Hydrotreated Esters and Fatty Acids) is the SAF variant for aviation. Starting with HVO, processes such as isomerization, cracking, and fractionation are performed to obtain fuels compatible with aviation fuel standards like DEF-STAN 91-091 or ASTM D7566.

For now, aviation decarbonization relies solely on SAF liquid biofuels. Other technological alternatives like electrification are currently unavailable or impractical for commercial and military aviation demands.

Pyrolysis

Pyrolysis of organic and plastic MSW is an energy source that produces syngas or pyrolytic liquids suitable for energy use. The final product, biochar, can be used as an adsorbent, soil enhancer, or for combustion.

Unlike composting and biogas, pyrolysis eliminates the contribution of macro and microplastics to soil and water. Thus, waste treated through pyrolysis ceases to be a source of plastic pollution.

Pyrolytic Gasification

Pyrolytic gasification is a form of pyrolysis in which the material is heated in the absence of oxygen, causing the organic matter and plastics to break down into synthesis gas. This gas can be combusted for energy or used to generate electricity.

Its main advantage over traditional combustion is the absence of dioxin and furan emissions, which require costly post-combustion treatments such as bag filters, electrostatic filters, or high-temperature oxidizers to eliminate VOCs.

Typical synthesis gas composition:

Carbon monoxide (CO): 20%–40%

Hydrogen ($H_2$): 25%–40%

Carbon dioxide ($CO_2$): 15%–25%

Methane ($CH_4$): 5%–15%

Light hydrocarbons (CxHy): 0%–10%

Water vapor ($H_2O$): 0%–10%

Nitrogen ($N_2$): 0%–15%

Hydrogen, methane, and light hydrocarbons contribute the calorific value of syngas. Whether hydrogen is classified as "green" or "gray" depends on regulatory frameworks, but if plastic is prevented from ending up in the soil, this represents both energy recovery and environmental improvement.

## 2. Conclusions

Although current MSW (Municipal Solid Waste) management models are progressively reducing landfill disposal, they are clearly insufficient, as the EU still sends 38% of its waste to landfills, and in Spain the percentage is even higher at 52%.

The proposed model improves composting performance, as this process emits $CO_2$ through a decomposition from which no value is derived. Additionally, it helps reduce the input of micro- and macroplastics into the soil. The biogas process is also optimized: on one hand, all the energy contained in oils and fats is utilized instead of being consumed in an anaerobic fermentation process; on the other hand, carbohydrates are transformed into ethanol, a product with greater added value than biogas. Furthermore, the new process eliminates the dumping of polluting plastics into the soil.

This model incorporates four processes that offer greater commercial and environmental value, producing the following outputs:

Lipid extraction → For use in biodiesel, HVO, or SAF.

Alcoholic fermentation → Ethanol production.

Pyrolysis → Hydrogen, synthesis gas, and combustible pyrolytic liquid.

This is a more economically efficient approach compared to current practices such as composting, bio-stabilization, and biogas production, as it enables the generation of high-value compounds that are also in high demand in today's society. It also drastically reduces the release of microplastics into the environment—and consequently into the food chain a growing and difficult-to-solve problem. Beyond the lipids and carbohydrates used for traditional biofuels (ethanol and biodiesel/HVO), the truly disruptive element is the generation of hydrogen from waste.

It is worth highlighting that any decarbonization strategy must include hydrogen, as it is a clean alternative to fossil fuels in hard-to-abate sectors such as heavy industry (e.g., metallurgy), long-distance transport, and even aviation. Its combustion does not generate $CO_2$, and when derived from renewable sources, it significantly reduces emissions.

Although green hydrogen, produced via electrolysis using renewable electricity, is key to a decarbonized economy, its current production is expensive and comes with a significant opportunity cost. This is because the renewable electricity used to generate hydrogen could be directed to the grid or to other, more economically efficient uses.

In this context, the development of less costly alternative technologies for hydrogen production—such as the pyrolysis of waste or industrial by-products offers a complementary and competitive pathway to accelerate decarbonization without putting additional strain on the renewable electricity system.

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