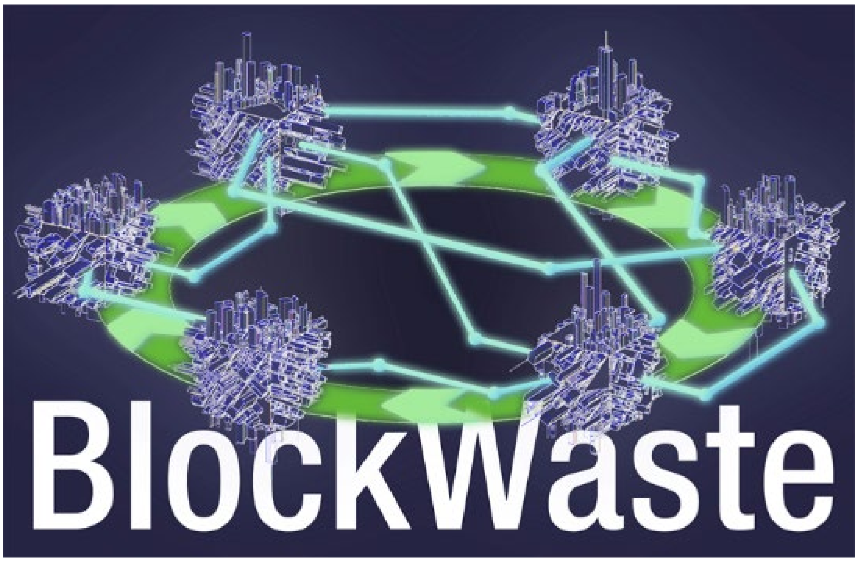
O1.A3 Handbooks of Circular Economy strategies applied to Municipal Waste Management using Blockchain technology

Handbook 1: Waste management and Circular Economy



ΙΔΡΥΜΑ ΚΡΑΤΙΚΩΝ ΥΠΟΤΡΟΦΙΩΝ IKY

Co-funded by the Erasmus+ Programme of the European Union

Output factsheet:

Funding Programme	Erasmus+ Programme of the European Union
Funding NA	EL01 Greek State Scholarship's Foundation (IKY)
Project full title	Innovative training based on Blockchain technology applied to waste management - BLOCKWASTE
Field	KA2 - Cooperation for innovation and the exchange of good practices KA203 - Strategic Partnerships for higher education
Project Number	2020-1-EL01-KA203-079154
Project Duration	24 months
Project Start Date	01-10-2020
Project End Date:	30-09-2022

Output details:

Output title: O1: Learning materials for interdisciplinary Blockchain-MSW

Task Title: A3. Handbooks of Circular Economy strategies applied to Municipal Waste Management using Blockchain technology

Output leader: NTUA

Task leader: Saxion UAS

Author(s): Maria Menegaki, menegaki@metal.ntua.gr, Dimitris Damigos, damigos@metal.ntua.gr, Athanassios Mavrikos, mavrikos@metal.ntua.gr, National Technical University of Athens, Greece, Viktoria Voronova, Tallinn University of Technology, viktoria.voronova@taltech.ee, Estonia, Juana María Torrecilla, Centro Tecnológico del Mármol, Piedra y Materiales, juanamari-toabril@ctmarmol.es, Spain

Reviewed by: Rainer Lenz, rlenz@fh-bielefeld.de, Bielefeld UAS, Germany, David Caparros Perez, Centro Tecnológico del Mármol, Piedra y Materiales , david.caparros@ctmarmol.es, Spain

Document Control

Document version	Version	Amendment
V0.1	31/03/2022	Final Version – 29/04/2022

Contents

List of tables

List of figures

List of abbreviations

Abbreviation	**Definition**
MSWM	Municipal Solid Waste Management
CE	Circular Economy
EU	European Union
IoT	Internet of Things

Executive summary

Municipal waste management (MWM) is going through major changes deriving from environmental, economic and political developments and challenges.

To address these challenges, considerable efforts have been made by EU institutions, national legislators and waste management organisations to create frameworks of regulation, classification, standardization and recommendations that harmonize and enable environmental and economic improvements. A detailed EU-wide accepted repertoire of waste classification has emerged that allows management, treatment, monitoring and value creation regarding waste.

Municipal waste streams themselves have also undergone considerable change with a trend towards less weight per unit, more packaging, more paper and more e-waste. Food and green waste continue to account for a large portion (44%) of overall municipal waste volume though.

Municipal waste generation per capita varies considerably across the EU with a 250% difference between high-volume-generating countries and low-volume ones. Although the increase of municipal waste volume is a major concern in the EU, other parts of the world show even faster growth so that overall impact of municipal waste has taken dramatic proportions with leachate and methane posing the biggest threats to clean water and air.

Current waste management has tried to counter this trend by introducing integrated systems of waste management relying on intervention hierarchies like the waste pyramid that ensure reductions in environmental impact in the limits of technological feasability, economic viability and social acceptability.

Attempts to speed up the search for large-scale solutions to the growth in waste volume have undermined confidence in linear waste management models and put Circular Ecomomy models in the focus of MWM. Its benefits are seen in the fact that they privilege re-use, recovery and recycling over disposal, incineration and landfilling by replacing linear flows of substances with circular cycles. Moving away from a 'take-make-dispose' logic to a decoupling of economic development and environmental impact from resource use will require a dramatic turnaround not only in waste management but in fundamental processes of an economy. This will require and lead to circular output models, circular innovation models and circular use models.

This again will require decisive political action and regulation, starting at EU level, but also a dramatic change in a society's mindset, transforming the idea of waste as a 'problem' into waste as a 'valuable resource'. MSW management will then have to become a vital part of circular production and consumption.

1 Introduction

1.1 Brief project description

The BlockWASTE project aims to address the interoperability between waste management and blockchain technology and promote its proper treatment through educational training, so that the data collected will be shared within a safe environment, where there is no room for uncertainty and mistrust between all parties involved. For this purpose, the objectives of BlockWASTE project are as follows:

- To conduct research on solid waste generated in cities and how it is managed, so that it can be used to create an information base of good practices, in order to reintroduce waste into the value chain, promoting the idea of Intelligent Circular Cities.
- To identify the benefits of the Blockchain Technology within the municipal solid waste management (MSWM) process.
- To create a study plan that allows the training of teachers and professionals of organizations and companies of the sector, in the overlap of the fields of Waste Management, Circular Economy and Blockchain Technology.
- To develop an interactive tool based on Blockchain Technology, which will make it possible to put into practice the management of data obtained from urban waste, thus visualizing the way in which the data is implemented in the Blockchain and enabling users to evaluate different forms of management.

BlockWASTE aims to implement transnationally new educational contents with the goal of training its students in the partner countries and providing them with the necessary basic skills that allow them to act professionally as future workers in the sector, adding digital competences required by companies that are embracing the process of digital transformation. In this sense, the project is addressed to:

- Enterprises and SMEs, IT professionals, urbanisms and waste management professionals.
- Universities (professors, students and researchers).
- Public bodies.

The project includes four Intellectual Outputs as follows:

- O1. Learning materials for interdisciplinary Blockchain-MSW
- O2. European common curriculum on MSW applying Blockchain technologies to Circular Economy strategies
- O3. E-Learning tool based-on Blockchain-MSW focused on Circular Economy
- O4. BlockWASTE Open Educational Resource (OER)

1.2 Objectives and methodological approach

This document presents the main definitions and characteristics of Municipal Solid Waste (MSW), management practices, as well as Policies and instruments in MSW management towards CE.

2 Municipal Solid Waste

2.1 Definition

In the EU's Landfill Directive 1999/31, municipal solid waste (MSW) is defined as "waste from households, as well as other waste which, because of its nature or composition, is similar to waste from households". According to Directive 2018/851, municipal waste means:

(a) mixed waste and separately collected waste from households, including paper and cardboard, glass, metals, plastics, bio-waste, wood, textiles, packaging, waste electrical and electronic equipment, waste batteries and accumulators, and bulky waste, including mattresses and furniture;

(b) mixed waste and separately collected waste from other sources, where such waste is similar in nature and composition to waste from households.

Municipal waste originates from households, commerce and trade, small businesses, office buildings and institutions (schools, hospitals, government buildings), and is collected door-to-door through traditional collection (mixed household waste), with specific fractions collected separately for recovery operations (through door-to-door collection and/or through voluntary deposits). This waste stream also includes waste from the same sources and similar in nature and composition, which is collected directly by the private sector (mainly separate collection for recovery purposes) not on behalf of municipalities and waste originating from rural areas not served by a regular waste service. Municipal waste does not include waste from production, agriculture, forestry, fishing, septic tanks and sewage network and treatment, including sewage sludge, end-of-life vehicles or construction and demolition waste.

The above-mentioned definition is followed in practically all partner countries. To wit, in Germany, municipal solid waste in the terms of the Circular Economy Act § 5a is defined (KrWG2020) as any mixed or separate waste collected from: (i) private households, especially paper and cardboard, glass, metal, plastics, organics, wood, textiles, packaging, electric and electronic appliances, batteries, bulky waste including mattresses and furniture and (ii) other sources if this waste is comparable, by nature and composition, to private household waste. In Greece, according to the Hellenic Statistical Authority, the MSW category includes household and similar waste that is collected via the municipal collection system or through third parties. In Estonia (Waste Act, §2,7), municipal waste includes waste from households and waste produced in trade, provision of services or elsewhere, which because of its composition or properties is similar to waste from households. In the Netherlands, municipal waste is defined as household waste materials: waste materials originating from private households, except those components of that waste that have been designated as hazardous waste.

Finally, in Spain MSW is defined as waste generated in households as a result of domestic activities and similar waste generated in services and industry. It also includes waste generated in households from electrical and electronic equipment, clothing, batteries, accumulators, furniture and fittings, as well as waste and rubble from minor construction and repair work in households. Furthermore, waste from the cleaning of public roads, green areas, recreational areas and beaches, dead domestic animals and abandoned vehicles are considered as domestic waste (Law 22/2011 of 28 July on waste and contaminated soil).

2.2 Classification

Municipal waste, according to Eurostat (2017), consists of the following categories:

A. Separately collected waste from households:

- Paper and cardboard
- Textiles
- Plastics
- Glass
- Metals
- Organic materials from HH (kitchen waste, garden waste - home composting is not considered).
- Hazardous household waste (e.g. spent solvents, acids, alkalines, photochemicals, pesticides, used oils, paints, WEEE, batteries and accumulators, detergents, etc.)
- Other waste (e.g. edible oil and fat, rubber waste, etc.)
- Bulky waste

B. Residual waste:

- Mixed waste from households and similar institutions with the exception of separately collected fractions.

C. Waste from municipal services:

- Organic materials from municipality services
- Waste from public bins and street sweepings
- Market cleansing waste
- Cemetery waste

Practically the same classification is followed in Germany (Circular Economy Act, 2012, amended 2020, KrWG2020), Greece (National Waste management Plan, Official Gazette 185/A/29-09-2020), Estonia (Waste Act, 2004, amended 01.01.21), the Netherlands (National Waste Management Plan 2017) and Spain (Law 22/2011).

2.3 MSW stream characteristics

The characterization of municipal solid waste (MSW) represents an important instrument for local governments and sanitation operators in setting and achieving targets for waste recycling and recovery. Towards this direction, performing a complete analysis of the characteristics and composition of household waste is an important element in national, regional and local strategies (Ciuta et. al., 2015).

2.3.1 Methods of characterising MSW

There are two primary methods for conducting a waste characterization study. The first is a site-specific approach in which the individual components of the waste stream are sampled, sorted and weighed. This methodology is useful in defining a local waste stream, especially if large numbers of samples are taken over several seasons.

Results of sampling also increase the body of knowledge about variations due to climatic and seasonal changes, population density, regional differences, etc. In addition, quantities of MSW components such as food scraps and yard trimmings can only be estimated through sampling and weighing studies.

Although this method is useful for defining a local waste stream, extrapolating from a limited number of studies can produce a skewed or misleading picture if, for example, atypical circumstances were experienced during the sampling. These circumstances could include an unusually wet or dry season, delivery of some unusual wastes during the sampling period, or errors in the sampling methodology. Any errors of this kind will be greatly magnified when a limited number of samples are taken to represent a community's entire waste stream for a year. Magnification of errors could be even more serious if a limited number of samples was relied upon for making the national estimates of MSW. Also, extensive sampling would be prohibitively expensive for making the national estimates. An additional disadvantage of sampling studies is that they do not provide information about trends unless performed in a consistent manner over a long period of time (EPA, 1998).

The second method is called the "material flows methodology." The idea for this methodology was developed at the EPA in the early 1970s. This methodology is based on production data (by weight) for the materials and products in the waste stream. To estimate generation data, specific adjustments are made to the production data for each material and product category. Adjustments are made for imports and exports and for diversions from MSW (e.g., for building materials made of plastic and paperboard that become construction and demolition debris.) Adjustments are also made for the lifetimes of products. Finally, food scraps, yard trimmings, and a small amount of miscellaneous inorganic wastes are accounted for by compiling data from a variety of waste sampling studies.

One problem with the materials flow methodology is that product residues associated with other items in MSW (usually containers) are not accounted for. These residues would include, for example, food left in a jar, detergent left in a box or bottle, and dried paint in a can. Some household hazardous wastes, (e.g., pesticide left in a can) are also included among these product residues.

2.3.2 Materials in MSW by Weight

In 2018, the total waste generated in the EU-27 by all economic activities and households amounted to 2,337 million tonnes. In the EU-27, households contributed 8.2 % of the total waste generated. Although municipal waste makes up less than 10% of total waste generated in the EU it appears as one of the most polluting waste type, because of its complex character, due to its composition, its distribution among many sources of waste, and its link to consumption patterns.

For 2020, municipal waste generation totals vary considerably, ranging from 282 kg per capita in Romania to 845 kg per capita in Denmark, with an average of about 500 kg in EU-27. The variations reflect differences in consumption patterns and economic wealth, but also depend on how municipal waste is collected and managed.

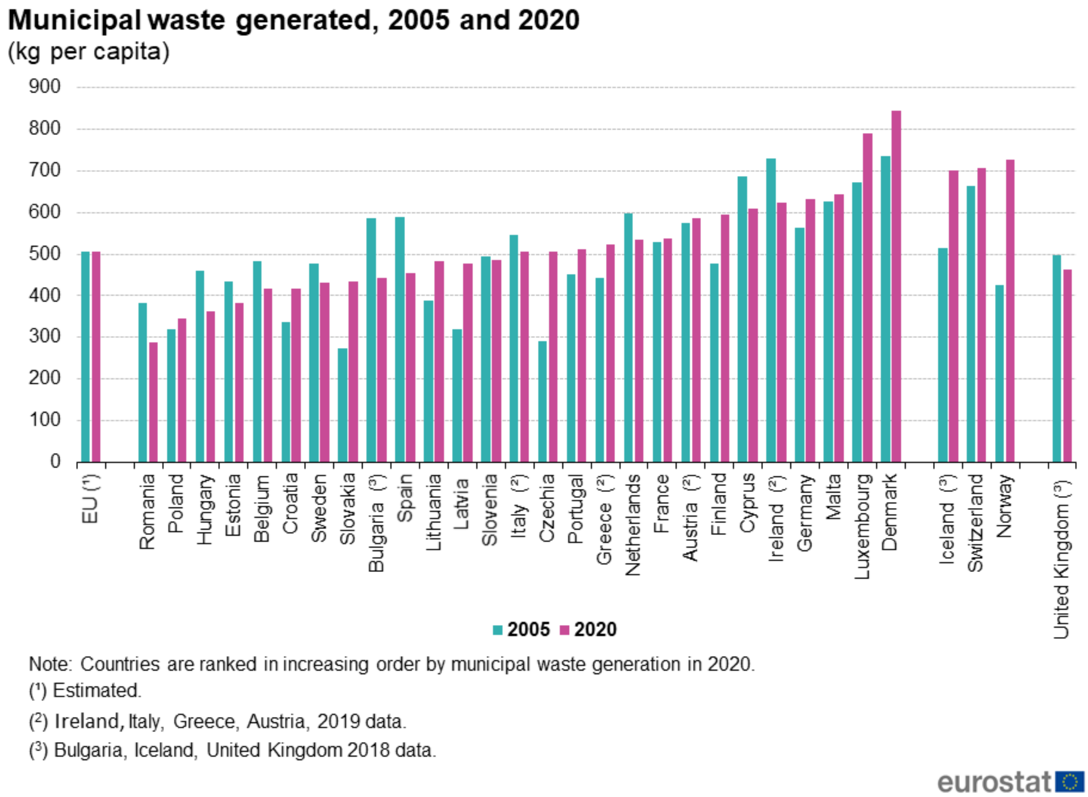


Figure 1: Municipal Waste generation EU-27, 2005-2020 (Source: Eurostat, 2021).

