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Options for closing the loop for plastic debris

Environmental analysis of beach clean-up and waste treatments

Master's thesis in Industrial Ecology

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Division of Environmental System Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Plastic debris (PD) is one of the biggest pollution problems in the marine environment. Nets, ropes, packaging, and pellets are the most common items that are spread around the world's oceans causing an impact on wildlife and human health, and economic loss. Although mitigation is tantamount, the question remains for what can be done with the plastics that are already in the oceans. We conducted a literature review of research on debris and plastics waste management. Studies as shown that much of the collected marine debris goes to landfilling because it is little-known, diverse, salty, and too dirty for both incineration and recycling. Also, it showed that there is a strong focus on describing the *environmental* problems of marine and plastic debris, and that plastic debris is described in natural science terms that the waste management industry cannot use for determining suitable treatments. In order to better translate beach debris data into *waste management data*, we have collected beach debris from the Swedish West coast and conducted physical and chemical analyses for the characterization of the debris in waste management terms. Based on this data and the literature review, we have identified several recycling options for the PD. To identify environmental pros and cons with the different treatments, we conducted a life cycle assessment (LCA) comparing mechanical, feedstock recycling and energy recovery to establish an appropriate and practical approach towards closing the loop for PD. These treatment options were analysed in the context of two clean-up operations. The analyses suggest that mechanical treatments are not suitable for most plastics (due to they are fragmented, degraded and with a wide range of additives) whereas chemical treatments are suggested as a suitable solution. Feedstock recycling allows the production of raw material, as well as it may have fewer emissions, in comparison with combustion or landfilling which have higher emissions per tonne of PD. Finally, the LCA of two clean-up operations were performed, using the data obtained in the previous processes to see the big picture: observing the ecological benefits of removing this debris, and seeing whether that benefit is juxtaposed according to the recycling option. Although the environmental profits are difficult to quantify, the LCA results suggest that the clean-up process can have a positive impact with both mechanical and feedstock recycling, as long as the operation itself has low emissions (e.g. reducing transport emissions of the volunteers).

Keywords: *Plastic debris, close the loop, recycling options, life cycle assessment, waste management*

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1. INTRODUCTION

1.1 BACKGROUND

Plastic Debris (PD) is one of the biggest pollution problems in the marine environment. Nets, ropes, packaging, and pellets are the most common plastic items that are spread around the world's oceans, causing an impact on wildlife and human health, and economic loss. It has been widely documented that numerous seabirds, turtles, fish and whale species suffer and die from ingestion of plastic particles mistaken for food and from entanglement in plastic items. Not only biota is affected, but also microplastics enter in the food chain creating a threat to human health. Together with the environmental impact, debris causes problems to navigation, producing costly vessel damages. Furthermore, the presence of trash on beaches badly affects the tourism income.

Although marine pollution prevention and cleaning initiatives are spread around the globe, the question remains for what can be done with the plastics that are already in the oceans. It seems that much of the collected marine debris goes to landfilling because it is little-known, diverse, salty and too dirty for both incineration and recycling. But, if waste is just dumped into the land, it causes pollution in the air, water and soil. For this reason, a review of the plastic debris treatments is performed to find a better environmental solution for this waste.

1.2 PURPOSE, SCOPE AND METHOD

This project aims to contribute the knowledge about sustainable solutions for treating the plastic debris after shore-line clean-up. In order to identify appropriate technologies, several aspects need to be known; such as waste quantity and properties, as well as characteristics of available methods for handling this material.

The project is therefore composed of different steps, each one uses different methodologies to provide information for designing appropriate Life Cycle Assessment (LCA) scenarios, and finding the data needed for the LCA calculations.

Firstly, an overview of the plastic debris (PD) problem is performed. This report summarises a literature review of the types, amounts and composition of the plastic debris, as well as the different dimensions of the PD problem. Further, a study on the knowledge and gaps in the literature was peformed, finding that there was a lack of appropriate recycling processes for the plastic debris once they have been collected as well as there was no data on the physical and chemical properties of this waste.

Secondly, with regard to the available methods, another research about plastic waste management was conducted. It has been studied both the recycling methods already on use for general plastic garbage (mechanical, chemical and recovery treatments) and the existing projects executed for marine debris. Similarities and limitations have been analysed of that methods and projects, and some suitable processes are suggested for the debris. Moreover, the physical and chemical properties needed for each method is described in order to know which data is necessary to select an appropriate technology and be able to analyse it with the LCA methodology.

Thirdly, due to the lack of data on the physical and chemical properties of this waste, the beach debris from the Swedish West coast has been collected and analysed to obtain this information. The physical characteristics were done with the naked-eye method with the help of a weight scale and two screens, while the chemical properties were determined with a Thermal Gravimetric Analyzer (TGA).

Finally, knowing that properties, an environmental impact analysis was accomplished to compare different recycling and recovery technologies by means of LCA, following the methodology of the book *The Hitch Hiker´s Guide to LCA* (Bauman & Tillman, 2004). This method was applied to identify environmental advantages and inconveniences of the different options, comparing mechanical treatment, combustion, feedstock recycling and landfill to establish an appropriate and practical approach towards closing the loop of plastic debris.

Additionally, two clean-up operations are also evaluated using the data obtained in the options. The aim of assessing a clean-up operation is to see the big picture: observing the ecological benefits of removing this debris, and seeing whether that benefit is juxtaposed according to the recycling option. One of these collections is an extent of the LCA performed by Lachmann (2016), which took place in the remote archipelago of Svalbard, Norway. And the other one is the Swedish West Coast clean-up performed in this project.

The results have been submitted and accepted for the conference *"Lives and Afterlives of Plastics" (2017)* presentation (Cañete Vela & Baumann, 2017).

1.3 REPORT OUTLINE

This master's thesis consists of seven chapters including this one. The next two chapters, 2 and 3, describe the theory and knowledge basis which the research is based upon – plastic debris problem and plastic recycling. After that literature review, chapter 4 presents the necessary data to perform the LCA, which includes the acquisition of more data not present in the current research, an explanation of the case study and how the data was collected. Chapter 5 provides the LCA for each of the selected solutions. Subsequently, the findings from the case study are discussed in the same chapter. Finally, chapter 6 provides a short discussion and the conclusion is presented in the chapter 7.

2. MARINE PLASTIC LITTER PROBLEM – An overview

Litter disposal and accumulation in the marine environment is one of the fastest-growing threats to the health of the world's oceans (Pham et al., 2014). Marine litter and trash that enter our oceans and waterways, affect the economies and the inhabitants of coastal communities worldwide, threaten wildlife and sensitive aquatic habitats, and impact the quality of life for local inhabitants and visitors (Brink et al., 2009).

The problem is almost ubiquitous around the globe and it has been broadly studied. This chapter summarises a holistic research on the marine litter challenge defining types, amounts and composition of the plastic debris, as well as the different dimensions of the PD problem, namely; environmental, socioeconomic and management. Moreover, it exposes some mismatches in the literature, exposing that there is not a contemplation on what to do with the litter that is already in the oceans.

2.1 MARINE PLASTIC LITTER

2.1.1 MARINE LITTER: DEFINITION

Marine litter (or marine debris) is any persistent, manufactured or processed solid material discarded, disposed of, or abandoned in the marine and coastal environment. Marine litter consists of items that have been made or used by people and deliberately discarded into the sea or rivers or on beaches; brought indirectly to the sea with rivers, sewage, storm water or winds; accidentally lost, including material lost at sea in bad weather; or deliberately left by people on beaches and shores (UNEP, 2005).

Marine litter is mainly composed of synthetic materials including plastic, foamed plastic, metal, glass and rubber, and this litter includes a variety of objects from large to small items. Regarding larger scale, more easily visible items range from cigarette butts and bottle caps, to plastic bags and bottles. There are also bigger objects such as abandoned fishing nets and ropes and lost or ageing buoys. On the contrary, little items can be hardly visible or even invisible to the naked eye. Nano-sized particles from fleece fibres and tyre dust are invisible, while microplastics are just visible (at <5mm), for instance, microbeads in personal care products and lost plastic pellets (see table 2.1).

Table 2 1 Marine litter composition (classified by size).
Source: Adapted from (Brink, Schweitzer, Watkins, & Howe, 2016).

Micro (<5mm) & Nano (<1um)	**Meso (<2.5 cm) & Macro (<1 m)**	**Mega (>1m)**
– Fragmentation of existing (plastic) products – Polystyrene – Plastic from blasting in shipyards – Particulates from waste incineration - Fibres from clothing and pharmaceuticals – Rubber dust from tyre wear – Microbeads from personal care products	– Beverage bottles and cans – Plastic bags – Food & another packaging – Disposable tableware/cutlery – Beer-ties – Fishing lines, floats & buoys – Tyres – Pipes – Balloons and toys – Textiles – Bottle caps – Cigarette filters and butts – Plastic pellets	- Abandoned fishing nets and traps - Ropes - Boats - Plastic films from agriculture - Construction PVC

2.1.2 PLASTICS DEBRIS: MOST COMMON ITEMS

As described above, marine litter consists of a wide range of materials; however, most of these items are plastics. According to UNEP and GRID-Arendal (2016), between 60 and 90 percent of the litter are made up of one or a combination of different plastic polymers. For example, in the North-East Atlantic Ocean, plastic constitutes 80% of the items found on beaches, where plastics and polystyrene items are 82,05% and rubber items are 1,51% (OSPAR, 2014).

Regarding the quantity of plastics debris (PD) found/accumulated in the marine environment, the pioneer study of Eriksen et al. (2014) estimates that there are 5 trillion pieces of plastic in the oceans, with an approximate weight of 250,000 tonnes.

The same study assesses that almost 87% of that mass are large items (75.4% macroplastic <1m, 11.4% mesoplastic <2.5cm) and the rest are microplastics.

Figure 2. 1 Most common plastic items in Marine Debris. Source: (UNEP and GRID-Arendal, 2016)

Table 2.1 shows all the different items that marine debris is composed of. As can be seen, except for some metals products (cans and another packaging), the majority are plastics objects. In fact, among this synthetic material, the most common and abundant plastic items examples include (Brink et al., 2009; Eriksen et al., 2014):

- **Smoking-related wastes** (e.g., cigarette filters, packaging, cigar tips and disposable lighters);
- **Plastics bags** (e.g., shopping bags and bin bags)
- **Fishing-related debris** (e.g., fish/lobster traps, crab pots, bait boxes, fishing lines, lures, nets and floats);
- **Beverage and food packaging-related wastes** (e.g., bottles, cans, lids, food wrappers and containers and disposable cups, plates, straws and utensils);

Plastic is the most common substance and is filling our waters. If nothing is done, as the Ellen Macarthur Foundation (2016) quotes “the ocean is expected to contain 1 tonne of plastic for every 3 tonnes of fish by 2025, and by 2050, more plastics than fish” There are many reasons because it is ubiquitous, from a widespread use of plastics in our daily life to the properties of this material, which is persistent and light.

Plastics items are broadly used on daily basis; computers and mobile phones have a polymer cases, cars and bicycles have parts made of this substance and food are wrap with this material. Indeed, approximately 50 percent of plastics is used for single-use disposable applications, such as packaging and disposable consumer items (Ellen Macarthur Foundation, 2017).

Many objects are made of polymers because its properties make them suitable for the manufacture of a wide range of products. They are strong, lightweight, durable, inexpensive and malleable, therefore can be moulded into solid objects of diverse shapes (Hopewell, Dvorak, & Kosior, 2009). However, at the same time, these properties make plastics easily dispersed being a threat to the environment.

First, this material is easily dispersed by wind and water because of its low density, making it a challenge for waste management to avoid from entering the ocean (Ryan, Moore, van Franeker, & Moloney, 2009). Second, plastics are strong and durable so they can persist in the environment for a long time, possibly for hundreds of years. Finally, this synthetic material deteriorates and fragments due to physical and chemical deterioration as well as the sunlight exposure. This breakdown of larger items results in numerous small plastic fragments (Ellen Macarthur Foundation, 2016).

Due to common uses of plastics, they are easily transported to the marine environment and, once they are in the ocean, persist and fragment, makes plastics hazardous for the aquatic ecosystem. As it will be further developed, plastic debris provokes both environmental impacts including pollution, entanglement and ingestion and socioeconomic impacts such as tourism and shipping losses (Ellen Macarthur Foundation, 2016).