As far as the partner countries are concerned, in 2019, Germany had the highest municipal waste generation per capita (i.e. 609), followed by Greece (524 kg) and the Netherlands (508 kg). Municipal waste generation per capita in Spain (476 kg) was below the EU-27 average (i.e. 502 kg). Estonia, as mentioned before, produces far less waste (i.e. 73.5% of EU's average or 369 kg per capita).

Waste composition is the categorization of types of materials in municipal solid waste. At an international level, the largest waste category is food and green waste, making up 44 percent of global waste (Figure 2). Dry recyclables (plastic, paper and cardboard, metal and glass) amount to another 38 percent of waste. Waste composition varies considerably by income level. The percentage of organic matter in waste decreases as income levels rise. Consumed goods in higher-income countries include more materials such as paper and plastic than they do in lower-income countries (Figure 3). The granularity of data for waste composition, such as detailed accounts of rubber and wood waste, also increases by income level (Kaza et. al., 2018).

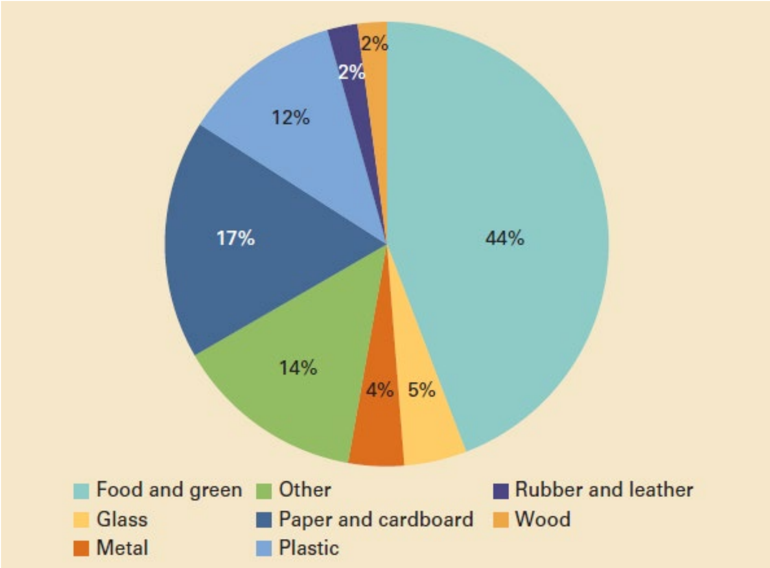


Figure 2: Global waste composition (Source: Kaza et. al., 2018).

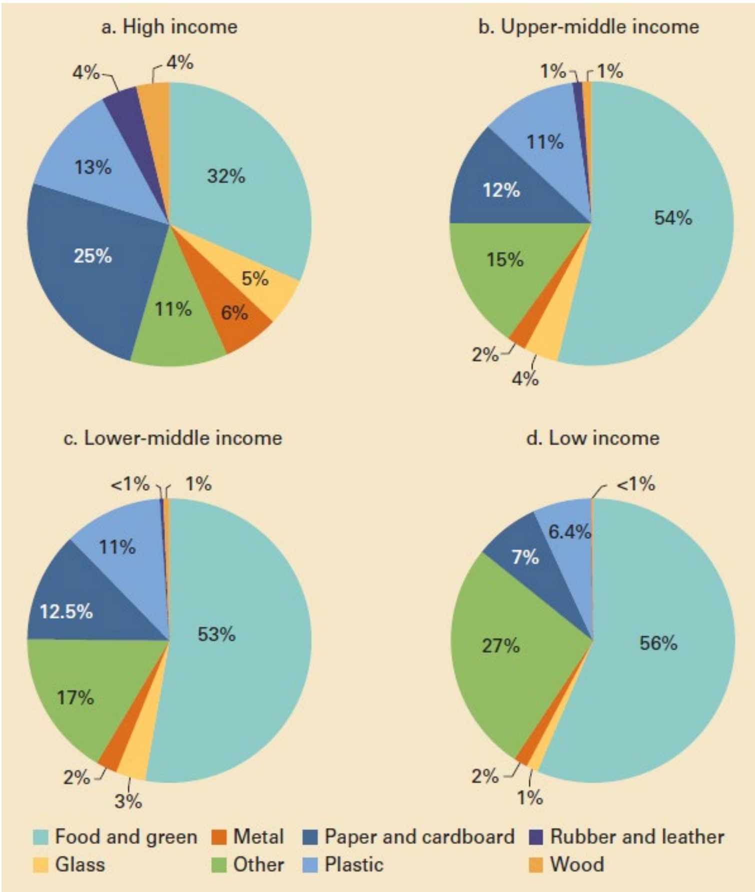


Figure 3: Waste composition by income level (Source: Kaza et. al., 2018).

The quantities of the total wastes (hazardous and non-hazardous) generated from households in EU-27 are presented in Figure 4.

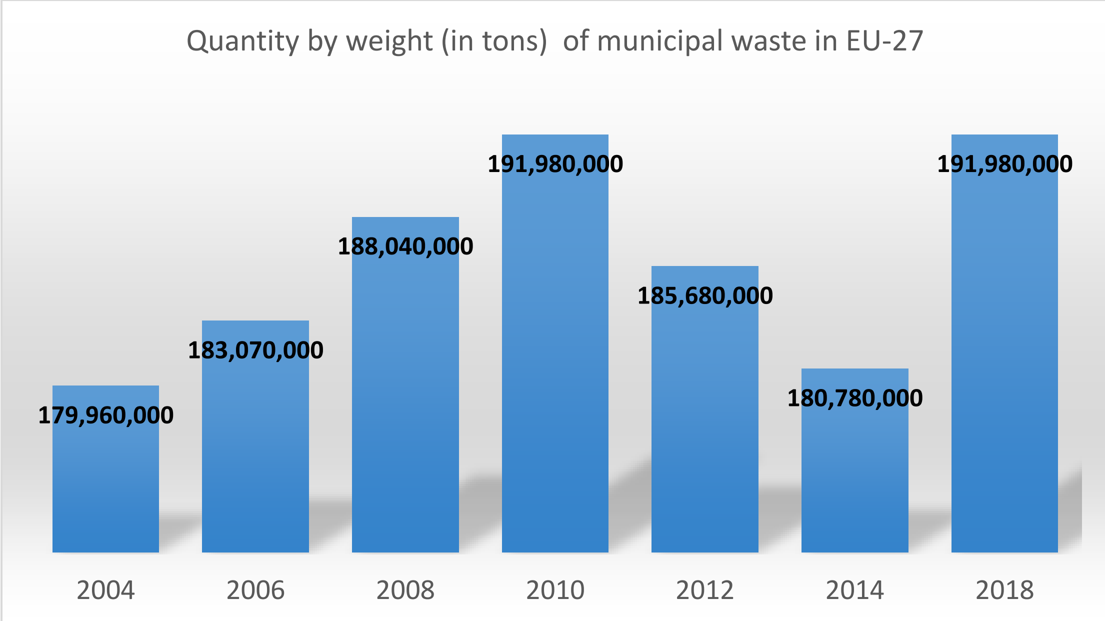


Figure 4: Waste generation from households in EU-27 by weight (in tons) (Source: Eurostat, 2022 – own editing process).

The quantities of specific categories of waste collected from households are presented in Figure 5.

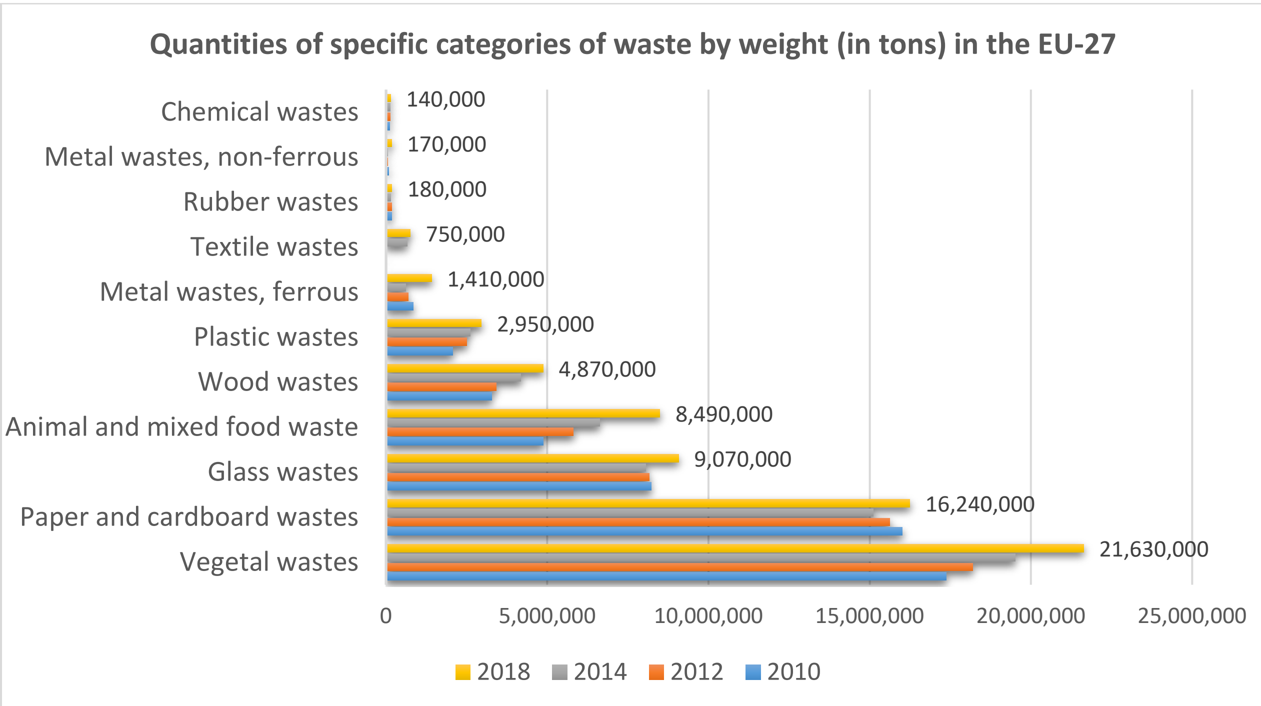


Figure 5: Waste generation from households in EU-27 by weight (in tons) and category (Source: Eurostat, 2022 – own editing process).

2.3.3 Variability of MSW Generation

2.3.3.1 Commercial vs. Residential Waste

In general, people are most conscious of the wastes coming from their own homes, whether single-family residences, apartment buildings, or other residential options. Large amounts of waste, however, are also generated where people work, shop, travel, attend classes, or engage in other activities. These latter wastes are generally classified as commercial. To add to the confusion, waste haulers often classify wastes collected from apartment buildings as commercial, although the nature of the wastes may be very similar to that from single-family residences (Tchobanoglous and Kreith, 2002).

2.3.3.2 Local/Regional Variability

Municipal solid waste managers generally agree that there are variations in the amount and characteristics of MSW around the country, although it is not easy to generalize with any degree of reliability. Some observations based on experience can be made, however (ibid).

First, there is some agreement that residential wastes vary less from location to location than do commercial wastes (Hunt, 1990). People across the country tend to buy much the same kinds of goods, whether they live in rural or urban areas or in different climates. Exceptions to this generalization include:

- *Yard trimmings.* Yard trimmings tend to be much more plentiful in warmer, moister parts of the country. In addition, there are marked differences in how yard trimmings are managed.
- *Food wastes.* Discards of food wastes in MSW will vary according to the prevalence of food disposers, which put the food wastes into the wastewater treatment system.
- *Newspapers.* Newspapers, which are mostly discarded from residences, vary greatly in size, and thus contribute to regional and urban/rural variations in MSW generation.

Generation of MSW in a particular locality will be strongly influenced by commercial activity in the area. A concentration of office buildings will produce office papers and other wastes. Shopping malls, warehouses, and factories generate large amounts of corrugated containers and other wastes as well. Schools, hospitals, airports, train and bus stations, hotels and motels, and sports facilities all contribute to the commercial waste stream. Thus, small towns and rural areas without concentrations of commercial activities will typically generate less MSW per person than urban areas.

2.3.3.3 Seasonal Variations

Another well-known phenomenon in municipal waste management is seasonal variations in waste generation. Yard trimmings are generally the important variable for most communities, with seasonal clean-up of yards and garages often contributing to peak generation weeks. Late spring and autumn are peak generation periods in many communities, while generation of yard trimmings may approach zero in winter months in cold climates. Touristic areas also present seasonal variations depending on the type of vacation that each area offers.

2.3.3.4 Changes over Time

Municipal solid waste generation presents fluctuations in time among different materials. An understanding of this phenomenon is especially important in making projections of MSW generation and in planning waste management facilities.

Some factors tending to increase MSW generation are:

- *Increasing population.* Obviously, more people use and throw away more things.
- *Increasing levels of affluence.* There is a rather strong correlation between generation of MSW and economic activity, as measured by gross domestic product (GDP) or personal consumption expenditures (PCE). Generation of paper and paperboard products is especially sensitive to economic activity. The reasons are obvious: when orders for goods go down, fewer boxes and other packaging are ordered for shipping. Also, advertising in newspapers and magazines declines during a recession.
- *Changes in lifestyles.* Changes in lifestyles are somewhat related to affluence. For example, individuals living alone, families with two wage earners, and single-parent families tend to buy more pre-packaged food and to eat out more, often at fast-food establishments using disposable packaging. They may also do more shopping through catalogues, which increases the amounts of mail received and discarded at home. In addition, each new household, however small, must have some appliances and furnishings.
- The explosion of information and shopping opportunities through on-line electronic communications is also causing changes in waste generation. For example, readership of newspapers is declining, but people with computers at home may generate more office-type paper as they print out information and e-mail communications.
- *New products.* New single-use products may increase the amounts of MSW generated. Disposable diapers are an example of this phenomenon.

While over time the MSW generation has been increased, some factors tend to decrease MSW generation. Some of these factors include:

- *Redesign of products.* Some products in MSW have actually grown lighter over the years. Appliances such as refrigerators are one example, due largely to changes in insulation and use of more lightweight plastics. Another example is rubber tires, which have not only been made smaller but last longer. Newsprint used to publish newspapers has been made lighter in weight, and sometimes page size has been decreased. Also, many kinds of packaging have been light-weighted over the years, often to save on transportation costs. Plastic waste has attracted a lot of attention recently, especially the single use plastic streams, mainly due to the massive research findings regarding the impacts of plastic pollutions to oceans[1]. The EU launched its plastic strategy in 2018, aiming to ensure all plastic packaging is reusable or recyclable by 2030. It also calls for 90% of all plastic bottles to be recycled by 2025. It is expected that this strategy will transform the way plastic products are designed, used, produced and recycled in the EU (Mavropoulos and Nielsen, 2020)[2].
- *Materials substitution.* Especially in packaging, there has been a tendency to substitute lighter materials in many applications. Thus, aluminium cans have replaced steel cans in beverage packaging and plastic bottles have been substituted for glass. This is reflected in declining or "flat" generation of steel and glass packaging, while aluminium and plastics

---

[1] Davies, S. The Great Horse-Manure Crisis of 1894 | Stephen Davies https://fee.org/articles/the-great-horse-manure-crisis-of-1894/ (accessed Feb 13, 2020)

[2] Mavropoulos A., and Nielsen A.W., 2020, Industry 4.0 and Circular Economy: Towards a Wasteless Future or a Wasteful Planet?, Wiley, ISBN: 978-1-119-69927-9

have shown rapid growth. Plastics have also substituted for paper in many applications. For example, even though generation of paper packaging has grown overall, generation of paper bags and sacks has declined, primarily due to increased use of plastic bags, which are much lighter.

Figure 6 presents the changing nature of waste as the world moves from one industrial revolution to another.