2.1.3 SOURCES: LAND AND SEA-BASED

Marine litter can be linked to human activities. In order to identify its origin, researchers classify debris sources into two categories: ocean -based or land-based, depending on where the debris enters the water (Brink et al., 2009).

The main origin of plastic debris (80%) comes from land-based sources (Jambeck et al., 2015). Some items derive from direct littering (land-based coastal) such as inappropriate or illegal dumping of domestic and industrial rubbish into the sea; public littering by touristic activities in the coast; or microplastics emitted with waste waters from production processes. Other items are carried to the coast from inland (land-based inland) by rivers or are transported by wind or water level changes into the sea. For instance, litter can begin on city streets, public parks or by mismanagement of waste (inadequately covered waste containers or poorly managed waste dumps) (Brink et al., 2009).

Sea-based sources are from ships and ocean activities (merchant ships, ferries and cruise liners, military and research vessel, boats used for recreational purposes, offshore oil and gas platforms, and fishing vessels) (Hammer, Kraak, & Parsons, 2012). One source is the fishing industry which dumps their waste including old gear, fishing nets and ropes, into the ocean (Sheavly & Register, 2007).

The quantity of debris that every year end up in the sea is uncertain; however, some researchers give approximate amounts for the different origins, making a total between 6 and 17 million of tonnes per year. Where land-based coastal debris range from 4.8 to 12.7 million tonnes per annum and land-based inland range 0.75 to 1.1 Mtn/year, sea sources range 0.3 to 3.25 Mtn/year (Jambeck et al., 2015).

As it will be further explained in the point 2.3, identifying the origin of the litter helps to address and to develop appropriate policies and regulations. However, it should be noted that in large ocean areas, many of marine litter cannot be source typed, largely due to the influence of winds, tides and currents which transport, move and degrade the debris once at sea (Brink et al., 2009).

2.1.4 PATHWAYS: FLOWS AND ACCUMULATION

Marine litter originates from different sources but, once the plastics enter into the sea, the problem is the persistence of some forms of litter which may circulate at sea for a long time, floating or sinking to the seabed. EUNOMIA (2016) estimates that most of the marine debris entering the sea ends up accumulating on the sea floor (94%), remaining on the shores (5%), and the water columns (1%), floating or near the ocean surface.

Although the majority of the litter is accumulated on the sea floor, the concentration is estimated to be only 70kg of plastic in each square kilometre of seabed. While the smallest concentration is found in floating debris, with varies from 1 to 18 kg/km^2, at certain mid-ocean locations (recorded in the North Pacific Gyre). In contrast, the highest concentration is on beaches, with an estimated amount of 2.000 kg/km^2 (EUNOMIA, 2016).

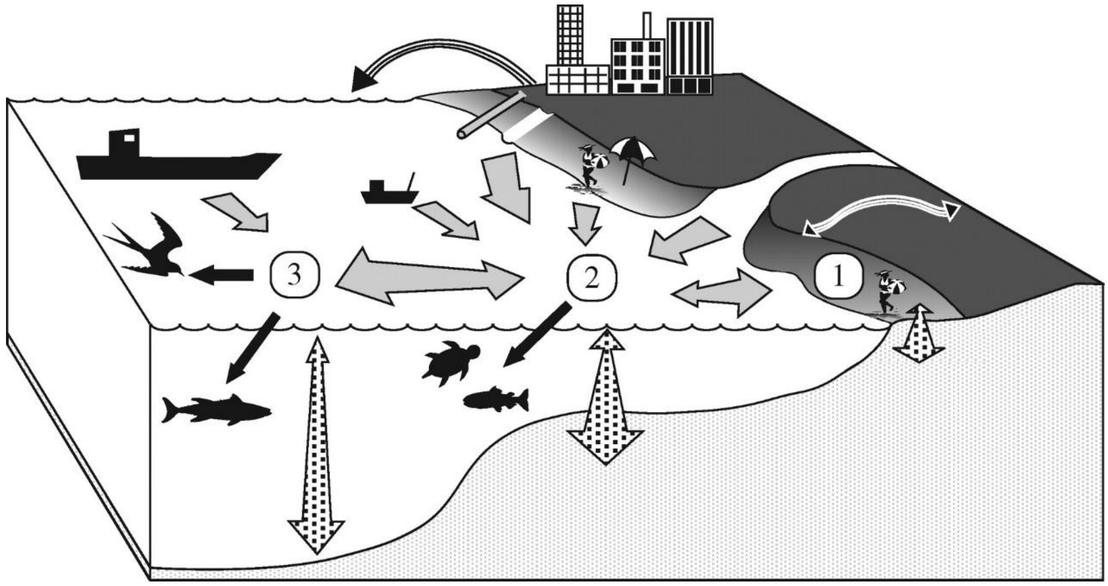

Figure 2. 2 Pathways of plastic debris. Source: (Ryan et al., 2009)

Figure 2.2 represents the flows of plastic debris from the sources to the accumulation areas. First, unidirectional-grey arrows illustrate the two sources of littering into the ocean, sea-based (big and small vessels) and land-based. As explained before, land-based origins can come directly from sewage outfall or beach littering or indirectly transported by rivers or wind, as depict curved arrows. Second, bidirectional grey arrows show the movement of the by water currents from beaches (1) to coastal water (2) and to the open ocean (3), and vice versa. Third, stippled arrows exemplify the vertical movement through the water column, where sometimes is buried in seafloor sediments. Finally, black arrows illustrate ingestion or entanglement by marine organisms (Ryan et al., 2009).

As described above, the produced plastic discards are accumulated in the beaches, floating or are washed to the seabed by water columns. Nevertheless, debris is not only dropped in, some plastics go out of the system by means of collection, decomposition or ingestion by marine organisms (see figure 2.3).

From the figure 2.3, it is important to note that avoiding the discards is necessary for combating marine litter problem. However, stopping the littering today will leave with 250,000 tonnes of plastic accumulated and constantly degrading in the marine environment. For this fact, the thesis's author wants to highlight the need for collection over the other two ways out, due to decomposition can last hundreds of years and ingestion can threat human health and the environment (Iñiguez, Conesa, & Fullana, 2016).

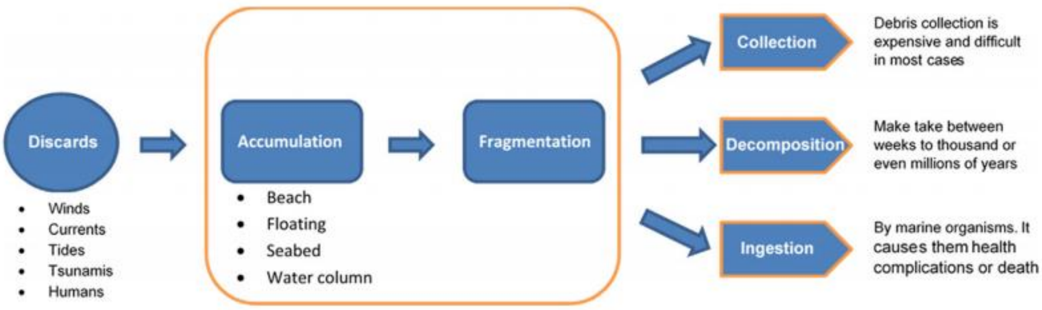

Figure 2.3 Diagram of the marine debris life cycle.
Source: adapted from (Iñiguez et al., 2016)

In fact, debris collection in the coastline can be more efficient because there is a higher concentration of items (2.000 kg/km^2). In addition, there is a back and forward movement of litter between beaches and the sea (represented by bidirectional arrows in figure 2.2). By removing beach litter, we are therefore cleaning the oceans avoiding them to return to the seabed or float again (EUNOMIA, 2016).

2.1.5 MICROPLASTICS AND FRAGMENTATION

Special attention must be given to Microplastics (<5mm) and Nano-plastics since they imply a bigger threat to biota and human health than big plastics. The smaller the items are, the smaller the animal that ingests them. In other words, plastics bioaccumulate in the food chain. Further, the consequences in both human health and ecosystems are unknown (van Cauwenberghe & Janssen, 2014).

On one side, Microplastics originate directly from cosmetic products, clothing or industry. For instance, they can come from wastewater because the microplastics are too small to be filtered out of the water at sewage plants. Also, cosmetics such as toothpaste or facial cleaners where the particles are used for their scrubbing effect as well as fibres from synthetic clothing produced while it is cleaned in the washing machines (Lachmann, 2016; Lachmann, 2016).

On the other side, little plastics derive from the fragmentation of bigger plastic debris. As said before, plastic deteriorates with the exposure of the solar radiation and wave movements. Chemical contaminants such as polychlorinated biphenyls (PCBs) and dioxins are released into the sea during this degradation. Moreover, it is important to highlight that this fragmentation is higher near coastlines where photodegradation and abrasion make plastic debris fragile (Barnes, Galgani, Thompson, & Barlaz, 2009).

As it was introduced before, cleaning the beach is cleaning the ocean too. Moreover, knowing that fragmentation is higher in shorelines, beach clean ups also can help to avoid the production of more microplastics due to this degradation. Equally important, it prevents the tough task of cleaning some microplastics and the pollution and ingestion of them.

2.2 PROBLEM DIMENSIONS OF PLASTIC DEBRIS

Plastic debris causes impact on wildlife, human health and economic loss. This section depicts a brief overview of the impacts that affect the ecosystems and the economy. The aim is to understand the size of the marine litter problem and comprehend why it is necessary to clean this plastic from the marine environment.

Not only PD is an environmental and socioeconomic problem, also it is a waste management trouble. Thus, an overview of the regulatory and management frameworks to address the littering is performed. This study underline that although marine pollution prevention and cleaning initiatives are spread around the globe, there is a lack of information with regards recycling methods. Namely, there is a lack of appropriate recycling processes for the plastic debris once they have been collected, as well as there is no data on the physical and chemical properties of this waste.

2.2.1 AN ENVIRONMENTAL PROBLEM

It has been widely documented that numerous seabirds, turtles, fish and whale species suffer and die from ingestion of plastic particles mistaken for food and from entanglement in plastic items (see table 2.2). Additionally, there are other impacts less understood such as habitat damage and transport of alien species and chemicals.

Table 2. 2 Number and percentage of marine species worldwide with documented entanglement or ingestion records Source: adapted from (European Commission, 2011)

Species group	Total number of species worldwide	Number and % of species with entanglement records	Number and % of species with ingestion records
Sea turtles	7	6 (86%)	6 (86%)
Seabirds *(penguins, grebes, albatrosses, shore birds, etc.)*	312	51 (16%)	111 (36%)
Marine mammals *(whales, seals, sea lions, manatees and sea otter)*	115	32 (28%)	26 (23%)
Fish	-	34	33
Crustaceans	-	8	0
Squid	-	0	1
SPECIES TOTAL		**136**	**177**

At least, 267 different species are known to have suffered from entanglement or ingestion of marine debris (European Commission, 2011). Abandoned or lost fishing gear (nets and ropes), can cause entanglement in seals, turtles and birds. For example, seals entangled with plastic collar-like debris, consequently, the animal cannot feed or breath normally and may cause death. On the contrary, ingestion is mainly produced because of biota mistake the plastic for food. This effect is known as "Ghost fishing" and it can affect many species of fish and invertebrates. A renowned case is the sea turtles which mistake plastic bags for jellyfish (United Nations, 2017).

As said before, other impacts and its effects are less known. For instance, habitat destruction and alien species introduction debris can physically damage shoreline or coral reef. Ropes and nets moved by the tides can destroy fragile aquatic habitats. Also, plastic travels long distances from one end of the world to another and can have attached organisms, transporting them where they can harm or compete with native species as invasive (Sheavly & Register, 2007).

2.2.2 A SOCIOECONOMIC PROBLEM

Marine litter burdens a range of sectors of the economy, notably fishing and aquaculture, tourism and recreation, and shipping (ten Brink, Schweitzer, Watkins, & Howe, 2016). These socioeconomic impacts are a difficult problem to measure, because many pollution problems and biological and environmental effects have taken a long time to identify and quantify (United Nations, 2017).

In the shipping industry, debris can damage the vessel by entanglement in the propellers, causing breakdowns and delays. For instance, in 2008, rescues of vessels with fouled propellers in UK waters were carried out at a cost of between EUR 830,000 and EUR 2,189,000 (Brink et al., 2016).

In the fishing sector, both vessel damage and catch reduction cause prejudicial effects. Catch reduction results from ghost fishing by discarded gear (lost nets in the waterways fish seafood and fishes without anyone profiting from the catches) and mortality related to ingestion of marine litter. For example, the European Union estimates that the fishing fleet causes losses of 61,7 million of euros per year (UNEP and GRID-Arendal, 2016).

Littering also affects tourism and recreation activities. Debris makes shorelines unattractive and potentially hazardous, as well as forces communities and governments to spend funds for beach cleaning (Sheavly & Register, 2007). The OSPAR Commission reported that the beach cleaning cost, for the coast of the United Kingdom, 19.7 M€/year and, in Sweden, debris on beaches reduced the tourism income by 5% (United Nations, 2017).

Finally, a less understood impact is the effect on the human health. Before, it was described that the ingestion of plastic by animals has harmful consequences. Not only biota is affected, but also microplastics can enter the food chain creating a threat to human health. Van Cauwenberghe & Janssen (2014) study estimated that an average European shellfish consumer could ingest up to 11,000 pieces of microplastic per year by eating mussels and oysters. However, the effect that has on our health is unknown (ten Brink, Schweitzer, Watkins, & Howe, 2016).

2.2.3 A WASTE MANAGEMENT PROBLEM

This section aims to give a brief overview of the regulatory and management frameworks to address the littering into the marine environment. Further, it intends to highlight that although marine pollution prevention and cleaning initiatives are spread around the globe, there is a lack of information with regards appropriate recycling methods for the cleaned plastics once they have been collected, as well as there is no data on the physical and chemical properties of this waste.

Numerous policies, international, national and local, address various aspects of marine debris, which can be divided into four categories: preventive, mitigating, removing and behavior-changing (Chen, 2015). (see figure 2.4)

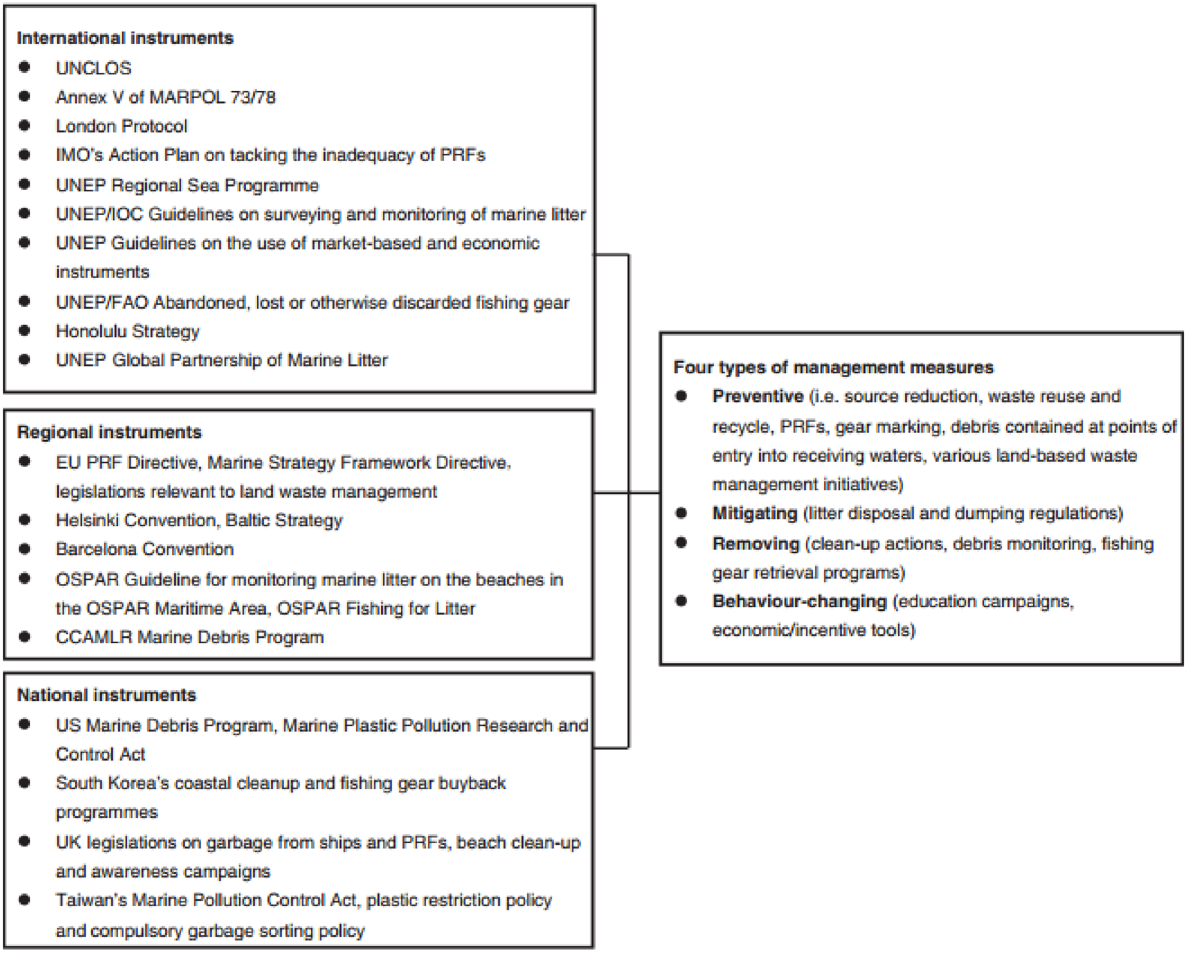

Figure 2. 4 Regulatory and management framework. Source (Chen, 2015)

There are many international instruments for marine debris, but *The Honolulu strategy* and United Nations Environment Programme (UNEP) stand out among the others.

The Honolulu strategy was developed in 2011 by UNEP and NOAA (National Ocean and Atmospheric Administration). As defined on its website: *"*The Honolulu Strategy *is a framework for a comprehensive and global effort to reduce the ecological, human health, and economic impacts of marine debris" (NOAA and UNEP, 2012).*

UNEP is a global authority that develops different plans and actions to address the marine litter problem. One recent initiative was the Global Partnership of Marine Litter (GPML), build on *The Honolulu Strategy* (in 2012). The aim of this partnership is to coordinate national, regional and international stakeholders to work together in an effective way to prevent and manage the marine debris (Chen, 2015).

An example of a regional instrument is the OSPAR Initiative on Monitoring Marine Litter[1]. This program has the objective to monitor marine beach litter in the OSPAR region, the North East Atlantic area, establishing the origin and amount of debris in order to propose preventing and mitigating strategies (Chen, 2015; OSPAR, 2010b).

Regarding national and local plans, many of them include education campaigns and activities raising awareness, such as beach cleaning. Some countries have banned outright the use of certain plastic derivative products (mainly plastic bags). While others are focus on investigating and preventing the adverse impacts of marine debris such as the NOAA Marine Debris Program, in United States (Lippiatt, Opfer, & Arthur, 2013).

All these instruments have in common preventive, mitigating, removing or behaviour-changing plans. However, none of them presents how to deal with the cleaned debris, for example, proposing a suitable recycling method for the collected plastics.

2.2.3.1 Removing and Monitoring Programs

As introduced above, the cleaning process is the last step defined by the instruments to manage marine debris. Together with the litter removing, these plans include monitoring programs that have the purpose to investigate and prevent debris. These programs frequently report quantity of items (or/and weight) per unit length of shoreline (Lippiatt et al., 2013). However, knowing physical and chemical characteristics are essential for selecting a suitable recycling method for plastics debris, but these material characteristics are not given by the monitoring programs.

Table 2.3 shows a comparison of the two most commonly used survey techniques. UNEP and NOAA frameworks define two different Shoreline Survey Methodology for Macro-Debris (size bigger than 2.5 cm). Both are designed to be useable by trained community volunteer organisations while simultaneously providing data to identify the

[1] This initiative was created in 1998 by the OSPAR Convention on the Protection of the Marine Environment of the Baltic Sea Area, also known as Helsinki Convention.

origin of the debris, as either land-based or sea-based (Lippiatt et al., 2013). As can be seen in the table, both techniques count items and record large items separately and, although UNEP also measures the weight, both rely on segregating objects. However, not only many debris items are difficult to identify (making harder the data collection) but also the number of items is insufficient to choose an appropriate technology to manage this waste.

Table 2.3 Comparison Shoreline Survey Methodologies for Macro-Debris. Source: Adapted from (Lippiatt et al., 2013)

	UNEP	***NOAA***
Report item count or weight?	Both	Count only
Minimum debris size	2.5 cm	2.5 cm
Large items recorded separately?	Yes	Yes

Considering regional initiatives, they are usually based on and compatible with UNEP framework (adding more indicators to a better monitoring), such as OSPAR and MARLIN strategies (MARLIN, 2013). Again, they are focus on preventive, mitigate, remove and behaviour changing measures. For example, OSPAR guideline says "The collection of data on marine beach litter provides information on amounts, trends and sources of marine litter. This information can be used to focus on effective mitigating measures and to test the effectiveness of existing legislation and regulations. The ultimate aim is that the amount of litter entering the marine environment is minimised" (OSPAR, 2010a).

As said above, the monitoring methods are compatible with the UNEP programme and the main survey information is (Cheshire & Adler, 2009):

- Beach characteristics (e.g. length, slope, location);
- Type of beach: Urban (i.e. mostly terrestrial inputs) or rural coast (i.e. mostly oceanic inputs);
- Number (and weight) of items (see code classification in table 2.5);
- Additional information of Large items: Status (floating, sunken, stranded, buried).

Table 2. 4 Code classification for plastic debris Source: adapted from (Cheshire & Adler, 2009)

CLASS	MATERIAL COMPOSTION	LITTER CODE	LITTER FORM (and examples)
1	Plastic	PL01	Bottle caps & lids
2	Plastic	PL02	Bottles < 2 L
3	Plastic	PL03	Bottles, drums, jerrycans & buckets > 2 L
4	Plastic	PL04	Knives, forks, spoons, straws, stirrers, (cutlery)
5	Plastic	PL05	Drink package rings, six-pack rings, ring carriers
6	Plastic	PL06	Food containers (fast food, cups, lunch boxes & similar)
7	Plastic	PL07	Plastic bags (opaque & clear)
8	Plastic	PL08	Toys & party poppers
9	Plastic	PL09	Gloves
10	Plastic	PL10	Cigarette lighters
11	Plastic	PL11	Cigarettes, butts & filters
12	Plastic	PL12	Syringes
13	Plastic	PL13	Baskets, crates & trays
14	Plastic	PL14	Plastic buoys
15	Plastic	PL15	Mesh bags (vegetable, oyster nets & mussel bags)
16	Plastic	PL16	Sheeting (tarpaulin or other woven plastic bags, palette wrap)
17	Plastic	PL17	Fishing gear (lures, traps & pots)
18	Plastic	PL18	Monofilament line
19	Plastic	PL19	Rope
20	Plastic	PL20	Fishing net
21	Plastic	PL21	Strapping
22	Plastic	PL22	Fibreglass fragments
23	Plastic	PL23	Resin pellets

Although removing and monitoring are necessary, the information state above is not enough to find the appropriate recycling method. Further data is necessary, for instance; it is unknown whether it is dirty (salty and/or with sand), whether it is humid or whether is degraded. In other words, there is no data of the physical and chemical properties of the marine plastic debris.

2.2.3.2 Plastic Debris as a waste: a challenge

While recycling of post-consumer waste plastics is sometimes a challenge, for the recycling of plastics from the oceans we need to think even harder to find proper process solutions. The main drawbacks of Plastic Debris are the following:

- **Soil content:** Because of PD is normally collected from the marine environment, such as beaches, it is dirty containing sand and organic matter. The drawback high soil content is that it contributes to large amounts of ash when it is combusted, as well as, decreases the efficiency of recycling processes. As a result, sand and organic matter must be washed away before any form of recycling process.