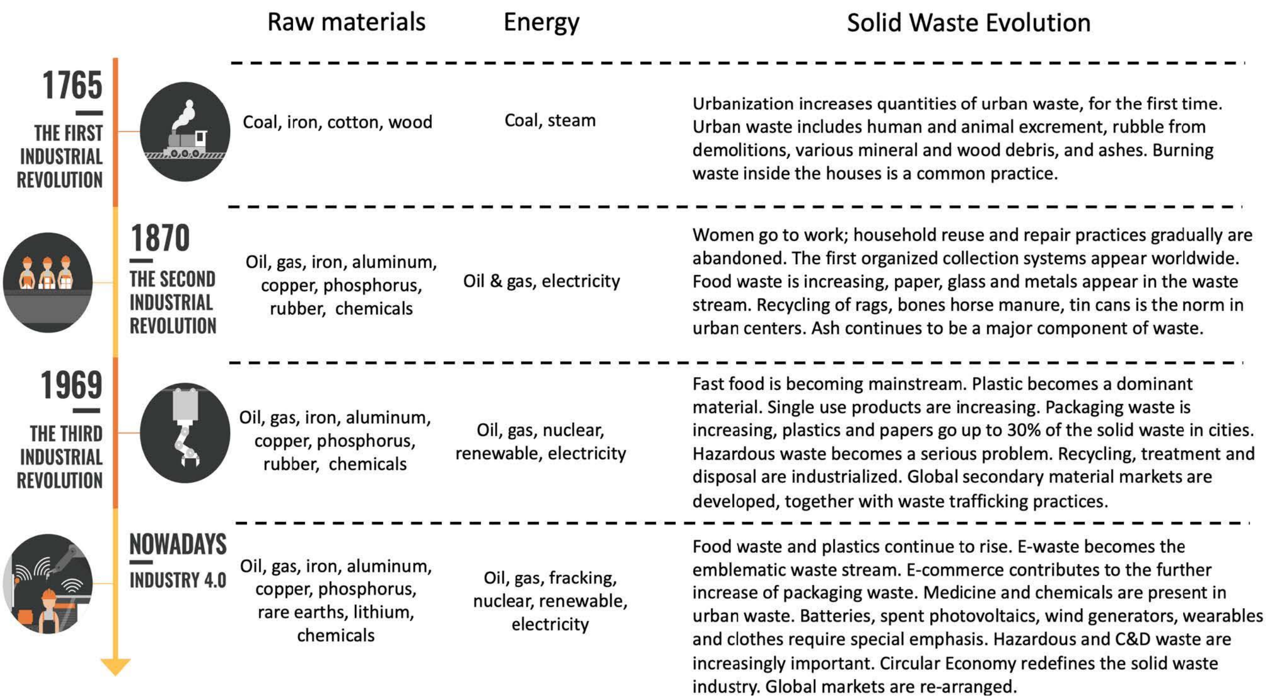


Figure 6: A snapshot of the evolution of solid waste during industrial revolutions (Source: Mavropoulos and Nielsen, 2020).

2.4 MSW and the environment

Municipal Solid Waste (MSW), more commonly known as trash or garbage, consists of everyday items people use and then throw away, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries. The sources of MSW are households, schools, hospitals, and businesses[3].

According to the World Bank[4], the world generates 2.01 billion tonnes of municipal solid waste annually, with conservative estimations calculating that at least 33% of this figure is not managed in an environmentally safe manner. Worldwide, waste generated per person per day averages 0.74 kilogram but ranges widely, from 0.11 to 4.54 kilograms. Though they only account for 16% of the world's population, high-income countries generate about 34%, or 683 million tons, of the world's waste. Regarding the future, forecasts expect waste quantities to grow to 3.40 billion tons by 2050, more than double the population growth over the same

[3] https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/

[4] https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html

period (Fig. 7). Overall, there is a positive correlation between waste generation and income level. Daily per capita waste generation in high-income countries is projected to increase by 19% by 2050, compared to low- and middle-income countries, where it is expected to increase by approximately 40% or more.

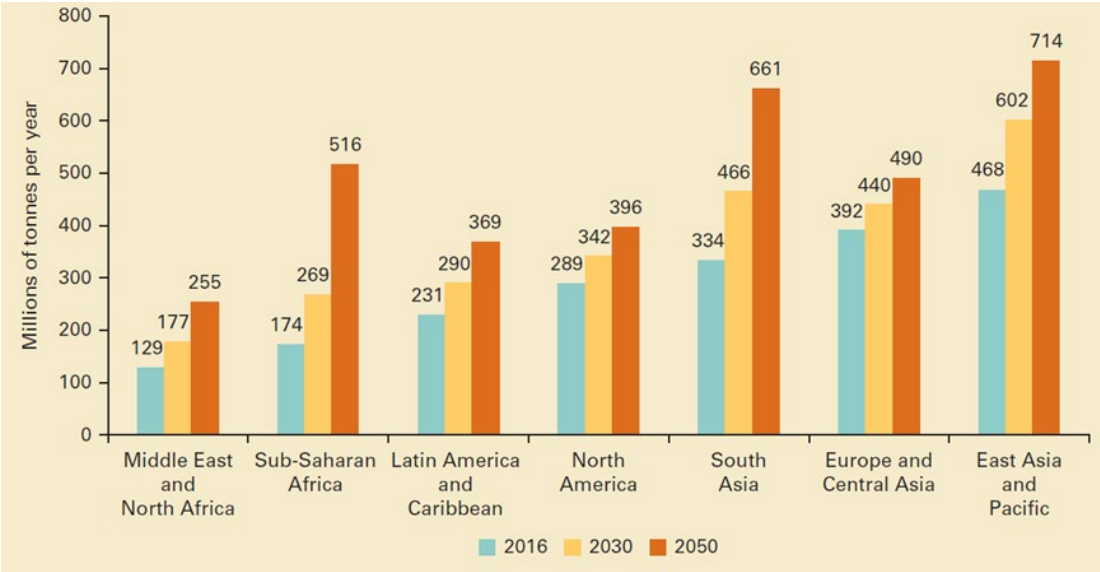


Figure 7: Projected waste generation, by region (Source: https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html).

Once generated, MSW must be managed through reuse, recycling, storage, treatment, and/or disposal. On a global scale, most waste is currently dumped or disposed of in some form of a landfill. Approximately 37% of waste is disposed of in some form of a landfill, 8% of which is disposed of in sanitary landfills with landfill gas collection systems. Uncontrolled landfills account for about 31% of waste, 19% is recovered through recycling and composting, and 11% is incinerated for final disposal (Fig. 8). Adequate waste disposal or treatment, such as controlled landfills or more stringently operated facilities, is almost exclusively found in high- and upper-middle-income countries. Lower-income countries generally rely on open dumping (Fig. 9): 93% of waste is dumped in low-income countries and only 2% in high-income countries. Incineration is used primarily in high-capacity, high-income, and land-constrained countries[5].

[5] https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html

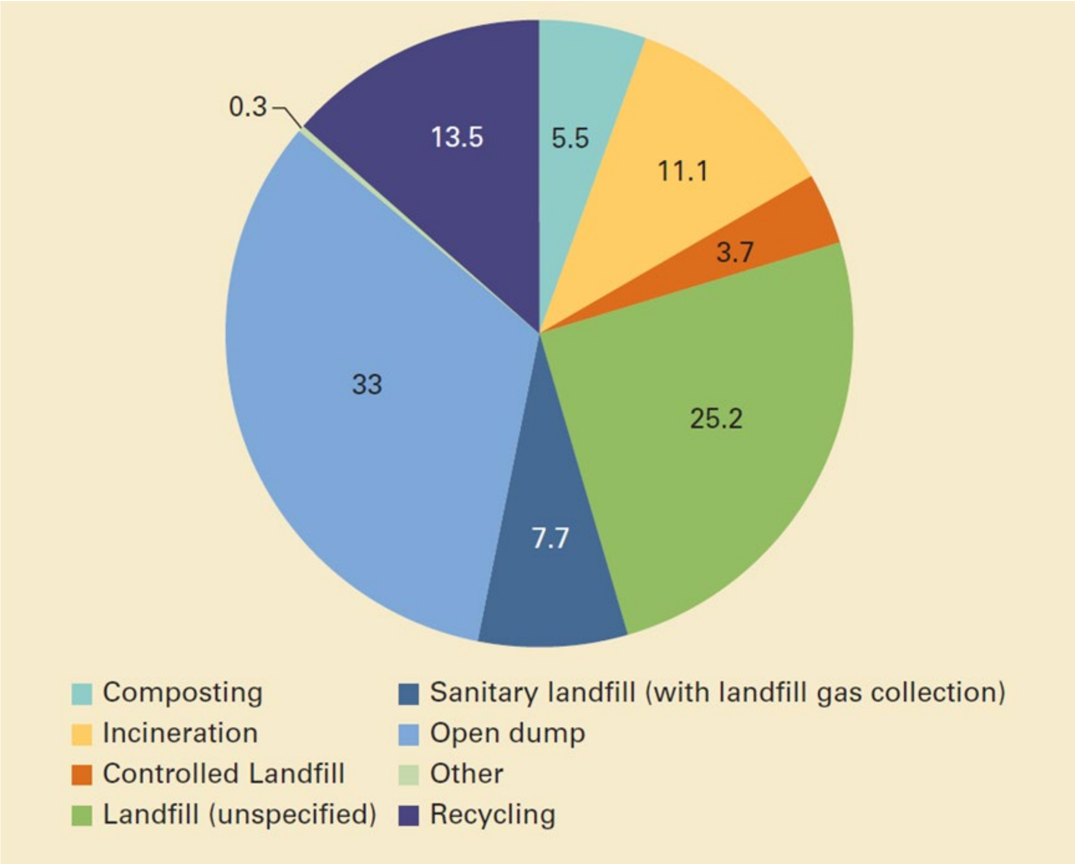


Figure 8: Global treatment and disposal of waste (Source: https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html).

2.4.1 MSW environmental impacts

Solid waste management is a universal issue affecting every single person in the world. Improper disposal can lead to adverse health outcomes, for example through water, soil and air contamination. Hazardous waste or unsafe waste treatment such as open burning can directly harm waste workers or other people involved in waste burning and neighbouring communities. Vulnerable groups such as children are at increased risk of adverse health outcomes[6]. Poorly managed waste is contaminating the world's oceans, clogging drains and causing flooding, transmitting diseases via breeding of vectors, increasing respiratory problems through airborne particles from burning of waste, harming animals that consume waste unknowingly, and affecting economic development[7].

About 54 million tons of e-waste, such as TVs, computers and phones, are created annually (2019 data) with an expected increase to 75 million tons by 2030. In 2019, only 17% of e-waste was documented as being properly collected and recycled. Exposure to improperly managed

[6] https://cdn.who.int/media/docs/default-source/who-compendium-on-health-and-environment/who_compendium_chapter4_v2_01092021.pdf?sfvrsn=b4e99edc_5
[7] https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management

e-waste and its components can cause multiple adverse health and developmental impacts especially in young children[6].

Figure 9: The Dandora municipal dumping site in Nairobi, Kenya (Source: https://en.wikipedia.org/wiki/Dandora#/media/File:Dandora_2.jpg)

In general, municipal solid waste contain various pollutants and dangerous substances. A kind of landfill is the primary method of municipal solid waste worldwide[8]. Without ignoring the importance of source-segregation of waste, so as for example to avoid disposing batteries or other hazardous materials in a landfill, the two most pressing environmental concerns regarding landfills are leachate and methane gas (Fig. 10).

[8] Mavropoulos, A., (2015). Wasted Health: the tragic case of dumpsites, ISWA (available at:https://www.researchgate.net/publication/281774422_Wasted_Health_the_tragic_case_of_dumpsites)

Figure 10: Typical cross-section of a modern sanitary landfill (Source: https://www.baltimorecountymd.gov/departments/publicworks/recycling/theresource/today-s-landfill-not-your-grandpa-s-dump).

2.4.2 Leachate and biogas

Leachate, a liquid produced by precipitation water passing through the waste volume in landfill sites, can contain high levels of ammonia (Fig. 11). When ammonia makes its way into ecosystems it is nitrified to produce nitrate. This nitrate can then cause eutrophication, or a lack of oxygen due to increased growth of plant life, in nearby water sources. Eutrophication creates "dead zones" where animals cannot survive due to lack of oxygen. Along with ammonia, leachate contains toxins such as mercury due to the presence of hazardous materials in landfills[9]. Methane gas is released as the organic mass in landfills decompose (Fig. 12). Methane is 84 times more effective at absorbing the sun's heat than carbon dioxide, making it one of the most potent greenhouse gases and a huge contributor to climate change. Along with methane, landfills also produce carbon dioxide and water vapour, and trace amounts of oxygen, nitrogen, hydrogen, and non-methane organic compounds. These gases can also contribute to climate change and create smog if left uncontrolled[7].

[9] https://www.colorado.edu/ecenter/2021/04/15/hidden-damage-landfills

Co-funded by the Erasmus+ Programme of the European Union

Parameters	Overall values		Overall range	
	Median	Mean	Minimum	Maximum
pH value	7.1	7.2	6.4	8.0
Conductivity (μS/cm)	7,180	7,789	503	19,200
Alkalinity (as $CaCO_3$)	3,580	3,438	176	8,840
COD (mg/l)	954	3,078	<10	33,700
BOD_{20} (mg/l)	360	>834	4.5	>4,800
BOD_5 (mg/l)	270	>798	<0.5	>4,800
TOC (mg/l)	306	717	2.8	<5,690
Fatty acids (as C) (mg/l)	5	248	<5	3,025
Kjeldahl-N (mg/l)	510	518	1	1,820
NH_4-N (mg/l)	453	491	<0.2	1,700
Nitrate-N (mg/l)	0.7	2.4	<0.2	32.8
Nitrite-N (mg/l)	<0.1	0.2	<0.1	1.4
Sulphate (mg/l)	70	136	<5	739
Chloride (mg/l)	1,140	1,256	27	3,410
Phosphate (mg/l)	1.1	3.0	<0.1	15.8
Sodium (mg/l)	688	904	12	3,000

* National Waste Database (1998)

Figure 11: Typical composition of leachate from Irish landfills (Source: Kalyuzhnyi et al, 2003).

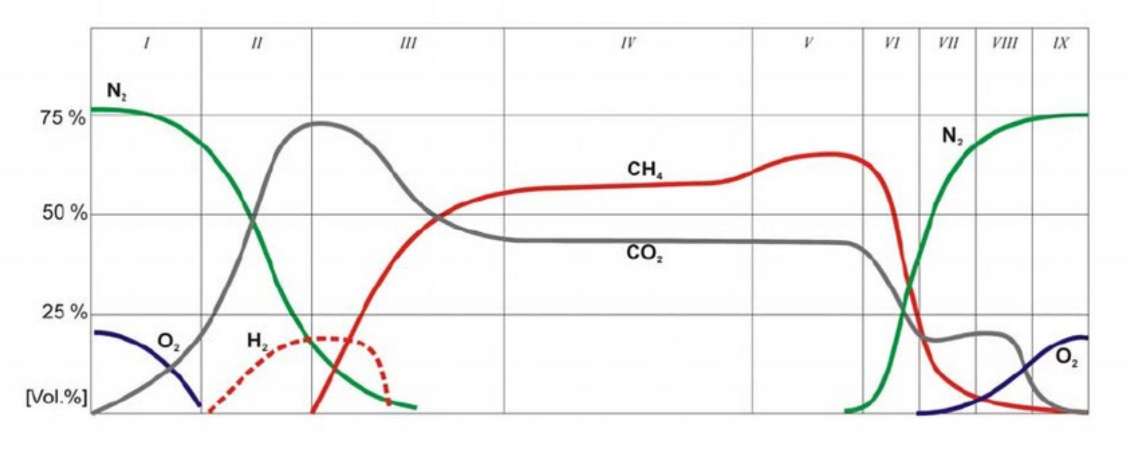


Figure 12: Long-term model of the landfill gas composition. I aerobic phase, II acid phase, III instable methane phase, IV stable methane phase, V long term phase, VI air infiltration phase, VII methane oxidation phase, VIII carbon dioxide phase, IX air phase (Source: Wagner et al, 2007).

Furthermore, landfills can also be associated with social impacts. Emissions from landfills pose a threat to the health of those who live and work around landfills. Large landfills, on average, decrease the value of the land adjacent to it by 12.9%. Finally, landfills bring hazards such as odour, smoke, noise, bugs, and water supply contamination[7].

Another common strategy for dealing with MSW is incineration. Incineration reduces solid waste quantities (up to 70%) and volumes (up to 90%) for landfill while at the same time killing pathogens. However, these advantages are offset by emissions of carbon oxides, sulphur oxides, particulates, heavy metals and other pollutants from the incinerators. Typically, for each ton of MSW that is incinerated, 15–40 kg of hazardous waste is produced, requiring further treatment[10]. Today, incinerators use advanced air pollution controls and can include technologies that remove 99% of the dioxins and furans emitted from incineration[11]. Moreover, incineration with energy recovery can result in a net saving in greenhouse emissions compared to bulk MSW incineration, although the robustness of this option depends crucially on the energy source replaced[12].