- **Water content:** Again, since it is in the marine environment, it can contain more water than post-consumer plastic waste. Hence, the processes efficiency can drastically decrease, and if the water content in waste is high, drying is needed.
- **Degradation:** As explained before, PD are degraded and fragmented, consequently, it properties can decrease. The problem with degradation is that it leads to reduced material quality in mechanical recycling.
- **Chlorine:** Due to the salt content in the sea water, one concern is the possibility that PD contains high concentrations of Chorine. High content of Chlorine is often a concern for chemical and energy recovery processes, since it may cause corrosion in the furnace and produce persistent organic pollutants (e.g. dioxin) in both techniques. Thus, chlorine also must be washed away before starting any recycling process.

For all this, it is important to know the physical and chemical properties of the marine plastic debris in order to find an appropriate recycling method.

2.3 KNOWLEDGE AND GAPS ON MARINE PLASTIC DEBRIS

Marine litter or plastic debris is almost ubiquitous around the globe and it is one of the most challenging problems to be solved. It varies in its composition and size, origin, pathways and impacts, affecting nature, society and economy.

Although that challenge has been broadly studied, many areas still need a better comprehension and research. What we know, or estimate, can be summarised as following:

- Marine litter (or debris) are plastic, glass and metal items discarded/abandoned in the waterways whose size varies from small particles (nm) to big objects (m).
- Every year, between 6 and 17 million of tonnes enters to the sea which comes from land-based sources (80%) and sea-based origins.

- Most debris are plastics (60-90%) such as plastic bags, fishing gear, beverage and food packaging and smoked-related items.
- Plastics are the most common debris because they are regularly used in our daily basis and persistent, remaining for hundreds of years and fragmenting into smaller and smaller pieces.
- Once the items are in the ocean the 94% end-ups in the sea floor, 5% on shore and 1% in the water columns. The oceans accumulate 250.000 tonnes of PD.
- Seems to be more efficient to clean up the litter on shore, since there is a higher concentration (2.000kg/Km^2), the current makes them ending-up in shorelines over and over, the degradation is higher in that areas, and therefore the fragmentation.
- Plastic debris impacts the marine biota: 267 species suffer entanglement or ingestion, and plastic can spread alien species and destruct habitats.
- Many sectors are affected by littering such as shipping, fishing and touristic industries. Moreover, the impact on the human health is unknown.
- Management measures are focus on preventing, mitigating, removing and creating awareness about marine litter.
- Debris monitoring programs are focus on knowing the items to know the source, in correlation with the management measures.

As can be noted from the summary above, and as described in this chapter, an overview of the marine litter problem is known. However, more research must be done. Reviewing the research papers published in relation with marine litter (see figure 2.5), it can be seen that: First, ingestion and entanglement have been reported since the latest 60s and it is widely known. Second, a lot of research have been developed about amounts and sources, as well as policies. Third, microplastics/chemical and fragmentation drew a recent attention, but still further studies are needed. Finally, it is also visible what it is unknown about the problem. For example, human effects are still unidentified and the economic cost is not quantified.

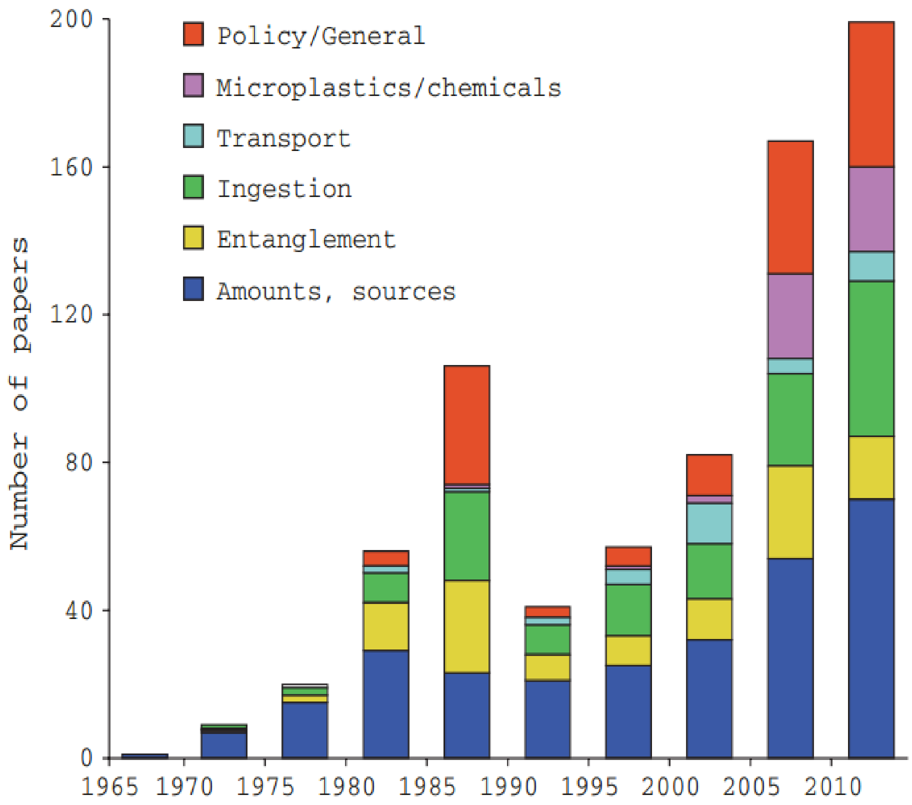

Figure 2. 5 Number of papers published in relation with marine litter. Source: (Ryan, 2015)

Indeed, one **gap** found in the literature is the lack of **appropriate recycling process** for the **plastic debris** once they have been **collected**. Moreover, there is **no data** on the physical and chemical **properties** of this waste, thus, designing a treatment is a tough task. In other words, plastic debris is described by items that waste management industry cannot use for determining suitable treatments.

3. PLASTIC RECYCLING, RECOVERY AND DISPOSAL

The aim of this project is to provide a sustainable solution for treating the plastic debris after they have been cleaned from on-shore. Therefore, to select an appropriate technology, it is necessary to identify existing methods for recycling those plastics. This chapter describes an overview of the techniques, namely; mechanical and chemical recycling, energy recovery and landfilling. Moreover, it describes the criteria considered for selection of technologies such as physical and chemical properties of the waste input, efficiency and availability of the process, and air and water emissions.

In relation with plastic debris, a description of existing projects that recycle debris is presented. Further, the benefits and limitations of these recycling projects are analysed from a technical process perspective. Finally, different suitable options are selected to analyse them by means of the LCA method in the following chapters.

3.1 PLASTIC WASTE TREATMENTS

Plastic Waste (PW) treatments can be allocated to four categories: mechanical and chemical recycling, energy recovery and disposal (see Figure 3.1). Each method provides different benefits and drawbacks which make it particularly beneficial for specific locations, applications or requirements. For instance, mechanical and chemical recycling produce recycled plastics or chemical compounds that can be used again to do new products; and energy recovery generates electricity and heat. In these methods, a portion of the resources is recovered. On the contrary, the disposal drawback from a sustainability aspect is that none the resources are recuperated.

Mechanical reprocessing into a product can be divided in primary and secondary recycling. In primary recycling, also called closed-loop recycling, the product obtained has equivalent properties to material recycled. By contrast, in secondary recycling, or downgrading, the material obtain has lower properties (Hopewell et al., 2009).

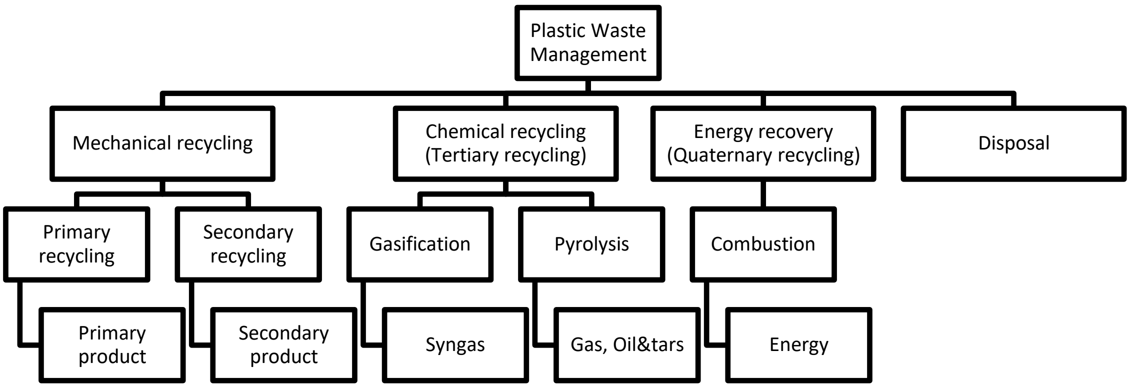

Figure 3. 1 Diagram Plastic Waste Management technologies.
Source: adapted from (Panda, Singh, & Mishra, 2010)

Chemical (or feedstock, or tertiary) recycling are advanced technology processes which break down plastic polymers into their constituent monomers, that are suitable for being used as a feedstock for manufacturing of new petrochemicals and plastics. Gasification and pyrolysis are two of these methods that have been researched extensively. The main differences are that gasification produces synthetic gas fuel and inerts, while pyrolysis generates synthetic gas, liquid or solid fuel (European Commission, 2011; Panda et al., 2010).

Energy recovery (valorisation, or quaternary recycling) involves combustion of the material producing heat, power and/or gaseous fuels, oils and chars besides by-products that must be disposed of, such as ash (Panda et al., 2010).

Disposal or landfilling consists on storing the waste to assure and control that pollutants do not enter into the environment. However, as said before, any product or good is obtained with this method.

All these methods provide different benefits and drawbacks which make it particularly beneficial for specific applications or requirements. In the following sections, a wider description is performed for each technology.

3.1.1 MECHANICAL RECYCLING

Mechanical recycling of plastics refers to processes which involve the reprocessing of plastic by melting, shredding or granulation (European Commission, 2011; Hopewell et al., 2009). As said before, primary recycling generates a product that has equivalent properties to material recycled, and in secondary recycling, the material obtained has lower properties (Hopewell et al., 2009).

Primary recycling is most practical when the polymer constituent can be effectively separated from the sources of contamination. Further, plastic waste stream for reprocessing would also consist of a narrow range of polymer grades to reduce the difficulty of replacing virgin resin directly (Hopewell et al., 2009). For example, the most used primary recycling is re-extrusion in plastic products production industries, which consists of re-introducing scrap or single-polymer edges again to the extrusion to make products of similar material (Al-Salem, Lettieri, & Baeyens, 2009).

However, it is only feasible with semi-clean scrap, therefore it is not popular among post-consumer PW recyclers, which is most of the time contaminated and it is only suitable for some products. For instance, PET bottles are made from similar grades, as a result, it is suitable for both the bottle manufacturing process and reprocessing to polyester fibre. On the contrary, HDPE used for blowing moulding bottles is less-suited to injection moulding applications. That is to say, the only parts of the post-consumer plastic waste stream that have routinely been recycled in a strictly closed-loop/primary recycling are clear PET bottles (Al-Salem, Lettieri, & Baeyens, 2010; Hopewell et al., 2009).

For this reason, secondary recycling is more frequent for Plastic Solid Waste (PSW). This method has been used on single-polymer plastic (e.g. PET, PE, PP, PS, PA). Table 3.1 summarises polymer’s mechanical recycling. It shows if it is currently possible to use this type of treatment for each plastic, as well as the effectiveness of these processes and its restrictions such as a limited type of products/items that can be used for, if additives or virgin material are needed or contamination problems.

Polymer	Mechanical recycling	Effectiveness in current recycling processes
PET	Yes	high with clear PET from bottles coloured PET is mostly used for fibre.
HDPE	some	high with natural HDPE bottles (when material is well specified), but more complex for opaque bottles and trays because of a wide variety of grades and colour and mixtures with LDPE and PP
PVC	some	poor recovery because of cross-contamination with PET plastics recycling packages. Moreover, it is also difficult due to the variety of materials and additives.
LDPE	some	poor recovery rates, mostly as mixed polyolefins that can have sufficient properties for some applications. Most post-consumer flexible packaging not recovered because it is often sensitive to contaminants leading to downgraded products
PP	in theory	not widely recycled yet from postconsumer, but has potential. Needs action on sorting and separation, plus development of further outlets for recycled PP. Normally stabilisers and antioxidants need to be added, and mixed with virgin material.
PS	in theory	poor extremely difficult to cost-effectively separate from comingled collection, separate collection of industrial packaging and EPS foam can be effectively recycled plastics but they are expensive to collect and reprocess
PA	some	For PA 6 and PA66 mechanical and chemical recycling is possible. There is a very little reduction in mechanical properties when recycled PA is blended with virgin PA and reprocessed.

Table 3. 1 Mechanical recycling of plastics.
Source: adapted from (Hopewell et al., 2009)

Although single-stream plastic can be recycled, it is difficult to recycle mechanically contaminated plastics. When the plastic is mixed, it is necessary to do separation, washing and preparation of the PSW (Al-Salem et al., 2010). These physical transformations are essential to produce a clean and homogeneous product in order to be mechanically recycled. Moreover, it is important to highlight that physical treatments are not only necessary for mechanical recycling, but also for the preparation of the waste for others recycling routes (namely: feedstock, energy recovery and disposal).

Even when the plastics are treated, not all the plastics are suitable for material recycling (e.g. some thermosets). Additionally, one of the main inconveniences of mechanical recycling is degradation, since plastics can undertake material recycling only limited number of times. Hence, every time it is recycled the plastic, it has lower quality grade and standard. When this situation occurs, options are either downgrading to plastic lumber (mainly used for outdoor/garden furniture) or feedstock recycling which is recommended if there are restrictions preventing direct recirculation of material (Al-Salem et al., 2010).

3.1.2 CHEMICAL RECYCLING

Chemical or feedstock recycling transforms plastic polymers into their constituent monomers, producing raw material for manufacturing of new petrochemicals and/or plastics. As said before, wide-study methods are gasification and pyrolysis which has the aim to maximise waste conversion to high heating valued gases and maximise thermal decomposition of waste to gases and oils (Arena, 2012).

Gasification consist of the partial oxidation of the waste in presence of air deficit, or another oxidant. As a result of this reaction, synthetic gas is produced (H_2, CH_4 and CO), which can be used either as chemical feedstock, or as a fuel to produce energy in the same facility (see figure 3.2). Also, it is generated vitreous slag that can be used in road construction as a backfilling material (Arena, 2012; Hopewell et al., 2009; ISWA and UNEP, 2015; ISWA and UNEP, 2015)

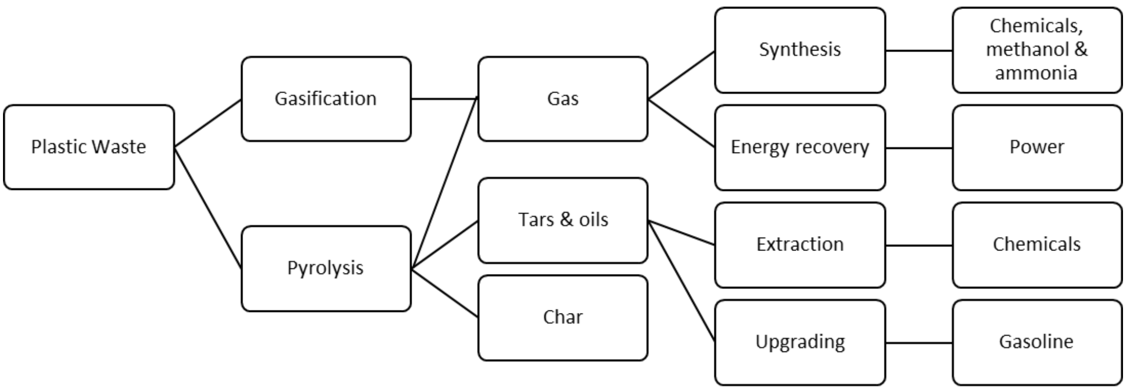

Figure 3. 2 Gasification and pyrolysis products

Pyrolysis consists of a thermal degradation in absence of oxygen (or another oxidant) which generates gas, tars and oils, and char (see figure 3.2). Similar to gasification, the gas formed can be utilised for chemical or energy production. Moreover, tars and oils can be converted into useful products such as chemicals and gasoline (by means of extraction and upgrading, respectively). On the contrary, char must be treated and disposed as a special waste.

Both chemical recycling technologies, not only produce feedstock, but they also reduce the volume of the waste (90%), therefore less landfilling space is needed. Another advantage is the possibility of treating heterogeneous and contaminated polymers with limited use of pre-treatment. Additionally, compared to energy recovery, they have potentially lower emissions of pollutants.

Thus, chemical recycling can be a suitable solution for plastic recycling because it can treat mixed materials, produces feedstock and fewer emissions and requires less space in landfill. Nevertheless, these techniques are under development and, although there are a number of pilot, demonstration, and commercial plants processing various types of plastic wastes, these techniques are not established yet.

3.1.3 ENERGY RECOVERY

Energy recovery is a well-known process that consists of a controlled combustion of waste to produce energy: heat, steam and electricity. Similar to chemical recycling, incineration also involves the 90-95% volume reduction of the waste, reducing disposal, and accepts versatile feedstock such as mixed plastic waste.

Indeed, plastics is a convenient energy source due to its high calorific value. Moreover, incineration allows the destruction of foams and granules resulting from PSW, and also destroys CFCs and other harmful agents present (Al-Salem et al., 2010).

However, some environmental concerns are associated with combustion, mainly emission of certain air pollutants such as CO_2, NO_x and SO_x. The combustion of PSW is also known to generate volatile organic compounds (VOCs), particulates, heavy metals, toxic compounds (PAHs, PCDFs), and dioxins (Al-Salem et al., 2009). As a result, a high pollution control is necessary, driving costs up.

3.1.4 DISPOSAL

Disposal consists of the storage of the waste into a landfill and, when it is controlled, the waste is confined in cells which are capped and isolated from the environment to avoid air and water emissions (European Commission, 2011). For instance, releases from landfills can occur from gas and leachate production, but also by erosion, surface run-off and transport via flora and fauna.

Although a well-managed landfill restricts environmental impacts, there are long-term risks of contamination of soils and waters by some additives and breakdown of by-products in plastics, which can become persistent organic pollutants (Hopewell et al., 2009). Different types of barriers around the landfilled materials are used, but barriers may not last forever. Therefore, ground water testing for waste leaks and post landfill closure care is essential for an adequate management of the site. As a result, an appropriate landfill space is becoming both scarce and expensive.

Possible long-term emissions may be even higher for plastics due to the slow degradability. Since only about 1-3% of the hydrocarbon content can be degraded during a period of 100 years in a landfill (Arena, 2012). Moreover, waste plastics have a high volume to weight ratio, requiring more space than other materials. Finally, another disposal drawback from a sustainability aspect is that none of the resources is recuperated.

To sum up, disposal has the risk of emissions in long-term, is scarce and expensive, and no material is recovered. Additionally, plastics need more space and last longer. Therefore, material or energy recovery treatments should be preferred as an alternative for plastic waste management to replace disposal.

3.2 PLASTIC DEBRIS RECYCLING: EXITING PROJECTS

There are several projects that use Plastic Debris as a raw material to produce new products. However, the range of items that they recycle are limited mainly to bottles (of PET or HDPE) and nets made of Nylon, and only one project uses mix plastic debris. Moreover, all of them need virgin or recycled material to achieve the quality standards.

In this section, a summary of all the projects found is described and divided into the types of items and materials they use: PET bottles, HDPE bottles, Nylon nets and mix plastic debris. Finally, the pros and cons of these processes are compared and analysed.

3.3.1 PET BOTTLES

Ocean plastics can be valuable sources for business opportunities. Many projects are currently making products out of PET bottles, contributing to address the plastics waste problem and to create the circular supply chains. These products can vary from clothes and shoes to packaging and boats.

Parley foundation helped to the creation of two partnerships between the fashion companies G-Star Raw and Adidas Group with the fibre producer Bionic Yarn. G-Star Raw and Bionic Yarn partners state that have recycled around 700,000 PET bottles into yarn for denim clothes. The other partner, Adidas, designed sports clothing and shoes also made of PET bottles. Indeed, the Adidas Parley running shoes use plastic debris from the clean-up operations in the Maldives and it uses around 80.000 PET bottles, which are 95% plastic debris and 5% recycled PET (Brink et al., 2016).

The company Bionic Yarn produces the yarn for these clothing which use a simple procedure: the bottles are collected, shredded, melted and turned into yarn. It produces 3 types of yarns (HLX, DPX and FLX) where only one is completely made of the new PET, the other two only the core is of this polymer ("Bionic website", 2017).

Although this process has transformed about 7 million plastic bottles pulled from shorelines, it is important to consider the degradation of the plastic debris in the marine environment. As Pharrell Williams, of the Parley nonprofit, explains in an interview “the longer the plastic has been in the ocean the more degraded it is. In cases where the ocean plastic is heavily degraded, we blend it with land-based recycled plastic to balance out the quality” (Brian Clark Howard, 2014).

As said before, ocean PET bottles are not only used for clothing, also packaging and boats are made of this material. For example, the company ECOVER use a 10% of PET bottles to do new food packaging (Jennifer Elks, 2013). Regarding the boat’s production, Plastic Whale is a non-profit that pursues to create awareness about the marine litter problem, and use plastic bottles fished in the Amsterdam canals to produce boats that will be employed to collect more plastics ("Plastic Whale Project", 2017).

3.3.2 HDPE BOTTLES

Dell Packaging is currently making products out of HDPE plastic debris. Dell stated that their leading technology could manufacture the packaging trays of laptops with 25 percent recycled ocean plastic content, from bottles and food storage containers, and 75 percent other recycled HDPE plastics (Hardcastle).

This company is producing trays made of this HDPE, which manufacturing process is straightforward. Firstly, ocean plastics are intercepted by Dell’s partners at the source in waterways, shorelines and beaches before it enters the ocean. Then, those plastics (25% ocean plastics mixed with other 75% HDPE plastics) are processed and refined. Finally, the plastic flakes are moulded to new packaging trays until final shipment and delivery. This pilot program from Dell is estimated to prevent 7,000 kg of plastic from entering the ocean (Hardcastle).

Another example to illustrate the circular economy from recycled ocean and HDPE plastics is the world’s first recyclable shampoo bottle made by Procter & Gamble, in partnership with recycling and environmental management companies TerraCycle and

Suez. Those shampoo bottles are also made from up to 25 percent recycled beach plastic (DELL).

However, the recycling percentage remains to be a challenge. As it can be seen, both companies use only up to 25% ocean plastic, because those plastics are degraded as well as they contain additives. Therefore, only a certain ratio mix (in this case 25%) could ensure the quality or chemical composition of the end plastic reaches the standard (DELL).

3.3.3 NYLON NETS

The company Aquafil collects nylon nets to produce a raw material, called Econyl® yarn, used to create new products such as clothes, swimwear and carpets (Aquafil S.p.A., 2016). The process to manufacture this new material consist of three steps: Nylon waste rescue; storage preparation, depolymerization and polymerization; and transformation and commercialization of the yarns (Aquafil).

First, the "Worldwide PA6 waste rescue" consists of different initiatives and projects that collect Nylon 6 from pre-consumer (namely; industrial plastic waste, yarn discards and fabrics scraps) and post-consumer such as spent Nylon carpets and fishing nets. That nets can be spent fish farming nets or ghost fishing nets. The ghost fishing nets are plastic debris recovered from the bottom of the seas in Belgium, the Netherlands, Italy, Greece and Croatia, by the initiative *The Healthy Seas* (Aquafil).

It is important to notice that the post-consumer waste is the 50% of the input, thus, the plastic debris content will be less than that. Moreover, the company states that the waste should contain a high percentage of Nylon 6. That is to say, the type and quantity of debris that enter into the process are limited (Aquafil).

Second, after the waste is collected, it is shipped to Slovenia where is storage and prepared. Nets and carpets are cleaned from organic material, other plastics and metals, and the final nylon is shredded compacted and transported to the next plant. In that plant, the depolymerization process takes place, which is the core of the system.

It transforms the waste into caprolactam which is transformed in new Nylon in the polymerization plant.

Finally, the PA6 polymers are processed into carpet flooring yarn and yarns for textiles. Subsequently, these products are sold to customers to produce new goods. For example, two partnerships which use Econyl® to make new products are Adidas Parley which produces swimming suits, and Interface that manufacture carpets.