[10] https://energsustainsoc.biomedcentral.com/articles/10.1186/s13705-018-0175-y
[11]https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/municipal-solid/environment.html
[12] https://ec.europa.eu/environment/pdf/waste/studies/climate_change_xsum.pdf

3 Existing MSW management strategies

3.1 Introduction to MSW management

The amount of waste increases all over the world as a result of population boom, economic growth, rapid urbanization and rise in human living standards.

Waste is also an issue for every European country and its amount continues to increase. Municipal solid waste (MSW) accounts for approximately 10% of total waste generated in Europe (Eurostat, 2022). However, MSW collection and management is a challenging task due to waste mixed composition, distribution among many sources and dependence on consumption patterns.

More than 225 million tonnes of MSW were collected in the EU in 2020, an average of 505 kg per capita (Eurostat, 2022). The collection of MSW varies considerably between countries and lies in the range of 282 kg/capita in Romania to 845 kg/capita in Denmark (Eurostat, 2022). These variations reflect differences in consumption patterns and economic wealth, but also depend on national approach to waste collection and treatment. In general, in countries with higher levels of GDP the waste generation is also tend to rise, although more advanced waste management processes are used in these countries (STOA, 2017).

Poor management of MSW leads to serious pollution problems, such as contamination of water, soil and atmosphere, negative impacts on human health, and its contribution to climate change. Historically, MSW was usually disposed of in landfills or incinerated. Both these methods have serious drawbacks due to toxins leaching from landfills or air pollution from incineration. Modern disposal technologies have reduced the potential for environmental contamination, however, EU waste policy aims at establishing a circular economy, where materials and resources are maintained in the economy for as long as possible and where the disposal of waste and incineration are the least preferable options of waste management.

Today MSW management requires a complex approach to maximize resource efficiency and promote technically appropriate, economically viable and socially acceptable solutions to waste management problems. Thus, the concept of Integrated Waste Management (IWM) has been developed.

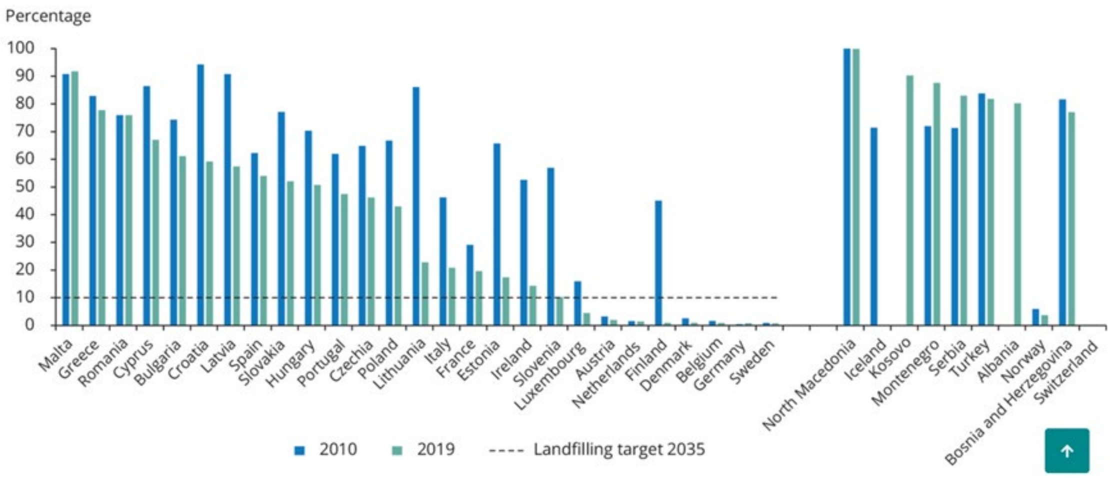
IWM consolidates waste streams, waste collection, transport, processing and disposal into a complex waste management system. Each IMW system is unique and combine mix of waste management techniques to treat the different types of waste in ways that are environmentally, financially and socially sustainable. Waste generation and management data play an important role in IWM. Knowledge about different technologies and their adverse impacts on the environment as well as estimation of the quantity and composition of generated waste together with population growth projections helps local governments to select appropriate waste collection and treatment technologies and plan for future demands (Sharma and Jain, 2020). Selection of appropriate IWM waste treatment techniques is based on waste hierarchy principles.

To assess the environmental and economic performance of IWM systems tools like Life Cycle Inventory (LCI) are used.

The multiplicity of the task and the number of preliminary assumptions is shown in Figure 13. Life Cycle Inventory investigates different routes of waste flow and its transformation, together with accompanying environmental impacts.

Figure 13: Integrated Waste Management: a Life Cycle Inventory (Adapted from Zbizinski et al., 2006).

A key goal of EU waste policy is to increase waste management efficiency and to decrease the amount of waste sent to landfill. Overall, the amount of waste disposed to landfill has decreased in Europe (in 2018 it was 7.6% less than in 2010), although the total amount of generated waste continued to increase. For MSW and similar waste decrease by 51% between 2010 and 2018 has been made towards diverting waste from the landfill (EEA, 2021). However, in line with the EU Landfill Directive, Member States must reduce the amount of municipal waste sent to landfill to 10% or less of the total amount of municipal waste generated by 2035. In 2019, only nine Member States had achieved this target (Austria, Belgium, Denmark, Finland, Germany, Luxembourg, the Netherlands, Slovenia and Sweden), as well as Norway, with several of these countries incinerating a considerable amount of municipal waste (Figure 14).



Co-funded by the Erasmus+ Programme of the European Union

Figure 14: Municipal waste landfill rates in EU Member States and other European countries (Source: EEA, 2021).

Waste policies proven to be successful in reducing landfilling include landfill taxes. Within EU Member States only Cyprus, Germany, Croatia and Malta (as well as Norway) do not have a landfill tax. Tax rates vary considerably between Member States, from 5 €/t in Lithuania to more than 100 €/t in Belgium (CEWEP, 2021). Certain correlation exists between landfill tax and landfilling, with a clear pattern of low levels of landfill as the landfill tax tend to rise (STOA, 2017).

Other important policy measures, contributing to shift up the waste hierarchy, include bans on landfilling biodegradable municipal waste or not pre-treated municipal waste, compulsory separate collection schemes for recycling of municipal waste or economic support to establish waste collection and recycling infrastructure. For example, Germany succeeded to achieve one of the highest recycling rates of municipal waste in Europe without having any landfill tax but with a combination of other political and financial instruments.

Some countries are also imposing taxes to waste incineration. For a more detailed analysis, interested readers are referred to BlockWASTE deliverable "O1.A1 - Comparative study of municipal solid waste (MSW) management regulations in each country".

3.2 Waste management hierarchy

The five-step waste hierarchy system for the first time was introduced by EU Waste Framework Directive (Directive 2008/98/EC) and has been widely used as a key for making waste management decisions at local, national and international level (Figure 15).

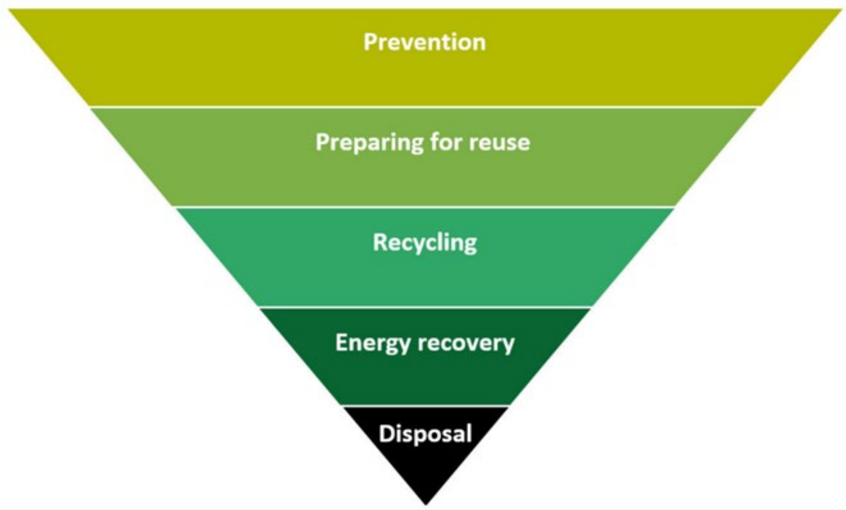


Figure 15: Waste Hierarchy. (Source: Waste Framework Directive, 2008).

The Waste Hierarchy illustrates the environmental impact of different waste management methods and has implications on the sustainability of the governance of the waste.

Waste prevention is at the very 'top' of the waste hierarchy. When waste is created, priority is given to preparing it for re-use, then recycling (including composting), then other recovery (for example, energy recovery), while waste disposal through landfills is the very last option. The EU waste legislation also has specific targets to increase the recycling of specific waste streams, such as electronic equipment, cars, batteries, construction, demolition, municipal and packaging waste, as well as to reduce the landfilling of bio-degradable waste (European Commission, 2022).

3.3 Common principles in MSW management

Modern MSW management is based on several principles:

Resource efficiency

Resource efficiency means the reduction of the environmental impact from the production and consumption of goods, from final raw material extraction to last use and disposal. From waste management perspective it means that creation of waste is not only an environmental problem, but also an economic loss. The MSW principle therefore is to change production and consumption patterns to produce less waste, while using all created waste as a resource. This approach is also reflected in Waste Hierarchy – to prevent waste generation as such, to use waste as new resource and to minimize the amount of waste disposed to landfill. Resource efficiency in waste management is also related to circular economy principles, where resource inputs, emissions and energy leakage are minimized by optimizing all processes and the waste generation is cut to the absolute minimum.

Polluter pays and Extended producer responsibility

Polluter-pays is a simple principle meaning that those who produce pollution are responsible for it and must pay to prevent damage to human health and/or the environment. In waste management, the polluter-pays principle refers to the requirement for a waste generator to pay for appropriate disposal of unrecoverable material. Extended producer responsibility scheme is one practical method to implement the polluter-pays principle. It is applied, for example, for WEEE, vehicles, batteries, packaging wastes, agricultural wastes. For the bottles collection this system includes deposit refund scheme.

"Pay as You Throw" Principle (PAYT): This model prices the disposal of MSW according to the per-unit amount of waste material, rather than based on a flat rate. This economic incentive is well established in some Member States and has significant impact on people's behaviour.

3.4 MSW treatment

3.4.1 Landfill

The disposal of waste, according to waste hierarchy is one of the least preferred options nowadays. The placement of solid waste on land is called a dump or dumping (Worell & Vesilind, 2012), which was one of the original methods almost for all inland communities until 1960-s. In late 1960-s, developed countries started to use engineered solutions for dumping the wastes, which leads to development of sanitary landfill. The sanitary landfill includes bottom liners, leachate collection systems, leachate treatment, gas collection, gas treatment, final covers, and air and water monitoring systems (EREF, 2022). In a landfill, waste degradation occurs based on the complex chemical, physical and biological processes. These processes are influenced by environmental conditions (such as temperature, pH, the presence of toxins, moisture content and the oxidation-reduction potential). As a results of these processes waste are degraded or transformed. The degradation rate depends also on composition of the waste and leads to leachate and landfill gas generation.

Leachate is generated from the percolation of water through the waste after placement and also includes that moisture retained in the waste prior to disposal (EREF, 2022). The quality of the leachate depending on the composition of the solid waste, precipitation rates, site hydrology, compaction, cover design, waste age, sampling procedures, interaction of leachate with the environment, and landfill design and operation (Worell & Vesilind, 2012). After collection, the leachate has to be treated on place or send to municipal sewerage for further treatment.

The landfill gas produced during the biological decomposition of municipal solid waste (MSW). Mathematical and computer models can predict the composition of the landfill gas, which is based mainly on composition of landfilled waste and moisture content.

European Union tries to limit the amount of waste sent to landfill by minimum. The main law entered into force in 1999 was the Landfill Directive. The Landfill Directive sets out strict operational requirements for landfill sites with the objective to protect both human health and the environment (EC, 2022).

3.4.2 Incineration and energy recovery

Most of MSW is combustible and can be burned with energy recovery in mass burn incineration facilities to reduce the volume of waste. Such combustors have a solid waste storage area for storing and sorting the incoming waste, a crane for loading the waste to combustion block, a combustion chamber consisting of bottom grates, the heat recovery system of pipes, in which water is turned to steam, the ash-handling system, and the air-pollution control system, which include scrubbers and baghouse filters for fly ash and particulate matter removal.

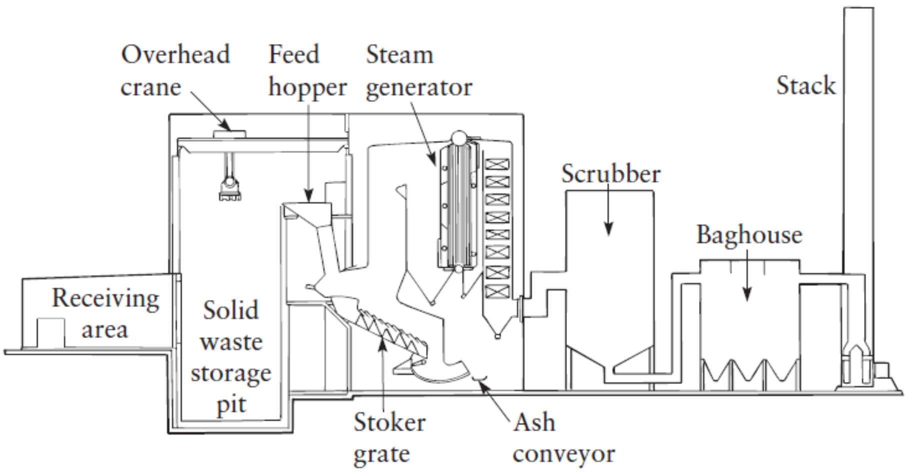


Figure 16: A typical scheme of municipal solid waste combustor (Adapted from Worell & Vesilind, 2012).

Waste to Energy (WtE) or energy - from - waste (EfW) is defined as a process of burning waste with energy recovery. The main types of WtE processes include:

- co-incineration of waste in combustion plants (e.g. power plants) and in cement and lime production;
- waste incineration and co-incineration in dedicated facilities;
- anaerobic digestion of biodegradable waste
- production of waste-derived solid, liquid or gaseous fuels and
- other processes including indirect incineration following a pyrolysis or gasification step;

Regarding the European Commission COM(2017)34, about the role of waste-to-energy in the circular economy, only the anaerobic digestion with production of biogas is positioned as recycling option according to Waste hierarchy. All other types of WtE processes are mostly related to the recovery option. Incineration and co-incineration with limited energy recovery are placed at the bottom of hierarchy under disposal option together with landfilling of waste. The open burning process is discouraged in European Union due to the problems associated with high air pollution.

3.4.3 Composting and biomethanisation

Composting can be defined as a degradation process of organic material in the presence of the microorganisms to water, carbon dioxide and microbial biomass. In composting, microorganisms convert organic materials to valuable product called "humus". The basic reaction is as follows (Worell & Vesilind, 2012):

$$[complex\ organics] + O_2 + microorganisms \rightarrow CO_2 + H_2O + NO_3^- + SO_4^{-2} + [other\ less\ complex\ organics] + [heat]$$

Composting occurs mainly in four phases:

a) **<u>Mesophillic initial phase</u>** - In the mesophilic initial phase, the bacteria that decompose organic matter start to reproduce intensively, the compostable mass heats up and the pH decreases.
b) **<u>Thermophillic phase</u>** - During the thermophilic phase, during which the temperature rises to 60-70 ° C, most of the pathogens, pests and parasites in the waste are killed and the weed seeds are destroyed.
c) **<u>Mesophilic maturation phase -</u>** In the mesophilic maturation phase, the temperature remains at 35-55 ° C and begins to decrease due to nutrient depletion. The content of persistent compounds decreases over time.
d) **<u>Cooling and after maturation phase</u>** - During the cooling and maturation phases, the microbiological activity is further reduced. The temperature no longer rises above 40 ° C even when the compost is mixed. Earthworms appear in the compost. During post-maturation, the compost matures and the most valuable "humus" is formed.

Main composting systems include (Atalia et al., 2015):

- Open Windows – involves placing a mixture of organic waste materials into long, narrow piles.

- Aerated static pile – organic waste are place into a piles which aerated by forcing air through the perforated pipes at regular intervals.
- In vessel composting – composting occur in different reactors. These systems usually include provisions for aeration, mixing, temperature control, and containment of odours.
- Vermicomposting - combined activity of microorganisms and earthworms.
- Biomineralization - The nutrients in form of soluble minerals are used which are absorbed by root system from fertile well mineralized compost soil.

Biomethanisation

Anaerobic degradation of organic matter (without oxygen) called also biomethanisation. The main end-products include methane (CH_4), carbon dioxide (CO_2), small amounts of hydrogen sulfide (H_2S), ammonia (NH_3), and a few others (Worell & Vesilind, 2012).

The process of anaerobic digestion can be described in three phases:

- Hydrolysis, i.e. bacteria breakdown high molecular organic compounds to low molecular compounds (monomers).
- Acidogenis, acetogenic bacteria converts in the first phase appeared degraded products to volatile fatty acids, carbon dioxide and hydrogen.
- Methanogenesis, bacteria converts organic acids and alcohols to acetic acid and molecular hydrogen. At the end of this phase, methane is generated from acetic acid, hydrogen and carbon dioxide.

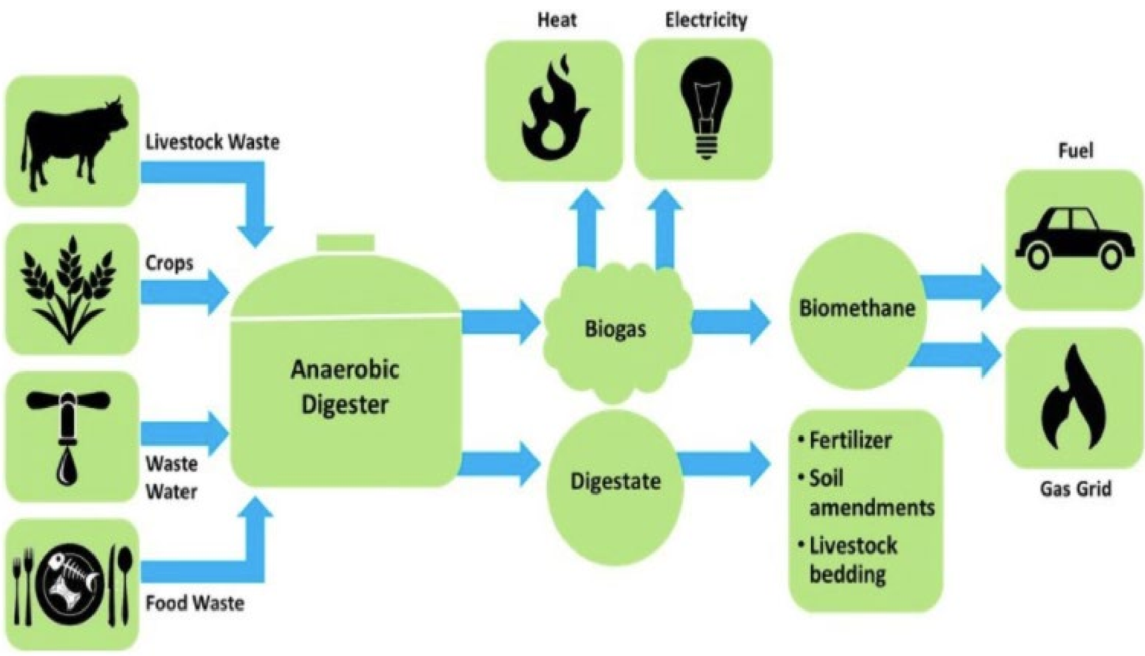


Figure 17: Anaerobic digestion process (Graphic by Sara Tanigawa, EESI).

The main feedstock for anaerobic digestion process include food waste, livestock waste, crop residues and sewage sludge from waste water treatment plants.

Produced biogas can be used in combined heat and power (CHP) operations, or biogas can simply be turned into electricity using a combustion engine, fuel cell, or gas turbine. Additionally, it can be modified to Renewable natural gas (RNG), or biomethane by removing carbon dioxide, water vapour and other trace gases. RNG can be injected into the existing natural gas grid (including pipelines) and used interchangeably with conventional natural gas (EESI, 2017). Like conventional natural gas, RNG can be used as a vehicle fuel after it is converted to compressed natural gas (CNG) or liquefied natural gas (LNG).

3.4.4 Recycling

The main principle of waste management in EU to prevent, re-use or recycle generation of MSW, following the principle of circular economy and to minimise the negative effects from usage of primary resources, by replacing them with secondary materials (EEA, 2022).

According to Waste Framework Directive 2008/98/EC recycling means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. In Europe, the tendency of recycling of different waste stream is grown within last 10 years (Figure 18).

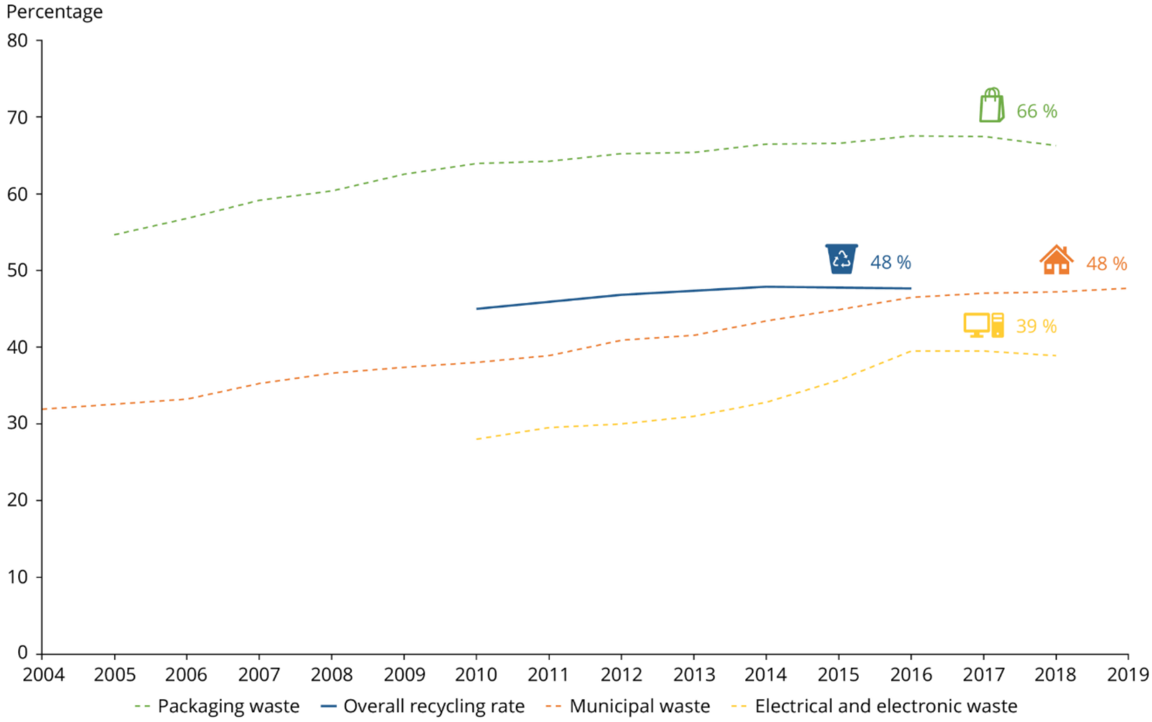


Figure 18: Recycling rates in Europe by waste stream (Source: EEA, 2022).

Co-funded by the Erasmus+ Programme of the European Union

4 Circular economy

4.1 The linear model of production and consumption

The growth of the population forces to modify the management systems that have been carried out until now. The population in the EU has grown by nearly one hundred million people since the 1970s. This fact has direct consequences on the generation of waste: more population, more waste. Despite national and EU efforts, the amount of waste generated is not decreasing. Waste generation from all economic activities in the EU amounts to 2.5 billion tonnes per year, and each citizen produces on average half a tonne of municipal waste.

According to Directive 2018/851 of the European Parliament and of the Council, municipal waste constitutes approximately 7-10% of the total waste generated in the European Union.

This waste flow is, however, among the most complex to manage, and the way in which it is managed generally gives a good indication of the quality of a country's overall waste management system.

The total EU resource consumption, measured in terms of mass, is shown in Fig. 19.

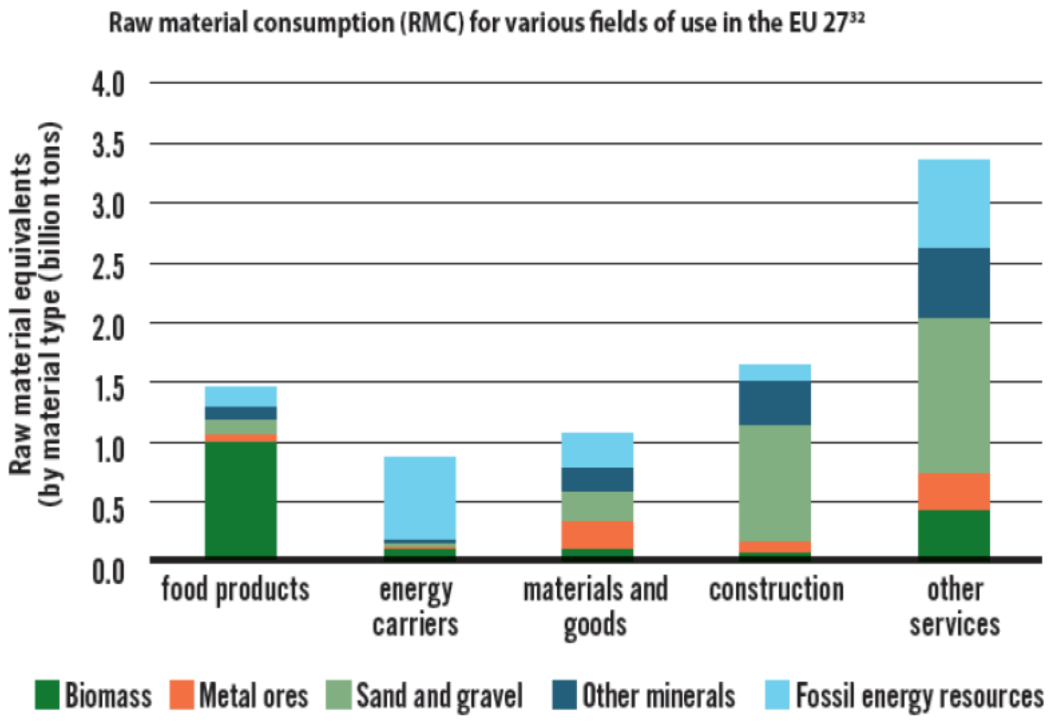


Figure 19: Raw material consumption (RMC) (Source: European Environmental Bureau 2012).

The traditional linear economy, based on "take-make-dispose", and the consumption of large quantities of energy and cheap raw materials that are easy to supply, has been the fundamental element of social and industrial development, and has generated levels of unprecedented growth in the history of humankind.

The traditional linear economic model is mainly characterised by:

- Cheap and easily obtainable resources.
- Fossil fuels.
- Extraction-Production-Use-Disposal.
- Overexploitation of raw material.
- High volume of waste generated.

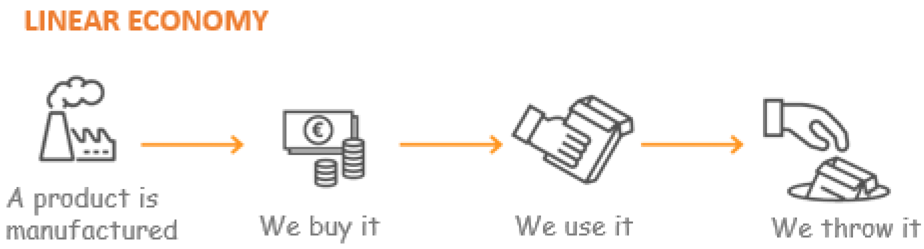


Figure 20: Linear economy scheme (Source: BIMgreen 2019).

In terms of environmental issues, the linear model entails different impacts affecting resources, consumption and production.

Resource-related:

- Large amount of waste.
- Traditional exploitation systems.
- Single use of raw materials (only once).
- Uncontrolled exploitation without previous design.
- High environmental impact.
- Depletion of natural resources and fossil fuels.

Consumption-related:

- Uncontrolled consumption.
- No product reuse.

Production-related:

- Low efficiency of resources and energy.
- Traditional business models.

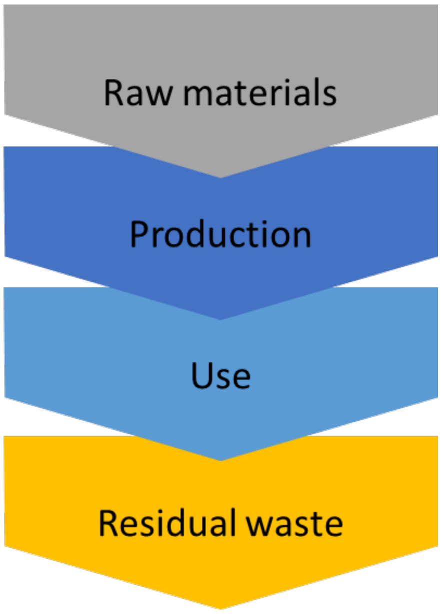


Figure 21: Outline of the linear economic model (Source: Marble and Stone Technology Centre, 2018).

The linear 'take-make-dispose' economy is reaching its limits:

- Relies on large quantities of cheap, easily accessible materials and energy.
- 2025: Growing world population (1.1 bn) and growing middle class (3 bn):
  - 24% higher food consumption.
  - 47% more packaging.
  - 41% more end-of-life materials (waste).
- Resource-related challenges to businesses and economies also growing:
  - Pressure on natural resources intensifying.
  - Low and poor recycling -> Unable to keep up stock of quality materials.
  - Higher price volatility-> higher business investment uncertainty.
  - Commodity prices increased 150% during 2002-2010 (metals, food and non-food from agriculture).

4.2 Circular economy: concept, origins and principles

The planetary economy is blocked in a system in which everything from the productive economy and contracting, to the regulation and behaviour of people, favours the linear model of production, distribution and consumption. However, this blockage is increasingly weak due to the pressure exerted by the occurrence of powerful disruptive tendencies. It is necessary to take advantage of this favourable combination of economic, technological and social factors to accelerate the transition to a circular, restorative and regenerative economy, in which products, by-products and waste are kept within the productive cycle as long as possible, seeking their reuse one and again.

In a circular economy, manufacturers design products to be reusable. For example, electrical devices are designed in such a way that they are easier to repair. Products and raw materials are also reused as much as possible. For example, by recycling plastic into pellets for making new plastic products. In a circular economy, we treat our surroundings responsibly. For example, by preventing litter on streets or in the natural environment.

A circular economy works according to the 3R approach of “Reduce, Reuse & Recycle”. Material extraction is reduced, where possible, by using less material, products are made of reused parts and materials and, after discarding a product, materials and parts are recycled. In a circular economy, value is created by focusing on value retention. By keeping a material stream as pure as possible during the complete value chain, the value of this material is retained. Pure materials streams can be used multiple times to provide a certain functionality or service, while only making one investment.

Figure 22: Outline of the circular economic model (Source: Marble and Stone Technology Centre, 2018).

In a circular economy, sustainability is improved by enhancing the eco-effectivity of the system. This means that next to minimizing the negative impact of the system, the focus is put on maximizing the positive impact of the system by radical innovations and system change.

In a circular economy, reuse is intended to be as high grade as possible. A residual stream should be reused for a function that is equal (functional reuse) or of a higher value (upcycling) than the initial function of the material stream.

This ensures that the value of the material is retained or enhanced. For example, concrete can be grinded into grains that are used to create a similar wall as before, or even a stronger constructive element.

Circular economy – a new concept is mainly characterised by:

- Distinguishing between technical and biological circles.
- Circular design.

- Modular products, purer material flows, easier disassembly.

- More and more people living in urban areas make sharing, repairing and recycling easier.
- Innovative business models: from ownership to performance and access-based service systems.
- Core competences and technologies along reverse cycles and cascades: RFID tags for easier identification and recycling; 3D printing for spare parts.

The main characteristics of the Circular Economy are the following:

- Improving economic performance while reducing resource use.
- Fighting climate change and reducing the environmental impacts of resource use.
- Switching from fossil fuels to the use of energy from renewable sources.
- Reuse and repair: finding a second life for deteriorated products.
- Making energetic use of waste that cannot be recycled.
- Preserve and enhance natural capital to achieve resilience through diversity.
- Optimise the use of resources and encourage the use of bio-based materials.