Another important point to observe is the life cycle of the process. As can be seen in Figure 3.1, the production of yarn from virgin material consists of Oil extraction, oil processing, caprolactam production, polymerization and yarn production. On the contrary, the Econyl yarn does not need oil extraction and processing by using waste. Therefore, the company states that a 58% of the emissions are avoided (Aquafil S.p.A., 2016).

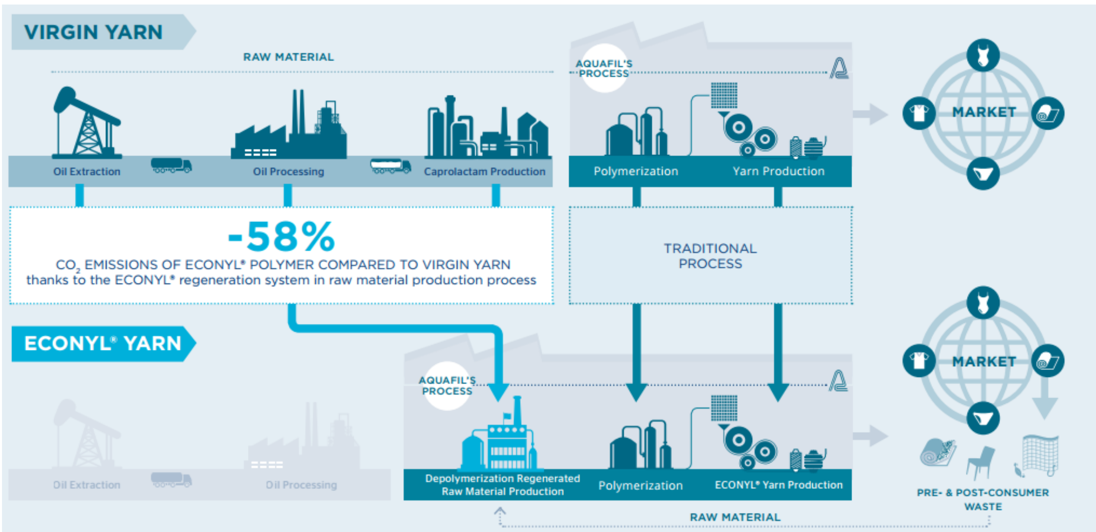

Figure 3.1 Life cycle comparison of the Econyl yarn with the conventional process. Source: (Aquafil)

3.3.4 MIXED PLASTIC DEBRIS

In relation to projects that use mixed plastic debris, only one operating project was found. The company Newtecpoly developed a new technology plastic collected from the beach to do outdoor furniture. The firm states that can handle hard and soft contaminated plastics and, that its process use 100% of plastic debris as a raw material.

The process consists of mixing, melting and delivering molten plastic that is used to manually manufacture raised garden beds and benches.

3.3.5 COMPARISON

As commented at the beginning of this section, the plastic items use is limited by four types of debris: PET and HDPE bottles, HDPE food packaging and Nylon nets. Moreover, all of them need virgin or recycled material to achieve the quality standards. Only one project (NewtecPoly) is able to produce new goods with 100% of mix plastic litter (see table 3.3).

Project	**G-star**	**Plastic Whale**	**Ecover**	**Adidas 1**	**Adidas 2**	**Interface**	**Procter & Gamble**	**Dell**	**NewtecPoly**
Material (PD)	PET bottles	PET bottles	PET bottles	PET bottles	Nylon nets	Nylon nets	HDPE bottles	HDPE bottles & food pack	Mix PD/all
% Plastic debris	95% PD + 5% rPET	n.a.	10%	95% PD 5% rPET	<50%	<50%	25%	25% PD 75% rHDPE	100%
Process	Bionic Yarm	n.a.	Closed Loop Recycling	Bionic Yarm	Econyl	Econyl	n.a.	Teracycle & SUEZ	Mix + melt
Products	Denim clothes	Boats	Food pack.	Shoes and clothes	Clothes	Carpets	Shampoo bottles	Laptop cases	Furniture

Table 3. 2 Projects that use PD as a raw material

The most common employed debris is PET bottles, because of these bottles are made from similar grades of PET making suitable reprocessing them (as explained before in this chapter). Also, Bionic Yarn is able to use post-consumer (rPET) to compensate the low quality of the debris. That is to say, even though a better material is needed, the process is fed only with waste. Closing the loop of at least this type of items.

Regarding HDPE bottles, a close loop process is also possible (Dell). However, fewer projects are available and only a 25% of debris can be used to ensure the quality, due to the heterogeneity of the products made with this material.

The company NewtecPoly achieved to make new furniture with mix and dirty plastic debris. Indeed, when the other recycling options are not available, that seems to be the best option.

The recycling process of these plastics is mechanical methods. On the contrary, Econyl company performs a chemical process by using pre- and post-consumer nets and carpets as a feedstock to produce new yarn. Once more, only less than 50% is lost ocean nets. Further, the company states that the waste should contain a high percentage of Nylon 6 in order to be feed in this process.

To sum up, with exception of the NewtecPoly, all the project use good/pleasant plastic debris, like complete/intact bottles or big nets and they need virgin (or other post-consumer waste) in order to achieve a good quality. Moreover, there are only a few processes which some companies share (e.g. Econyl and Bionic Yarn). In other words, it is a limited recycling methods available for plastic debris and mainly use pleasant debris.

3.3 TECHNICAL CONSIDERATIONS FOR SELECTING AN APPROPRIATE TREATMENT

Selection of an appropriate recycling or recovery technology is fundamental for closing the loop for plastic debris. Thus, not only resource recovery must be taken into consideration, but also the environmental impact.

In section 3.1, treatment options were explained as well as the material recovery and possible impacts of each one. Additionally, significant criteria to select among these methods is the waste characteristics such as chemical and physical properties, composition and contaminants. Both, treatments description and the required waste for each method are summarised in table 3.2.

Noticeably, the performances of the treatments are related to the properties of the plastic waste. Mechanical recycling requires mainly physical properties in order to design the process. Additionally, the composition of the waste is also necessary to know, for example, if recycling of PET bottles is wanted; first, the particle size is a prerequisite to choosing a screen to sort different fractions such as fines, films and packaging. Once packaging is sorted, it is necessary to know the items that this fraction has (e.g. PET bottles, PE food packaging, etc.) to separate PET from the others.

Although the physical properties are needed in chemical recycling and energy recovery for the pre-treatment, the most important characteristics are the chemical ones, namely; elemental composition, proximate analysis and energy content (Arena, 2011). These aspects assist for determining the outputs of that processes. For instance, for gasification, the proximate analysis informs about the volatile matter which determines how much gas will be produced.

Moreover, the detailed composition of the waste may be critical with respect to the emissions from the chemical and energy recovery facilities (Panda et al., 2010). Contaminants, such as chlorine, sulphur and others, are essential to know the air and water releases to the environment.

Finally, also the elements' content is required for knowing possible emissions in landfilling, as well as some physical properties such as density (to know the space needed), and permeability and field capacity (to know the leachate production).

To sum up, the properties of the waste, together with the process characteristics and efficiencies determine the outputs of the process (such as new plastics or chemicals) and the possible air and water emissions. Hence, this information is a prerequisite to select an appropriate technology, from sustainable and operational perspectives.

Recycling method	Mechanical recycling	Feedstock recycling		Energy recovery	Landfilling
		Gasification	*Pyrolysis*		
Description	Reprocessing of plastic by melting, shredding or granulation.	Partial oxidation of the wastes in the presence of air deficit (or another oxidant).	Thermal degradation in the complete absence of air or another oxidizing agent.	Direct combustion of waste in the presence of excess air (oxygen) to recover the energy content of the waste.	Waste confined in cells which are capped and isolated from the environment to avoid emissions
Waste input	Mixed MSW or after source separation of dry recyclables ('residual MSW').	Prepared waste. More suitable for treating the RDF or SRF produced by MBT rather than MSW. Also, applicable to a range of other relatively homogeneous organic waste and plastic waste.		Mixed MSW, PW or prepared fuel (RDF). Versatile feedstocks, if they are combustible.	Indifferent (non-toxic)
Outputs	Depending on plant type	Synthetic gas (syngas). Further combustion or conversion to chemical feedstock.	Liquid fuel products. Further combustion or conversion to chemical feedstock.	Heat only, electricity only, or both. Secondary products: *Fly ash Bottom ash*	None
Volume reduction	Variable, depend on plant	90%	90%	90-95%	-
Conditions	Market needed for outputs.	Market needed for electricity /heat or synthetic gas.	Market needed for electricity/heat or liquid fuels.	Market needed for electricity /hot water. Cold climate with heat demand.	-
Pollution	Low pollution control.	Medium pollution control. Potentially lower emissions of pollutants.	Medium pollution control.	High pollution control	High pollution control
Technology development	Very widespread in Europe	Interest in Europe for small/ medium scale.	Not widely established for MSW or PW.	Widely applied, with an established track record in Europe, Japan, the PRC and the US.	Widely applied, taxes and conditions increasing.
Required waste physical properties	Specific weight (density) Particle size and distribution	Specific weight (density) Moisture content Particle size and distribution	Specific weight (density) Moisture content Particle size and distribution	Specific weight (density) Moisture content Particle size and distribution	Specific weight Field capacity Permeability of compacted waste
Required waste chemical properties	Variable	Proximate analysis Energy content Ultimate analysis	Proximate analysis Energy content Ultimate analysis	Proximate analysis Energy content Ultimate analysis	Ultimate analysis

Table 3.3 Comparison plastic waste treatments. Source: adapted from (World Waste Outlook, 2016)

3.4 TOWARDS IDENTIFICATION OF LCA OPTIONS FOR PD TREATMENT

As said before, the aim is to find a suitable method to treat plastic debris, as well as analysing the environmental implications. For this reason, in this chapter, the different recycling options for plastics have been described together with the properties required for selecting the method and existing projects that recycle PD.

The treatments defined were mechanical and chemical recycling, energy recovery and disposal. As mention above, each method provides different benefits and drawbacks which make them beneficial for applications. First, mechanical techniques generate new products which similar or lower properties, but requires a sorted and clean material. Second, chemical and energy recovery technologies can produce new chemicals or energy and allow mixed and dirty inputs. Finally, disposal should be employed only when the other options are not available, because no resource is recovered and can have long-term emissions.

Regarding the properties of the waste, in chapter 2 it was noticed that Plastic debris is normally only defined by items and this information is not enough to select a suitable method. Thus, the required properties (chemical and physical) for each of the recycling options were demarcated. Additionally, knowing the characteristics needed for choosing the technology, an analysis of a debris sample was performed (see section 4.2) to fulfil the lack of information of this material.

Existing projects were also analysed, and it was noticed that there are some limitations. Only a few items are recycled, PET, HDPE bottles and Nylon nets, and it is always needed virgin material. Moreover, no chemical treatments were found. Conversely, a promising project has developed a process to treat mixed plastic debris to produce plastic lumber, which can be used as outdoor furniture.

To conclude, knowing the recycling options, as well as the limitations of the existing projects enables the selection of appropriate treatment techniques. Further, the plastic debris properties influence in the process of choosing one technique or another (these characteristics are shown in next chapter). In other words, finding a suitable method to treat plastic debris is now possible since both its properties and recycling options are known. Indeed, the options selected to be comparated by means of the LCA study are: **Disposal** (baseline scenario), **Energy recovery** (Option 1), **Feedstock recycling** (Option 2) and **Mechanical recylcing** (Option 3).

4. PLASTIC DEBRIS CHARACTERISTICS

In the previous chapters, it was exposed that monitoring programs report the plastic debris by items and this data is not enough to find a suitable recycling method (chapter 1), as well as which characteristics are necessary to establish an appropriate treatment (chapter 2).

In this part of the thesis, a deeper analysis of the existing data about the composition of plastics is performed. Subsequently, since there was no data about the physical and chemical properties of this waste, the beach debris from the Swedish West coast was collected and analysed to obtain this information. Finally, a comparison of all the data is performed to summarise it, with the aim to define the recycling options in chapter 5.