There are a few concepts that are necessary for the implementation of the circular economy model:

- **Eco-conception**: It considers the environmental impacts throughout the life cycle of a product and integrates them from its conception.
- **Industrial and territorial ecology**: The establishment of a mode of industrial organisation in the same territory characterised by an optimised management of stocks and flows of materials, energy and services.
- **The economy of "functionality"**: Privilege the use against the possession, the sale of a service versus a good.
- **The second use**: Reintroduce in the economic circuit those products that no longer correspond to the initial needs of consumers.
- **The reuse**: Reuse certain waste or parts of them, which can still work for the development of new products.
- **Repair**: Find a second life to the damaged products.
- **Recycling**: Take advantage of the materials found in the waste.
- **Valorisation**: Take advantage of energy waste that cannot be recycled.

Circular economy arises from the increasingly evident scarcity of resources, the increasing demand for raw materials and the fact that some of them are finite, which leads to dependence on third countries.

Another reason for the rise of circular economy is the impact it has on the environment. The extraction and use of raw materials means an increase in energy consumption and an increase in pollutant emissions.

Circular economy is beneficial both for the environment and for societies, as it is a way to preserve and optimise the use of resources, promoting the efficiency of the system.

The principles and claimed results through the implementation of a circular economy are:

- Keeping products, components, and materials at their highest utility and value always.
- Controlling stocks of finite materials and balancing renewable resource flows.

- Decoupling global economic development from finite resource consumption.

Advantages of circular economy:

Circular economy has many advantages. Reducing waste and reusing materials results in significant savings, while at the same time reducing annual greenhouse gas emissions.

Consumers also benefit from more durable products, which means greater savings and a higher quality of life.

Disadvantages of circular economy:

Achieving a circular economy and reducing the use of resources in turn means limiting energy consumption and reducing waste production. For many, this reorientation of global productivity is difficult to achieve.

One of the problems to be faced is that some products are difficult to recycle, because those who design them do not value waste management. On the other hand, this model requires intense inter-company collaboration, which many companies are not willing to take on.

Decoupling economic development, resource consumption and environmental impacts:

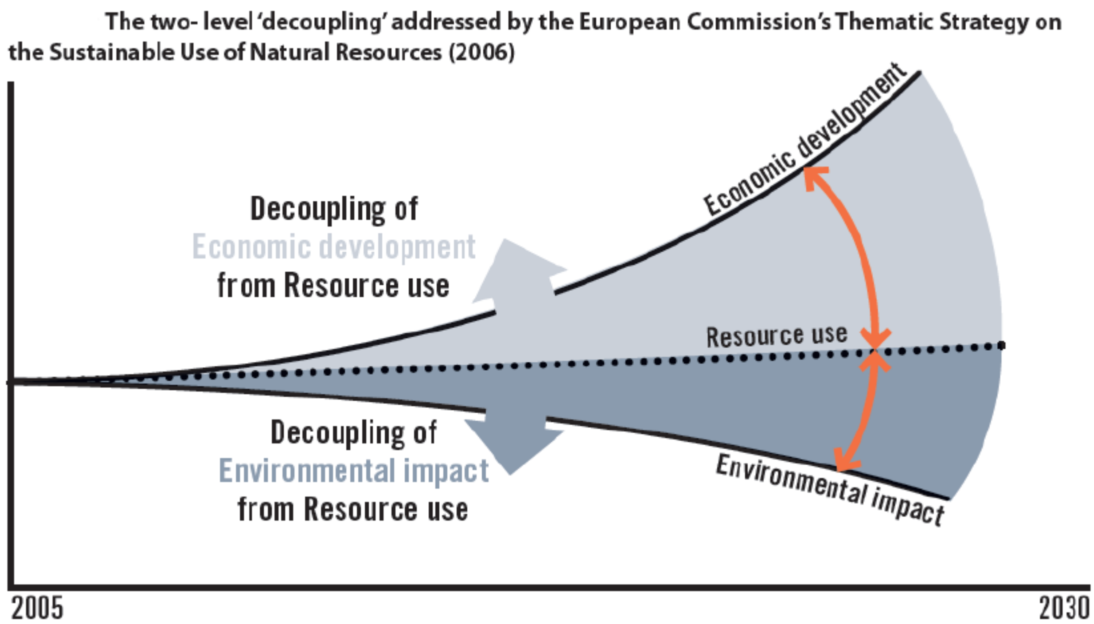


Figure 23: Decoupling addressed by the EC (Source: European Environmental Bureau, 2015).

One of the main principles underpinning the circular economy is **design**. Design at all stages and/or aspects of the life cycle of products.

Design and materials:

- Avoid heavy metals as cadmium, lead, and dangerous substances (RoHS).
- Use of recycled materials (metals, etc.).

- Recyclability and recoverability.
- Reduction of weight (dematerialisation).

Design, durability and repair:

- Modular design, standard component, easy to repair and to up-grade.
- Easy to dismantle with common tools.
- Bill of Material (BoM).
- Mono-materials and few different materials.

Design for end-of-life:

- Avoid substances that make recycling expensive / problematic.
- Product take-back + organise waste streams to avoid down-cycling.
- Reuse of components.

4.3 Challenges and benefits of circular systems

4.3.1 Challenges

Currently, it becomes increasingly clear that the linear economy is no longer a tenable model within the limits of our planet. The disadvantages of the linear economy outline the urgency for an alternative model, which can be interpreted as opportunities for the circular economy. The main disadvantages of a linear economy are found in the lack of solutions for the growing shortage of materials, increased pollution, increased material demand and the growing demand for responsible products.

In a linear economy, the uncertainty about material availability grows. This uncertainty is based on the fact that the planet has a finite number of materials and their availability depends on several mechanisms. This uncertainty is filled by an increase in price fluctuations, growth of industries that are dependent on critical materials, the interconnection of products and processes, and geopolitical developments.

Degradation of ecosystems

Following the linear model of 'take-make-dispose' leads to the creation of waste. During production processes and because of the disposal of products large streams of material are generated that are not used but burned or left on a garbage dump. This will eventually lead to excess of unusable material mountains overloading ecosystems. This ensures that the ecosystem is hampered in providing essential ecosystem services (such as providing food, building materials and shelter, and the processing of nutrients).

Decreasing lifetime of products

In recent years, the life of products decreased drastically. This is one of the driving forces behind the increasing material consumption in the Western world. The service life of products is still decreasing, by a process of positive feedback: Consumers want new products more often and are using their "old" products for a shorter period. This results in a decreased need for quality products that can be used on the long term, which stimulates consumers to buy new products even faster.

4.3.2 Benefits

A circular economy is an economic system where products and services are traded in closed loops or 'cycles'. A circular economy is characterized as an economy, which is regenerative, by design, with the aim to retain as much value as possible of products, parts and materials. This means that the aim should be to create a system that allows for the long life, optimal reuse, refurbishment, remanufacturing and recycling of products and materials.

Closing Loops

In circular economy, material cycles are closed by following the example of natural ecosystems: Toxic substances are eliminated, there is no waste because all residual streams are valuable as resource, products are taken back after use for repair and remanufacturing to reuse the products a second, third or fourth time and residual streams are separated in a biological and technical cycle.

System thinking

Circular economy asks for system thinking. All actors (businesses, persons, organisms) are part of a network in which the actions of one actor affect other actors. In circular economy, this is considered in decision-making processes by including both short- and long-term consequences of a decision, considering the impact of the complete value chain and aiming for the creation of a more resilient system, which is effective at every scale.

Decoupling economic growth

The Goal of a circular economy is to decouple economic growth form resource consumption by focusing on value retention. To secure the ecosystems and natural capital on which we rely, more than financial capital is of value.

Social capital and natural capital play a role in the stability of our systems as well. In circular economy, these values are reflected in the costs of products and services. The energy required to fuel this cycle should be renewable by nature.

Several strategies are proposed to achieve the transition from the linear to the circular economy:

Transversal strategies

- Regulations.
- R&T&D.

Direct strategies

- Waste management.
- Economic actors.
- Consumers.

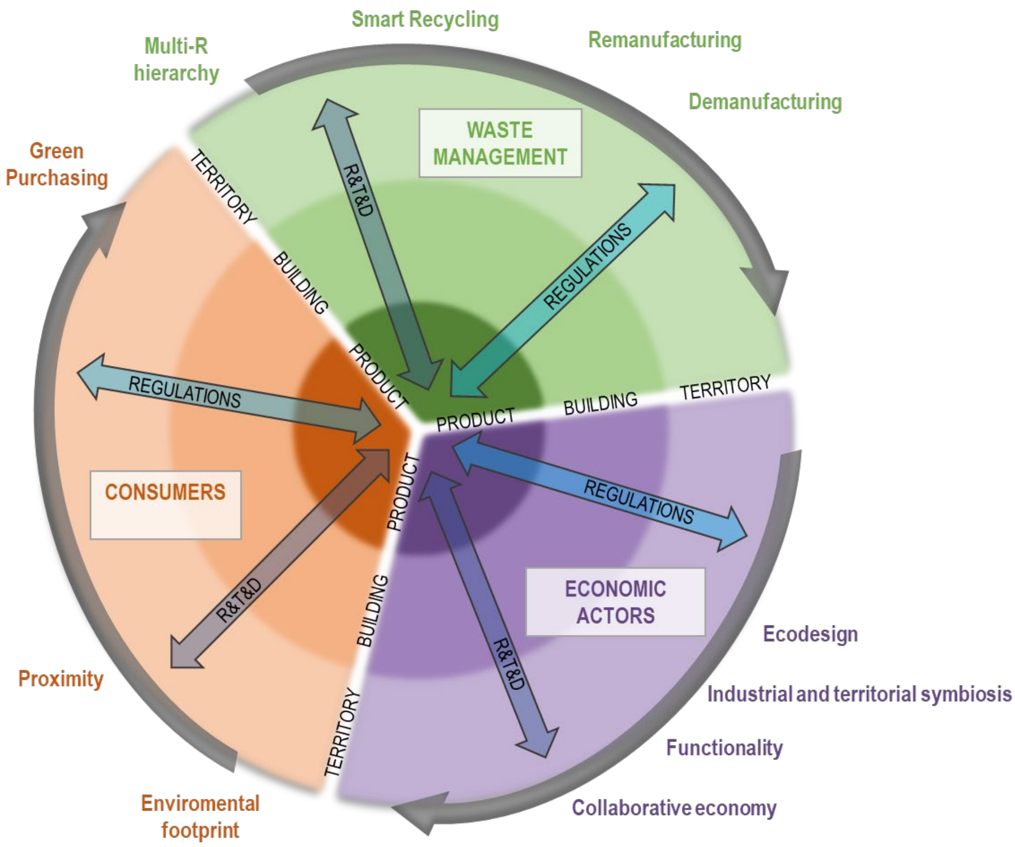


Figure 24: Outline transition to Circular economy (Source: Caparrós-Pérez, D., 2017).

4.3.3 Transversal strategies

In 2015, the European Commission adopted the EU Action Plan for the Circular Economy (December 2015) with the objective to point out the different measures (up to a total of 54) on which the European Commission estimates that action is needed in the next 5 years to advance the circular economy. In this direction, five areas were identified as priorities by the Commission (plastics, food waste, critical raw materials, construction and demolition, biomass and bio-based products), addressed through the following Communications:

- COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS.

Towards a circular economy: A zero waste programme for Europe /* COM/2014/0398 final */

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52014DC0398

- COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS (COM/2015/0614 final).

Closing the loop – An EU action plan for the Circular Economy.

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614&qid=1524124780099

- REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS (COM/2017/033 final).

On the implementation of the Circular Economy Action

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0033&qid=1524125695611

- COMMISSION OF EUROPEAN COMMUNITIES. COMMUNICATION NO. 29, 2018. MONITORING FRAMEWORK FOR THE CIRCULAR ECONOMY; COM NO. 29.

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2018%3A29%3AFIN

- COMMISSION OF EUROPEAN COMMUNITIES. COMMUNICATION NO. 98, 2020. A NEW CIRCULAR ECONOMY ACTION PLAN FOR A CLEANER AND MORE COMPETITIVE EUROPE.

https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

Also, numerous European initiatives promote circularity through calls for proposals and programmes. The European Commission adopted the new circular economy action plan (CEAP) in March 2020. It is one of the main building blocks of the European Green Deal, Europe's new agenda for sustainable growth. The EU's transition to a circular economy will reduce pressure on natural resources and will create sustainable growth and jobs. It is also a prerequisite to achieve the EU's 2050 climate neutrality target and to halt biodiversity loss.

The new Action Plan announces initiatives along the entire life cycle of products. It targets how products are designed, promotes circular economy processes, encourages sustainable consumption, and aims to ensure that waste is prevented and the resources used are kept in the EU economy for as long as possible. The Action Plan introduces legislative and non-legislative measures targeting areas, where action at the EU level brings real added value.

4.3.4 Direct strategies

Among the aware of all agents involved in the process, three categories of circular business models are identified:

- Circular Output Models.
- Circular Innovation Models.
- Circular Use Models.

4.3.4.1 Waste Management

Circular Output Models

These business models focus on the output and added value of a product's after-use phase. In these business models, revenue is generated through transforming after-use products into new products or useful resources to add value, reduce costs or reduce waste. The development of reverse logistics is essential for this model.

Examples of business models in this category include:

- Recaptured material supplier: Sells recaptured materials and components to be used instead of virgin or recycled material.

- Refurbish & Maintain: Refurbishes and maintains used products to sell them.
- Recycling facility: Transforms waste into raw materials. Additional revenue can be created through pioneering work in recycling technology.
- Recovery provider: Provides take-back systems and collection service to recover useful resources from disposed products or by-products;
- Support lifecycle: Sells consumables, spare parts and add-ons to support the life cycle of long-lasting products.

4.3.4.2 Economic actors

Circular Innovation Models

Circular Innovation Models focus on the development phase of a product. Products are designed to last longer and are easy to maintain, repair, upgrade, refurbish, remanufacture or recycle. Additionally, new materials are developed and sourced, e.g. bio-based or fully recyclable materials.

Examples of business models in this category include:

- Product design: Provides products that are designed to make them long and useful life and/or be easy to maintain, repair, upgrade, refurbish or remanufacture.
- Process design: Develops processes that increase the reuse potential and recyclability of industrial and other products, by-products, and waste streams.
- Circular supplies: Provides input materials such as renewable energy, bio-based, less resource-intensive or fully recyclable materials.

4.3.4.3 Consumers

Circular Use Models

These business models focus on the use phase by optimally using the product and maintaining added value. These business models make it possible to retain ownership of the product (e.g. by servicing a product rather than selling it) and take responsibility for the product throughout its useful life (e.g. through maintenance services or add-ons to extend the life of a product).

Examples of business models in this category include:

- Product-as-a-service: Delivers product performance rather than the product itself through a combination of product and services. Ownership of the product is retained by the service provider.
- Sell and buy-back: Sells a product on the basis that it will be purchased back after a period.
- Sharing Platforms (Access provider): Enables an increased utilization rate of products by enabling or offering shared use, access or ownership.
- Lifetime extension: Extends the useful life of products and components through repair, maintenance, or upgrade.
- Tracing facility: Providing services to facilitate the tracing, the marketing and trade of secondary raw materials.

4.3.4.4 Final objectives

The following actions are going to be promote towards the transition to a circular economy:

- Advance in the **reduction of the use of non-renewable natural resources**, reusing in the production cycle the materials contained in the waste as secondary raw materials if the health of the people and the protection of the environment are guaranteed.
- Promote the **analysis of the life cycle** of the products and the incorporation of eco-design criteria, reducing the introduction of harmful substances in their manufacture, facilitating the reparability of the goods produced, prolonging their useful life and enabling their recovery at the end of this.
- Encourage the **effective application of the principle of hierarchy of waste**, promoting the prevention of its generation, encouraging reuse, strengthening recycling and promoting its traceability.
- Promote guidelines that **increase innovation** and the **overall efficiency of production processes**, through the adoption of measures such as the implementation of environmental management systems.
- Promote innovative forms of **sustainable consumption**, including sustainable products and services, as well as the use of digital infrastructures and services.
- Promote a model of **responsible consumption**, based on the transparency of information on the characteristics of goods and services, their duration and energy efficiency, using measures such as the use of the eco-label.
- Facilitate and promote the creation of adequate channels to facilitate the **exchange of information** and coordination with administrations, the scientific and technological community and economic and social agents, to create synergies that favour the transition.
- Disseminate **the importance of moving from the linear economy towards a circular economy**, promoting the transparency of the processes, the awareness and sensitization of the citizens.
- Encourage the use of **common, transparent, and accessible indicators** that allow knowing the degree of implementation of the circular economy.
- Promote the incorporation of **social and environmental impact indicators** derived from the operation of companies, to evaluate beyond the economic benefits generated in them, because of their commitment to the circular economy.