4.1 EXISTING DATA OF THE COMPOSITION OF PLASTIC DEBRIS

4.1.1 FROM INTERNATIONAL AND REGIONAL MONITORING PROGRAMS

Many of the international reports are based on the same survey data published by the Ocean Conservancy (e.g. MARLIN, NOAA and UNEP) (Cheshire & Adler, 2009; MARLIN, 2013; NOAA and UNEP, 2012; UNEP and GRID-Arendal, 2016). This organisation arranges the International Coastal Clean-up (ICC), a global volunteer effort to clean up our beaches and waterways, and publishes a yearly report with the most common items found in these debris collections (Ocean Conservancy, 2015).

Table 4.1 shows the top 10 items internationally collected by ICC. As can be seen, all of them are disposable and packaging objects. Further, both in 2014 and 2015, 8 out of 10 are plastic items, indeed 89,27% of the items were plastics in 2015. Although this information is useful to define mitigation strategies (i.e. ban plastic bags), the number of items is not enough to know how to recycle it. For instance, it is unknown which materials the plastic beverage bottles are made of. The most used plastics can be PET, HDPE or PVC, and the recycling method widely varies between these materials. Moreover, it is also unidentified if it is degraded, have additives and/or is dirty.

International Coastal Clean-up				
Top 10 items collected		2015 (number of items)	2015 (%)	Ranking 2014
1	Cigarette butts	2.127.565	29,13%	1
2	Plastic beverage bottles	1.024.470	14,03%	3
3	Food wrappers	888.589	12,17%	2
4	Plastic bottle caps	861.340	11,79%	4
5	Straws, stirrers	439.571	6,02%	5
6	Other plastic bags	424.934	5,82%	6
7	Glass beverage bottles	402.375	5,51%	8
8	Plastic grocery bags	402.122	5,51%	7
9	Metal bottle caps	381.669	5,23%	*9. Beverage cans*
10	Plastic lids	351.585	4,81%	*10. Cups and plates*
	Total	7.304.220	100%	

Table 4. 1 Top 10 items collected internationally in 2014 and 2015. Source: (Ocean Conservancy, 2015)

The same happens with the previous cited regional frameworks, OSPAR and MARLIN. As shown in the tables 4.2 and 4.3, both report the composition of debris by the material of the items. Equally, most of them are plastic objects (OSPAR more than 83,5%, MARLIN 64%). Although the classifications differ a bit, disposable and packaging objects are widespread both in these areas and internationally. However, it is also reflected that there is again a lack of data to define the recycling methods, due to the given items composition.

OSPAR area		
Material type		%
1	Plastic/Polyestyrene[1]	82,05%
2	Sanitary	5,87%
3	Paper & cardboard	2,67%
4	Metal	2,66%
5	Wood	2,06%
6	Foamed plastic	1,51%
7	Clothes	1,41%
8	Glass	1,03%
9	Ceramics	0,48%
10	Medical	0,21%

[1]Include: bags, bottles, containers, cap/lids, cutlery, gloves, strings, and ropes

Table 4. 2 % of material type of the plastic debris in the OSPAR area, 2014 Source: (OSPAR, 2014)

MARLIN – Baltic Sea		
Material type		%
1	Plastic/Polystyrene	56%
2	Glass & Ceramics	8%
3	Metal	8%
4	Paper & cardboard	8%
5	Foamed plastic	6%
6	Wood	4%
7	Other litter	3%
8	Clothes	3%
9	Organic	2%
10	Rubber	2%

Table 4. 3 % of material type of the plastic debris in the Baltic Sea – 2013. Source: adapted from (MARLIN, 2013)

4.1.2 FROM RESEARCH PAPERS

An extensive search has been performed of academic articles regarding the composition of Plastic Debris, here it is presented a summary of the more detailed and newer data found. While many papers base their data in the monitoring programs, some of them present a more comprehensive data which is summarised in this section.

Recent articles suggest that the most common plastics are polyethene (PE), polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP) and polyethene terephthalate (PET), since they are also the most globally produced, approximately 90% (J.A. Conesa, 2016; Li W.C., 2016). Conesa (2016) underlines that unexpected amount of cellulose acetate (CA), used in cigarette filters, is found. Furthermore, the article indicates some estimations of the percentage of this materials (expressed by items) in shorelines: CA 5-30%; PE 20-50%; PP 10-30%; PET 5-20% and PS 5-10%. Not only these plastics are found but also others such as Nylon (PA) and PVA are found in sediments microplastics, as a consequence of the degradation of bigger items (Li, Tse, & Fok, 2016).

Regarding the physical and chemical properties of the plastic debris, only two sources have been found:

South Korean PD characterization (Cho, 2005; Jung, Sung, Chun, & Keel, 2010)

These articles specify properties of Sea-based beach plastic debris which are composed by mainly plastics (around 90%) such as fishing gear, nets and ropes and the rest is polystyrene buoys (Styrofoam). The chemical characteristics indicated are: the elemental analysis (C73,58% H6,30%; N0.338%; S0,391%; Others19.387%), a range of the energy content (4000-6700 kcal/kg) and the ash content (<5%). Moreover, it is described that the plastic debris is dirty because of the sea water (salty), sludge and contaminants. Finally, the calorific value of the Land-based plastics is also given (1500-2000 kcal/kg).

Although many information is provided, it is not complete. First, Land-based plastic is barely defined, only the energy content is identified but it is not known if it is high or low calorific value (HCV or LCV), likewise for the Sea-based debris. Second, any physical property is provided for none of them (such as moisture, specific weight or particle size). Finally, the chemical features (of Sea-based) are partial: the proximate analysis is missing and the elemental analysis only says 81% of the components and it is not described what components are the 19% remaining (that normally corresponds to Oxygen and pollutants, but also can include the moisture content).

Mediterranean PD Characterization (Iñiguez, Conesa, & Fullana, 2017)

Simultaneously with the execution of this thesis, this article was published (February 2017). Iñiguez et al. (2017) analysed the properties of Mediterranean plastic debris collected near Torrevieja and Santa Pola. Mainly, chemical and thermal characteristics were investigated:

- Immediate analysis: Moisture 9,3%, Ash 29.1% (Volatile matter not specified)
- Elemental analysis: C38.2%, H4.9%, N0,3%, S0,1%, O27,5%, main contaminants: Fl 0.005%, Cl 1.83%, Br 0.008%
- Energy content: Net Calorific Value (NCV) 25,6MJ/kg

In addition, it is presented the decomposition curves of MDs in different atmospheres, modelling similar conditions feedstocks and energy recovery treatment. The study concludes that the presence of oxygen accelerates the decomposition; in other words; the mass loss rate is higher in combustion than in pyrolysis.

This research paper performs a complete characterization of the plastic debris, but a few properties are missing: volatile matter, particle size distribution and density.

4.2 SWEDEN WEST COAST CLEAN-UP – PD CHARACTERISTICS

The purpose of beach Clean-up was to comprehend the plastic debris characteristics from a waste management perspective. As have been persevered in this report, items composition is not sufficient to identify recycling options. Therefore, during this thesis project, it had been collected beach debris from the West coast of Sweden and conducted physical and chemical analyses to characterise the debris.

This section describes both this clean-up and the analysis. First, the clean-up method is defined, following by the physical characterization. After that, the chemical analysis performed in the laboratory is explained. Finally, based on this data, in next chapter it is identified and described several recycling options for the plastic debris.

4.2.1 CLEAN-UP WEST SWEDEN

The clean-up was carried out in the Gåsevik beach, near Fiskebäckskil, in the Swedish West Coast. This beach is a natural monument due to its ecological importance[2]. Moreover, this shore is used for research by Lovéncentret Kristineberg of the University of Goteborg (see figures 4.1 and 4.2).

Figure 4. 1 Gåsevik beach. Landscape

Figure 4. 2 Gåsevik beach. Cleaned area

The beach was cleaned before summer season by this research centre. On the 15th of November of 2016, the sample analysed in this study was collected by 3 people (Florina Lachmann, the supervisor of this thesis, Henrikke Baumann, and the author of this report). The collection was picked up manually (see figure 4.3) in an area of approximately 100 m^2, with a length of 20 m and a width of 5 m (see figure 4.2).

Figure 4. 3 Picking up debris

Figure 4. 4 Detail entagled debris

[2] *Gåsevik beach is a meadow (or grassland) that attract and support flora and fauna which live in open and sunny areas.*

During the clean-up, it was observed that mixed up and many debris were under the flora due to the rainstorm the morning before the collection. For instance, many of the debris were sea-based (mainly ropes) which were entangled with the vegetation, making difficult to remove them and when they were separated a lot of organic matter was attach to the plastic (see figure 4.4). Moreover, a lot of films were found, which also carry a lot of soil stocked on it. Additionally, it was traced that many plastic fragments bellowed to the bigger items.

After these preliminary reflections and established that the sample was considered representative of a conventional marine waste, the physical characterization was executed to give quantifiable data.

4.2.2 PHYSICAL CHARACTERIZATION

In the accomplished physical characterization, the bulk density, particle size distribution and classification were studied. The classification was done with the naked-eye method and the weight and the particle distribution examinations were performed manually with the help of a weight scale and two screens with mesh size 40x40 mm and 10x10 mm (fines).

Table 4.4 shows the classification of the plastic debris sample which had a total weight of 4,2kg, and a bulk density of 25 kg/m^3. It was sorted in seven categories and each weight and percentage are also presented in the table. Moreover, some comments and the main components of each group is added. (Images of each of the categories can be seen in figure 4.5).

<table>
<tr><th colspan="2">Classification</th><th>Kg</th><th>%</th><th>Items</th><th>Comments</th></tr>
<tr><td>1</td><td>Ropes
(>30 cm)</td><td>1,88</td><td>45,0%</td><td>Ropes (ø >1 cm) and String & cord (ø <1 cm)</td><td>Due to it was tangled with the vegetation, it contains organic matter and water.</td></tr>
<tr><td>2</td><td>Object 1
(>30 cm)</td><td>0,19</td><td>4,5%</td><td>Piece of a fish tray/box (used in ship)</td><td rowspan="2">Rather clean, low water content expected.</td></tr>
<tr><td>3</td><td>Object 2
(>30 cm)</td><td>0,29</td><td>6,9%</td><td>Bucked</td></tr>
</table>

Classification		Kg	%	Items	Comments
4	Plastics objects (<30 cm)	0,32	7,7%	Food packaging, 2 gloves, a decorative flower, a firework and a smoking container.	May contain corrugated cardboard in a cookie packaging (material undefined). Gloves may contain textiles that absorb water.
5	Films (<30 cm)	1,20	28,7%	Bags, food films and wrappers,	Observed contains organic matter and water stocked to the films.
6	Plastics (<40 mm)	0,25	6,0%	Mainly fragmented films and plastics, some fragmented ropes and bottle caps/lids.	Perceived/traced many plastic fragments bellowing to the bigger items (categories 1 and 5).
7	Fines (<10 mm)	0,05	1,2%	Mainly organic matter, also sand and plastics.	Observed small (<1mm) particles of plastics. Very high water content expected.
	TOTAL	4,18	100%		

Table 4. 4. West Coast Plastic Debris 1(size, undefined or sea/land-based)

Apart from the observations described in the table above, other remarks must be done. First, only one metal item was found (an Aerosol/spray-can showed in figure 4.5), the rest were plastics. Second, all the sample contains soil and water which was higher in ropes, plastic items and films. Third, as realised during the collection, it was traced that many plastic fragments bellowed to the bigger items such as ropes, plastic bags and food wrappers. That is to say, the degradation of the plastics was noticeable. Fourth, because of the sea water, it is possible that plastic debris includes a high Chlorine content. Finally, this plastic debris come from both land and sea-based sources, indeed, categories 1 and 2 (ropes and object 1) are sea-based litter which is a 50% of the debris, also the bucket and the gloves (from categories 3 and 4) may belong to this origin.

Category 1. Ropes

Category 2. Object 1

Category 3. Object 2

Category 4. Plastic objects

Category 5. Films (1)

Category 5. Films (2)

Category 6. Plastics (<40 mm)

Category 6. Plastics (<40 mm): Detail lids/caps

Category 7. Fines

Metal item: aerosol/spray can

Figure 4. 5 Images of the collected plastic debris in the Swedish West Coast

4.2.3 CHEMICAL CHARACTERIZATION

The purpose of the chemical characterization is to know if the Plastic Debris is suitable for energy recovery and/or feedstock recycling, as well as comprehend the outputs (energy and products) that can be produced with these methods. In order to discern this, the immediate analysis and the energy content were established. Although other properties are valuable to a better study of the treatments, such as elemental analysis (to know pollutants), due to lack of resources and time, only the mentioned characteristics were obtained. Despite this, a primary study can be done to have a clear synopsis of the recycling options.