5 Circular economy and MSW management

5.1 MSW management in a CE

So far, the current economic model of production and consumption remains linear, i.e. resources are extracted, processed, used, and at the end of their life, for the most part, typically disposed of by incineration or landfill. Consequently, materials are withdrawn from circulation and destroyed, even if thermal utilisation does at least produce energy (Hollins et al., 2017). In this regard, municipal solid waste (MSW) management is an important part of the EU's plan for transformation towards a circular economy (CE).

The key challenge in CE is to establish a perception that waste should not be seen as a 'problem' to but as a 'valuable resource'. The fundamental idea is to keep materials and products for as long as possible and as high as possible in the production and consumption system based on "…*sharing, leasing, reuse, repair, refurbishment and recycling, in an (almost) closed loop*…" (Bourguignon, 2016). To achieve that perspective, MSW management in a CE will have to become an integral part of a circular production and consumption model, as shown in Figure 25.

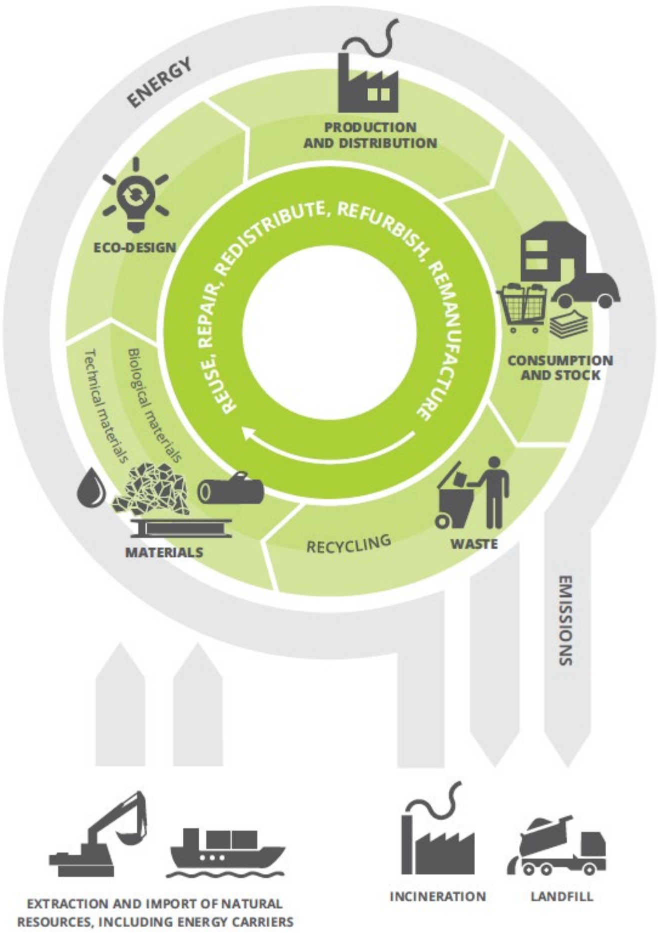


Figure 25: A simplified model of the circular economy for materials and energy (Source: EEA, 2017).

In line with the principles of CE, the foundation of EU waste management, according to the Waste Framework Directive, is the five-step "waste hierarchy", which establishes an order of preference for managing and disposing of waste.

Waste prevention has been established as a priority, with reduction as the top priority, through the waste hierarchy, following by extending the lifetime of valuable resources through re-use, repair, refurbishing or remanufacture is critical to promoting CE. Infrastructural lock-in should be overcome, especially if the demand for energy generation and recycling competes with prioritising re-use, repair and refurbishing (Hollins et al., 2017). However, CE cannot exist without functioning markets for secondary materials, although today virgin materials in many cases are cheaper than the recovered ones (Silva Filho et al., 2021). The introduction of the waste hierarchy shifted waste management from processing large volume, low value materials to low volume, high value materials (Berg et al., 2020).

5.2 Policies and instruments in MSW management towards CE

Building on the work done since 2015, the European Commission adopted a new Circular Economy Action Plan, on March 11, 2020, which includes measures covering the whole cycle, from production and consumption to waste management and the market for secondary raw materials. Regarding waste management, the focus is on avoiding waste altogether and transforming it into a high-quality and well-functioning market for secondary raw materials. In this direction, the Action Plan sets an EU-wide, harmonised model for the separate collection of waste and labelling and puts forward actions to minimise EU exports of waste and tackle illegal shipments.

The Action Plan includes four legislative actions introducing new waste management targets regarding reuse, recycling and landfilling, strengthening provisions on waste prevention and extended producer responsibility, and streamlining definitions, reporting obligations and calculation methods for targets.

The most important and recent legislative acts[13] relating to MSW management and CE are the following:

- COM(2020) 798/3, Proposal for a regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020
- COM/2020/98 final, A new Circular Economy Action Plan For a cleaner and more competitive Europe, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions

[13] It should be pointed out that there exist certain differences between EU Directives, Regulations, Decisions and Recommendations (https://europa.eu/european-union/law/legal-acts_en). Most EU legislation with regard to Circular Economy and MSW consists of Directives and provides much scope for national EU member states to fulfil the target and the speed of implementation by leaving 'transposition' to national legislators.

- Commission Delegated Regulation (EU) 2020/2174 of 19 October 2020 amending Annexes IC, III, IIIA, IV, V, VII and VIII to Regulation (EC) No 1013/2006 of the European Parliament and of the Council on shipments of waste
- Directive 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment
- Directive 2018/852 of the European Parliament and of the Council of 30 May 2018 amending Directive 94/62/EC on packaging and packaging waste
- Directive 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste
- Directive 2018/850 of the European Parliament and of the Council of 30 May 2018 amending Directive 1999/31/EC on the landfill of waste
- Directive 2018/849 of the European Parliament and of the Council of 30 May 2018 amending Directives 2000/53/EC on end-of-life vehicles, 2006/66/EC on batteries and accumulators and waste batteries and accumulators, and 2012/19/EU on waste electrical and electronic equipment
- COM(2017) 34 final, *The role of waste-to-energy in the circular economy*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions

Based on the latest Directives and their amendments, the following timeline has been set:

- Separate collection of bio-waste by 31/12/2023 and of textiles and hazardous waste from households by 1/1/2025
- Preparing for re-use and recycling of municipal waste to a minimum of 55% by weight by 2025, 60% by 2030 and 65% by 2035, respectively
- Recycling of packaging waste to at least 65 % by 31 December 2025 and 70 % by 31/12/2030
- Reducing landfill to a maximum of 10 % of generated municipal waste by 2035
- Ban on landfilling of waste suitable for recycling effective from 2030
- Recycling rate per material by 2025: Plastics: 50%; Wood: 25%; Ferrous metals: 70%; Aluminium: 50%; Glass: 70%; Paper and cardboard: 75%
- Recycling rate per material by 2030: Plastics: 55%, Wood: 30%, Ferrous metals: 80%, Aluminium: 60%, Glass: 75%, Paper and cardboard: 85%
- Separate collection of plastic bottles up to 3 lt, to achieve 90% recycling by 2029 with an interim target of 77% by 2025. These bottles should contain at least 25% recycled plastics as raw material by 2025 (for PET bottles), and 30% by 2030 (for all bottles).

Towards achieving the above-mentioned targets, various instruments are used at European, regional and national levels (Table 1).

Table 1: Policy instruments used at European, regional and national levels to waste management

Policy instrument	**Examples to waste management**
Legislation	Directives and regulations used to: ● set targets for and reporting requirements for individual waste streams ● (e.g. recycling targets and landfill reduction targets)

	• establish extended producer responsibility schemes • establish economic instruments • encourage improved eco-design
Economic incentives	Investment in waste collection infrastructure supported through the Cohesion Fund, funding for R&D and innovation
Market-based instruments	Landfill tax and gate fees, incineration tax and fees, plastic bag taxes; Pay As You Throw (PAYT) schemes
Information requirements	Consumer recycling information on packaging, voluntary reporting of waste production and target setting by companies
Voluntary tools	Awareness raising campaigns for the public, voluntary industry commitments, product design and labelling (e.g. through the EU Ecolabel) provision of good practice information, business led initiatives

For a more detailed analysis, interested readers are referred to BlockWASTE deliverable "O1.A1 - Comparative study of municipal solid waste (MSW) management regulations in each country".

5.3 Digital technologies for a circular MSW management

The transition of the MSW management sector to the CE will undoubtedly require the application of Industry 4.0 technologies, which will complement or, in some cases, replace technologies and processes currently in use (Mastos et al., 2021). Nowadays, various technologies related mainly to the recovery of the material streams are well cited. For example, mechanical sorting technologies, e.g. drum screens, permanent magnetic and electromagnetic eddy current separators, flotation tanks, X-ray and infrared or Near Infrared (NIR) sensors, etc., are used in mechanical biological treatment (MBT) plants for tackling mixed waste in order to separate the technical materials and the biological phase and limit the residual amount left for disposal to landfill. Based on their configuration, MBT plants can provide the required recycling, recovery and biodegradable diversion performance. Similar sorting technologies are used in lightweight packaging and plastic sorting plants. Lightweight packaging plants can sort and classify different types of packaging waste that has been collected as commingled recycling streams and plastic sorting plants can sort different types and grade of plastic polymer (Hollins et al., 2017). Besides separation, there exist well-established recycling technologies for processing and recycling technical materials recycling such as glass, aluminium, steel and even plastic (mainly PET and HDPE). For instance, in the case of plastics mechanical recycling is usually employed, while technologies that are more sophisticated emerge towards removing contaminants and enabling recovered plastic to be converted into food-grade polymers (Hollins et al., 2017). Finally, various technologies are in place to generate value (in a more general sense) from bio-waste, such as anaerobic digestion, composting and valorisation (although many of the technologies for waste valorisation are emerging and are not currently used on a large scale). It should be noted, however, that regardless of the technologies used, the improvement of the CE objectives, both qualitative and quantitative, requires - to a greater or lesser extent - the separate collection of waste streams. This is why the separate collection is emphasised and required by the relevant legislation.

The 4th Industrial Revolution (Industry 4.0) is expected to contribute in many ways to better MSW management in the context of the CE. Berg et al. (2020) identified three main areas of digitalization in MSW management: communication, waste collection and internal processes (Table 2).

Table 2: Main areas of digitalization in MSW management

Communication	Waste collection	Internal processes
Websites	Sensor-equipped vehicles	Billing
Mobile apps	Route planning	Accounting
Integration in other services	Resource planning	Controlling
Third party social media apps	Inventory tracking	Process of orders
	Documentation	Documentation

(Source: Berg et al., 2020)

Berg et al. (2020) argue that the waste industry will be impacted mainly by six digital technologies:

- Robotics: it will allow producing waste streams of high purity and will facilitate the collection process and the logistics involved in waste handling.
- Internet of things (IoT): it will improve logistics via sensor-supported bins and containers, electronic processing of documentation, and networking of waste trucks.
- Cloud computing: It can help in storage and processing of sensor data or software solutions for the management, collection, administration and documentation tasks.
- Artificial intelligence and neural networks: AI and NN can provide solutions in sorting applications through the use of image recognition, autonomous vehicles and sweeping robots, in waste collection optimization, in customer services, in citizen information services, etc.
- Data analytics: it supports disposition of waste collection vehicles, evaluation of sensor data for automated sorting plants, control of waste incineration plants, recording of waste quantities and material flows, etc.
- Distributed ledger technology ("Blockchain"): it will facilitate tracing of material flows and passing on data on materials and products in the supply chain, as a product's lifecycle will be stored in the Blockchain.

Mavropoulos and Nilsen (2020) mention that the digital revolution has already transformed waste management, at least at some extent. For example, over the last few years GPS trackers provide logistic operation with real-time information on waste trucks and containers. Sensors measure the waste amounts within bins and containers, creating new opportunities for route optimisation. Robots, scanners and optical recognition algorithms are finding their way in automated MSW sorting facilities. Newton (2021) points out that Industry 4.0 innovations bring important improvements in the waste management sector by identifying waste sources and patterns, by keeping waste infrastructure in prime condition and by reducing energy consumption among other through IoT sensors and data analytics algorithms. Jamrozik (2019) provides an example from the New York City where IoT-powered bins with real-time monitoring and notifications managed to increase the total trash capacity by nearly 200% and, at the same time, decrease the frequency of collection per bin by 50%.

6 References and sources for further reading and information

6.1 References

Atalia K.R.,Buha D.M., Bhavsar K.A., Shah N.K., (2015). A Review on Composting of Municipal Solid Waste. Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT). e-ISSN: 2319-2402,p- ISSN: 2319-2399.Volume 9, Issue 5 Ver. I (May. 2015), PP 20-29. DOI: 10.9790/2402-095 12029

Berg, H., Sebestyén, J., Bendix, P.p, Le Blevennec, K., Vrancken, K. (2020). Digital waste management, Eionet Report - ETC/WMGE 2020/4, European Topic Centre Waste and Materials in a Green Economy, Mol, Belgium.

Bourguignon, D. (2016). Closing the loop: New circular economy package. European Parliamentary Research Service (EPRS), Briefing to the European Parliament. (https://www.europarl.europa.eu/RegData/etudes/BRIE/2016/573899/EPRS_BRI%282016%29573899_EN.pdf) Accessed 30 September 2021

Caparrós-Pérez D. (2017). Feasibility to generate sustainable territories. Eco-efficient application of materials and construction systems in urban development and rehabilitation.

CEWEP, (2021). Overview of landfill taxes and bans in EU Member States. Available at: https://www.cewep.eu/wp-content/uploads/2021/10/Landfill-taxes-and-bans-overview.pdf

Ciuta, S., Apostol, T. & Rusu, Valentin. (2015). Urban and Rural MSW Stream Characterization for Separate Collection Improvement. Sustainability. 7. 916-931. 10.3390/su7010916. (https://www.researchgate.net/publication/271528610_Urban_and_Rural_MSW_Stream_Characterization_for_Separate_Collection_Improvement) Accessed September 2021.

Davies, S. The Great Horse-Manure Crisis of 1894 | Stephen Davies https://fee.org/articles/the-great-horse-manure-crisis-of-1894/ (accessed Feb 13, 2020)

EC, (2022). Landfill waste. Available at: https://ec.europa.eu/environment/topics/waste-and-recycling/landfill-waste_en

EEA, (2021). Diversion of waste from landfill in Europe. European Environmental Agency. Available at:https://www.eea.europa.eu/ims/diversion-of-waste-from-landfill

EEA, (2022). Waste recycling in Europe. Available at: https://www.eea.europa.eu/ims/waste-recycling-in-europe

EESI, (2017). Fact Sheet Biogas: Converting Waste to Energy. Available at: https://www.eesi.org/papers/view/fact-sheet-biogasconverting-waste-to-energy

EREF, (2022). Introduction to municipal solid waste landfilling. Available at: https://erefdn.org/introduction-municipal-solid-waste-landfilling-2/

Ergene Şentürk, D., & Alp, E. (2016). Planning for the closure of uncontrolled landfills in Turkey to reduce environmental impacts, Waste management & research: the journal of the International Solid Wastes and Public Cleansing Association, ISWA, 34(11), 1173–1183, https://doi.org/10.1177/0734242X16665915.

European Commission COM(2017) 34. The role of waste-to-energy in the circular economy. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52017DC0034&from=EN#footnote17

European Commission, (2022). Waste prevention and management. Available at: https://ec.europa.eu/environment/green-growth/waste-prevention-and-management/index_en.htm

European Environmental Agency (2017). Circular by design. Products in the circular economy. EEA Report No 6/2017, Copenhagen (https://www.eea.europa.eu/publications/circular-by-design) Accessed 29 September 2021

European Union, Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste (https://eur-lex.europa.eu/eli/dir/1999/31/oj)

European Union, Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (Text with EEA relevance) (https://eur-lex.europa.eu/eli/dir/2018/851/oj)

Eurostat (2021). Municipal Waste Statistics. (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Municipal_waste_statistics) Accessed 20 January 2022.

Eurostat (2022). Generation of waste by waste category, hazardousness and NACE Rev. 2 activity(http://appsso.eurostat.ec.europa.eu/nui/show.do?lang=en&dataset=env_wasgen) Accessed 29 January 2022.

Eurostat, (2022). Municipal waste statistics. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Municipal_waste_statistics

Hollins, O., Lee, P., Sims, E., Bertham, O., Symington, H., Bell, N., Pfaltzgraff, L., and Sjögren, P. (2017). Towards a circular economy - Waste management in the EU. European Parliament. (https://www.europarl.europa.eu/RegData/etudes/STUD/2017/581913/EPRS_STU%282017%29581913_EN.pdf) Accessed 29 September 2021

Hunt, R. G., et al., (1990). Estimates of the Volume of MSW and Selected Components in Trash Cans and Landfills. Franklin Associates, Ltd., with The Garbage Project for the Council for Solid Waste Solutions.

Jamrozik, N. (2019). Smart waste management (https://medium.com/@NadJam/smart-waste-management-17db1bd5bc6b#:) Accessed 16 November 2021

Kalyuzhnyi, Sergey & Epov, A & Sormunen, Kai & Kettunen, R & Rintala, Jukka & Privalenko, V & Nozhevnikova, Alla & Pender, S & Colleran, E. (2003). Evaluation of the current status of operating and closed landfills in Russia, Finland and Ireland with regard to water pollution and methane emission. Water science and technology: a journal of the International Association on Water Pollution Research. 48. 37-44 (https://iwaponline.com/wst/article-abstract/48/4/37/10950/Evaluation-of-the-current-status-of-operating-and?redirectedFrom=fulltext).

Kaza S., Yao, L., Perinaz Bhada-Tata, P. and Van Woerden, F. (2018). What a Waste 2.0. A Global Snapshot of Solid Waste Management to 2050. World Bank Group.

(https://openknowledge.worldbank.org/handle/10986/30317) Accessed 15 Septmber 2021.

Klundert, A. van de, Anschutz, J. (2001) Integrated sustainable waste management - the concept. Gouda, 2001, 44 p.

Mastos, T. D., Nizamis, A., Terzi, S., Gkortzis, D., Papadopoulos, A., Tsagkalidis, N., Ioannidis, D., Votis, K. and Tzovaras, D. (2021). Introducing an application of an industry 4.0 solution for circular supply chain management. Journal of Cleaner Production, 300. https://doi.org/10.1016/j.jclepro.2021.126886

Mavropoulos, A., (2015). Wasted Health: the tragic case of dumpsites, ISWA (https://www.researchgate.net/publication/281774422_Wasted_Health_the_tragic_case_of_dumpsites). Accessed 25 January 2022.

Mavropoulos, A. and Nilsen, A.W. (2020). Industry 4.0 and Circular Economy: Towards a Wasteless Future or a Wasteful Planet?. International Solid Waste Association Series, Wiley, New York, pp. 448.

Newton, E. (2021). How Is Industry 4.0 Optimizing the Waste Industry? The IOT Magazine (https://theiotmagazine.com/how-is-industry-4-0-optimizing-the-waste-industry-bfd4d35770f4) Accessed 15 December 2021

Shaoli De, Biswajit Debnath, (2016). Prevalence of Health Hazards Associated with Solid Waste Disposal- A Case Study of Kolkata, India, Procedia Environmental Sciences, Volume 35, pp. 201-208, ISSN 1878-0296, https://doi.org/10.1016/j.proenv.2016.07.081.

Sharma, K.D. and Jain, S. (2020), "Municipal solid waste generation, composition, and management: the global scenario", Social Responsibility Journal, Vol. 16 No. 6, pp. 917-948. https://doi.org/10.1108/SRJ-06-2019-0210

Silva Filho, C. RV, Appelqvist, B. and Woolridge, A. (2021). The future of the waste management sector - trends, opportunities and challenges for the decade 2021-2030. International Sloid Waste Association – ISWA. (https://www.iswa.org/wp-content/uploads/2021/10/ISWA-The-Future-of-Waste-Management-1.pdf) Accessed 15 November 2021

STOA, (2017). Towards a circular economy – Waste management in the EU. Science and Technology Options Assessment. EPRS/European Parliamentary Research Service. 140 pp. doi: 10.2861/978568

Tamiru, A., (2001). The impact of uncontrolled waste disposal on surface water quality in Addis Ababa, Ethiopia, SINET: Ethiopian Journal of Science, Vol. 24 No. 1, https://doi.org/10.4314/sinet.v24i1.18177

Tchobanoglous, G. and Kreith, F. (2002). Handbook of Solid Waste Management. 2nd Edition, McGraw Hill Handbooks. New York.

U.S. Environmental Protection Agency (1998). Characterization of municipal solid waste in the United States: 1997 update, Municipal and Industrial Solid Waste Division Office of Solid Waste, Report No. EPA530-R-98-007.

Vinti G, Bauza V, Clasen T, Medlicott K, Tudor T, Zurbrügg C, Vaccari M., (2021). Municipal Solid Waste Management and Adverse Health Outcomes: A Systematic Review.

International Journal of Environmental Research and Public Health, 18(8):4331. https://doi.org/10.3390/ijerph18084331.

Wagner, Jean-Frank & Rettenberger, G & Reinert, P. (2007). Modern landfill technology – landfill behavior of mechanical- biological pre-treated waste, Proceedings Sardinia 2007, 11th International Waste Management and Landfill Symposium, S. Margherita di Pula, Cagliari, Italy, 1 - 5 October 2007 (https://www.researchgate.net/publication/267996591_MODERN_LANDFILL_TECHNOLOGY_-_LANDFILL_BEHAVIOR_OF_MECHANICAL-_BIOLOGICAL_PRE-TREATED_WASTE).

Warell, W.A. & Vesilind , P.A., (2012). Solid waste engineering second edition. Cengage Learning. ISBN-13: 978-1-4390-6215-9.

Waste Framework Directive, (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098

Zbicinski, I., Stavenuiter, J., Kozlowska, B., van de Coevering, H., (2006). Product design and life cycle assessment. The Baltic University Press © 2006. Printed by Nina Tryckeri, Uppsala 2006. ISBN 91-975526-2-3

Ziraba, A.K., Haregu, T.N. & Mberu, B., (2016). A review and framework for understanding the potential impact of poor solid waste management on health in developing countries. Arch Public Health 74, 55, https://doi.org/10.1186/s13690-016-0166-4.

6.2 Further sources

Videos

Webinar: Introduction to Smart Waste Management | WasteHero: https://www.youtube.com/channel/UCbKk5uAsVfRmkJLOg0DsdxQ

Circular Economy and solid waste management: https://www.youtube.com/watch?v=1UePkisQqJs

Circular Economy in Waste management: https://www.youtube.com/watch?v=fpDrUwd1uq4

Can A Circular Economy Make Trash Obsolete?: https://www.youtube.com/watch?v=JgcWmE_2T6Q

Towards a circular economy - waste management in the EU: https://www.youtube.com/watch?v=8pxM0_uRzbE

Waste management and Circular Economy at POLIMI (Part 1): https://www.youtube.com/watch?v=yQJOkBEJhQc&list=RDCMUCOKtBGblWKlkE-KIf-S0Fvg&start_radio=1&rv=yQJOkBEJhQc&t=36

Waste Management 4.0 and Tech Trends – Waste Metering Powered by AI: https://www.youtube.com/watch?v=H95YRZydijg

Recycling Robots - Companies Turn to Robots to Help Sort Recyclables & Waste - Waste Robotics: https://www.youtube.com/watch?v=QbKA9uNgzYQ

Robotics & AI Innovation Network | Using RAI to support waste management: https://www.youtube.com/watch?v=Yl62S5BU178

Case study: IoT based waste management for Santander smart city: https://www.youtube.com/watch?v=lmk9kMO4MsY

A Novel IOT and AI based Smart Waste Management System: https://www.youtube.com/watch?v=WVWyvcisdlA

Environmental impacts of landfill leachate: https://www.youtube.com/watch?v=QYBvntdO6YM

How does a landfill work?
https://www.youtube.com/watch?v=n8KdoMYYWnE

Learn the Principles of Landfill Gas Generation:

https://www.youtube.com/watch?v=p-CQqXf5N4E

How gases and liquids are drained from landfills: https://www.youtube.com/watch?v=QHWxQgbmo_k

Advantages and Disadvantages of Waste Incineration: https://www.youtube.com/watch?v=6vzcbgBAewU

Impacts and limitations of recycling: https://www.youtube.com/watch?v=1biGAcRIM3I

What a Waste 2.0: Everything You Should Know About Solid Waste Management: https://www.youtube.com/watch?v=1CSm4GG2VrU

Why don't we just burn our trash?:
https://www.youtube.com/watch?v=OPVUrO-_7SM

Video on Waste Hierarchy:

https://www.youtube.com/watch?v=LaT07IeDVR4

Brief introduction to landfills:

https://youtu.be/2Ot2C4FKzts

Organics Decomposition in a Landfill:

https://youtu.be/A2J74wxQ9-4

Landfill leachate:

https://youtu.be/C-j1jGB8CiM

Landfill gas:

https://youtu.be/8z7lbX5CSQo

Waste to Energy – process explanation:

https://youtu.be/DROZUstnsnw

Waste to Energy: Inside the SYSAV Plant in Malmo, Sweden:

https://youtu.be/I8_i1gU3gRg

Waste-To-Energy Pyrolysis Conversion Process:

https://youtu.be/7P5WF53KfdI

Waste to Energy by Advanced Gasification:

https://youtu.be/vVvCEkKxWs0

Lecture "RDF from municipal solid wastes" by Dirk Lechtenberg: https://youtu.be/MwT3lepTFag

Organic waste treatment (18videos) available: https://youtube.com/playlist?list=PLNG_YQG6XtkXxCFHJCy2APfkxYJwsrRrj

Recycling municipal waste:

https://youtu.be/bxF3-wdxUKk

Linear Economy Model:

https://youtu.be/eETqWSDwCh4

Explaining the Circular Economy and How Society Can Re-think Progress | Animated Video Essay: https://youtu.be/zCRKvDyyHmI

Circular Economy: Beyond Recycling:

https://youtu.be/eOgXxTj5kGk

What is a linear economic model?

https://youtu.be/q_6GalOImPc

Defining linear vs circular economy:

https://youtu.be/fF_H07BrJOE

How to move from a linear economy to a circular economy:

https://youtu.be/ECHiWnSvklo

EU policies, legislation and instruments

Circular economy action plan: https://ec.europa.eu/environment/strategy/circular-economy-action-plan_en

Waste and recycling: https://ec.europa.eu/environment/topics/waste-and-recycling_en

Waste Framework Directive: https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-directive_en

Closing the loop - An EU action plan for the Circular Economy COM/2015/0614 final: https://www.eea.europa.eu/policy-documents/com-2015-0614-final

Monitoring Framework for the Circular Economy: https://ec.europa.eu/eurostat/web/circular-economy/indicators/monitoring-framework

European Commission. Commission of European Communities. Communication No. 398, 2014. Towards a Circular Economy: A Zero Waste Programme for Europe; COM no. 398;

European Commission: Brussels, Belgium, 2014. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52014DC0398

European Commission. Commission of European Communities. Communication No. 614, 2015. Closing the Loop—An EU Action Plan for the Circular Economy; COMno. 614; European Commission: Brussels, Belgium, 2015. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614

European Commission. REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS (COM/2017/033 final) - On the implementation of the Circular Economy Action, 2017. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0033&qid=1524125695611

European Commission. Commission of European Communities. Communication No. 29, 2018. Monitoring Framework for the Circular Economy; COM no. 29; European Commission: Brussels, Belgium, 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2018%3A29%3AFIN

European Commission. Commission of European Communities. Communication No. 98, 2020. A New Circular Economy Action Plan for a Cleaner and More Competitive Europe; COM no. 98; European Commission: Brussels, Belgium, 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

European Commission. Waste Law. https://ec.europa.eu/environment/topics/waste-and-recycling/waste-law_en

Study on modelling of the economic and environmental impacts of raw material consumption: https://ec.europa.eu/environment/enveco/resource_efficiency/pdf/RMC.pdf

Books/Papers/Reports

Berg, H., Bendix, P., Jansen, M., Le Blévennec, K., Bottermann, P., Magnus-Melgar, M., Pohjalainen, E. and Wahlström, M. (2021). Unlocking the potential of Industry 4.0 to reduce the environmental impact of production, Eionet Report - - ETC/WMGE 2021/5, European Topic Centre Waste and Materials in a Green Economy, Mol, Belgium. https://www.eionet.europa.eu/etcs/etc-wmge/products/unlocking-the-potential-of-industry-4-0-to-reduce-the-environmental-impact-of-production/@@download/file/Final%20for%20website.pdf

European Environment Agency - EEA (2016). Municipal waste management across European countries. European Environment Agency. https://www.eea.europa.eu/themes/waste/municipal-waste

European Environment Agency (2016). More from less—material resource efficiency in Europe. 2015 overview of policies, instruments and targets in 32 countries, EEA report, no 10/2016. https://www.eea.europa.eu/publications/more-from-less

European Environment Agency - EEA (2020). Waste management. European Environment Agency. https://www.eea.europa.eu/themes/waste/waste-management/waste-management

European Environment Agency - EEA (2020). Recycling of municipal waste. European Environment Agency. https://www.eea.europa.eu/airs/2018/resource-efficiency-and-low-carbon-economy/recycling-of-municipal-waste

European Environmental Bureau – EEB (2018). Towards an EU Product Policy Framework contributing to the Circular Economy. https://eeb.org/publications/79/resource-efficiency/89942/briefing-on-the-eu-product-policy-framework.pdf

ISWA (2019). How Industry 4.0 transforms the waste sector, International Solid Waste Association. https://www.pac.gr/bcm/uploads/ind_4-0_final_compressed_web.pdf

World Business Council for Sustainable Development – WBCSD (2018). LINEAR RISKS. https://docs.wbcsd.org/2018/06/linear_risk_report.pdf

Other sources

https://www.epa.gov/landfills/municipal-solid-waste-landfills#whatis

https://nepis.epa.gov/Exe/ZyNET.exe/2000Q3ZF.txt?ZyActionD=ZyDocument&Client=EPA&Index=1976%20Thru%201980&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5CZYFILES%5CINDEX%20DATA%5C76THRU80%5CTXT%5C00000004%5C2000Q3ZF.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1

https://www.epa.gov/sites/default/files/2021-01/documents/msw_infographic_jan2021-sm.pdf

https://www.eea.europa.eu/soer/2015/countries-comparison/waste

https://datatopics.worldbank.org/what-a-waste/

https://datatopics.worldbank.org/what-a-waste/challenges_to_the_solid_waste_sector.html

https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html

https://www.iswa.org/climate-change-and-waste-management/?v=f214a7d42e0d

https://www.colorado.edu/ecenter/2021/04/15/hidden-damage-landfills

https://www.epa.gov/report-environment/wastes

https://ec.europa.eu/environment/pdf/waste/studies/climate_change_xsum.pdf

https://energsustainsoc.biomedcentral.com/articles/10.1186/s13705-018-0175-y

World Health Organization, (2021). Solid waste. In: Compendium of WHO and other UN guidance on health and environment, Geneva. (https://cdn.who.int/media/docs/default-source/who-compendium-on-health-and-environment/who_compendium_chapter4_v2_01092021.pdf?sfvrsn=b4e99edc_5). Accessed 26 January 2022.

Municipal waste generated in EU countries (kg/capita) in 2005 and 2020 https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Municipal_waste_statistics

https://ec.europa.eu/eurostat/web/waste/policy-context

'Generation Awake' - the European Commission awareness raising campaign on resource efficiency: https://ec.europa.eu/environment/generationawake/index_en.htm

Example of Deposit System in Estonia: https://eestipandipakend.ee/en/how-does-the-deposit-system-work/

Environmental research and education foundation (EREF) - Introduction to Municipal solid waste landfilling: https://erefdn.org/introduction-municipal-solid-waste-landfilling-2/

Eionet Portal - Assessment of waste incineration capacity and waste shipments in Europe: https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/assessment-of-waste-incineration-capacity-and-waste-shipments-in-europe

Springer Link - Status and Opportunities for Energy Recovery from Municipal Solid Waste in Europe: https://link.springer.com/article/10.1007%2Fs12649-018-0297-7

Bio-waste in Europe - https://www.compostnetwork.info/policy/biowaste-in-europe/

The case for increasing recycling: Estimating the potential for recycling in Europe: https://www.eea.europa.eu/publications/the-case-for-increasing-recycling

Limits of recycling 2020: https://trinomics.eu/project/2119-limits-of-recycling/

Integrated Waste Management for a Smart City: https://www.classcentral.com/course/youtube-integrated-waste-management-for-a-smart-city-47757/classroom