The immediate analysis was determined with a Thermal Gravimetric Analyzer (TGA 701). The experiment[3] has a duration of nine hours and consisted of three steps to determine the moisture content, the volatile matter and the ash content, respectively. It included 19 samples of 1g ± 0,05g, where 14 of them were samples of the plastic debris, 2 sampling of each of the 7 categories (ropes, object 1 and 2, plastics objects, films, small plastics and fines), 2 of PE pellets and 3 of RDF. The PE pellets and the RDF had the aim to compare the PD with both a pure plastic and mix waste used for Energy recovery. The data obtained is presented in the following table (4.5):

	Moisture %	VM %	Ash %	FC %	NCV (kJ/kg)
1 **Ropes**	21,30	75,30	2,86	0,55	24328 [ii]
2 **Object 1**	0,09	99,84	0,06	0,01	32945 [ii]
3 **Object 2**	1,05	94,50	3,32	1,14	31159 [ii]
4 **Plastics Obj.**	27,56	65,25	5,44	1,76	20857 [ii]
5 **Films**	19,53	73,78	5,69	1,00	23870 [ii]
6 **S. Plastics**	0,98	96,24	2,31	0,47	31735 [ii]
7 **Fines**	69,64	12,28	14,30	3,80	384 [iii]
TOTAL PD[i]	**18,26%**	**77,04%**	**3,88%**	**0,82%**	**24.953**
PE pellets	0,04	99,97	0,02	0,01	43000
RDF	2,27	77,12	11,77	8,84	18100

[i] Total calculated considering the different % of each category; [ii] Estimation assuming is only plastic (GCV_{awf}=33MJ/kg); [iii] Estimation assuming is only organic matter (GCV_{awf}=17MJ/kg).

Table 4. 5 Proximate analysis of the plastic debris (Results of the TGA plus NCV estimations)

[3] *For a detailed explanation of the experiment, parameters, results, photos, graphs and ash study see the* ***Appendix 1****.*

Additionally, with the data obtained in the TGA, the energy content (Net Calorific Value) was calculated using the equation given by the EU according to information available: Volatile Matter (VM), Fix Carbon (FC) and Moisture (W):

$$NCV_u\left(\frac{kJ}{kg}\right) = GCV_{awf} \cdot 0{,}01 \cdot (VM + FC) - 0{,}02445 \cdot W$$

The estimation of the energy content is also showed in table 4.5.

Examination of the data obtained

In general, it can be noted that the plastic debris possesses good features for chemical treatments: the moisture is relatively low <20%, also the ash content which is around 4%, as a consequence the energy content is reasonably high, approximately 25MJ/kg. Moreover, if each component/category is analysed one by one, it can be seen that the previous observations (table 4.4) are correlative with the TGA results:

1. Ropes: It was perceived that they contain organic matter and water and the analysis shows a high moisture (21%) and a relatively elevated ash content (3%).
2. Object 1: It was rather clean and low water content was expected and the data confirms that (moisture 0,09%, ash 0,06%).
3. Object 2: Like the number 2. However, unexpected relative elevated ash content (3%) a bit higher humidity (1%). The reasons can be either that it was a bit dirty or a higher quantity of additives.
4. Plastic objects: As anticipated, it has a high water content (27%) and high ash content (5,4%) which can be because of the cardboard, textiles or both.
5. Films: It was observed that they contain organic matter and water stocked to the films, and the analysis depicts an elevated moisture content (27%) and ash (5,7%). The high residue content may be due to the soil or/and the pigments found in the wrappers films.
6. Small plastics: Low moisture content (1%) and rather high ashes (2,3%). The small humidity can be explained due to the small pieces of plastic can only

contain the water attached to the surface (while bigger plastic can be tangled with it).

7. Fines: A very high water content and ash were expected, due to is mainly organic matter and sand, 70% and 14% respectively.

Moreover, a comparison with PE pellets and RDF was performed to see the differences with pure plastic and a fuel made of waste. Regarding the PE pellets, it can be discerned that pellets are clean, it has almost negligible moisture and ash content. As a consequence, the calorific content is higher (43MJ/kg) than for the PD. On the contrary, RDF has a particularly low energy content, 18MJ/kg, and an elevated ash content, 11,77%, (both due to the paper/cardboard and textile compounds). Finally, the moisture is quite low (2,3%) because it had been dried before was storage.

To sum up, the plastic debris studied seems to be suitable for chemical recycling due to its relatively low moisture and ash content and a high calorific value. Although pure plastic has better properties, if it is compared to RDF, PD has superior characteristics.

4.3 TOWARDS IDENTIFICATION OF WASTE CHARACTERIZATION FOR PLASTIC DEBRIS

Selecting an appropriate technology is one of the key considerations for the success of the plastic debris management, thus knowing physical and chemical characteristics is necessary to select the best treatment. However, the literature review showed that most of them are expressed by items, giving a partial knowledge of the litter.

Only it was found two chemical studies of plastic debris (see section 4.2.2): Korean's PD (Jung et al., 2010) and Mediterranean's PD (Iñiguez et al., 2017). The Korean characterisation was only for sea-based plastics, and the other was published while performing this thesis. However, neither of them analysed the physical properties. Given this absence of data, it was made a physical and chemical analysis of debris in the Swedish West Coast.

		PD-West Coast of Sweden	PD-Med (Iñiguez et al., 2017)	PD-Sea (Jung et al., 2010)
Physical properties	**Bulk density (kg/m3)**	**25**	n.a.	n.a.
	Particle size (mm)	**40-400**	n.a.	n.a.
	Particle distribution	**Available**	n.a.	n.a.
Energy content	**NCV (kJ/kg)**	**25.000**	**25.600**	**17.000-28.000**
Immediate analysis	**Moisture**	**18%**	9%	n.a.
	Ash	**4%**	29%	<5%
	Volatile matter	**77%**	n.a.	n.a.
	Fixed carbon	**1%**	n.a.	n.a.
Elemental analysis	**CHSNO**	**n.a.**	Available	Available
	Contaminants	**n.a.**	Fl, Cl, Br	n.a.

Table 4.6 Comparison PD characteristics

Table 4.6 summarises the different data available of the plastic debris; namely: Swedish West Coast PD, Mediterranean PD and Korean Sea-based PD. As can be seen, there are only the physical characteristics of the Swedish's PD, therefore, it is not possible to compare them. Nevertheless, it is possible to evaluate the other properties. First, the energy content is similar to the three examples. Second, the moisture is higher in the Swedish litter than in the Mediterranean one, in contrast, the ash content in the Mediterranean sample is seven times higher than Swedish. Finally, it is important to highlight the high Cl content (1,83%) in the Mediterranean debris which it is significant to consider for chemical recycling.

To sum up, the performed analysis generated new data which is useful to selecting a suitable recycling method and the usage of each data for the calculous in the LCA is summarised in table 4.7. For instance, the studied plastic debris seems to be suitable for chemical recycling due to its relatively low moisture and ash content and a high calorific value. Furthermore, the physical characteristics facilitate the design of the mechanical treatment as well as necessary pre-treatments for chemical recycling. Finally, both properties (chemical and physical) assist for a better understanding of the disposal of these plastics.

Table 4.7 Usage of the Plastic Debris properties for the LCA

PROPERTIES		Use	Technical options
Physical properties	**Bulk density (kg/m3)**	Volume occupied & equipments' size or technology	All (disposal, energy recovery, feedstock & mechanical recycling)
	Particle size (mm), particle distribution & fractions	Technology choice & useful material (e.g. fines cannot be recycled)	All. Mainly mechanical recycling & pre-treatment for chemical recycling & combustion
Energy content	**NCV (kJ/kg)**	Energy able to produce	Chemical recycling & energy recovery
Immediate analysis	**Moisture**	Technology choice (due to the low value, PD can be used for all the technologies without drying)	All. Mainly chemical recycling & energy recovery
	Ash	Technology choice & ashes produced in chemical and energy recovery	All. Mainly chemical recycling & energy recovery
	Volatile matter & Fixed carbon	Technology choice, possible emissions & gas and liquid production in pyrolysis & gasification	All. Mainly chemical recycling & energy recovery
Elemental analysis	**CHSNO Contaminants**	Technology choice & possible emissions	All. Mainly chemical recycling & energy recovery

5. LIFE CYCLE ASSESSMENT

The objective of this study was to compare different options for plastic debris management from an environmental perspective. Selecting a suitable solution for a sustainable waste management, whilst considering the technology, requires a comparison of environmental benefits and drawbacks. Life Cycle Assessment (LCA) has been demonstrated to be an appropriate tool for this aim and its application in this field has rapidly expanded over the last few years (Fiorentino, Ripa, Protano, Hornsby, & Ulgiati, 2015).

In this chapter, different recycling options are considered and studied by means an LCA. The baseline scenario considered is disposal, due to it is assumed that it is the most used treatment for plastic debris. Thus, it is used as a starting to point to compare the other options with landfill. Those options are mechanical and chemical recycling and energy recovery, considering one tonne of the Swedish West Coast plastic debris (see section 4.2).

Additionally, two clean-up operations are also evaluated using the data obtained in the options. The aim of assessing a clean-up operation is to see the big picture: observing the ecological benefits of removing this debris, and seeing whether that benefit is juxtaposed according to the recycling option. These LCA scenarios are applied to identify possible improvements in two clean-up operations, where the waste treatment is changed (LCA change-oriented type). For this reason, site specific data is used and the functional unit is one clean-up operation. But also, due the the intrinsic different between clean-ups, the emissions per kg of PD are compared.

5.1 TECHNICAL OPTIONS

5.1.1 BASELINE SCENARIO: DISPOSAL

The baseline scenario is disposal, which consists on confining the plastic debris into a landfill (see figure 5.1). Considering the Swedish West Coast debris, the disposal of one compacted[4] tonne will use approximately 6 m^3 of land, 235 kg of cover material and 1.500 MJ of energy (for the operation, compaction and close down)[5].

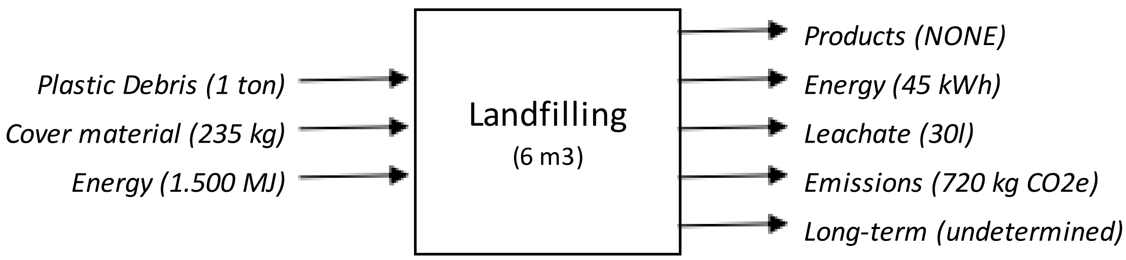

Figure 5. 1 Diagram LCA baseline: Disposal (inputs and outputs)

On the contrary, the outputs obtained will be 45 kWhe of energy from the landfill gas, 31 litres of leachate (which can contain PCDD, PCBs and chlorine), and 720 kg CO_2 eq. during the operation of the landfill site. In addition, it must be considered that none of the resources is recuperated, and possible long-term emissions.

5.1.2 OPTION 1: ENERGY RECOVERY

The first option considers that all the plastic debris goes to energy recovery. As said before, that process consists of the combustion of the plastic producing energy and involves the 90-95% volume reduction of the waste (ash).

Figure 5.2 shows the different inputs and outputs of the incineration. If one tonne of plastic debris is combusted around 16.000 kg of air and 2.600 kg of water is needed, as well as energy such as natural gas (852 MJ) and electricity (372 kWh) to start the process. Moreover, to achieve the EU air emissions regulation, 100 kg of auxiliary materials are necessary for the gas treatment.

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[4] *Taking into account that the density is 25 kg/m3 and the compaction factor (CF) is 0.15.*
[5] *Considered a period of time of 100 years.*

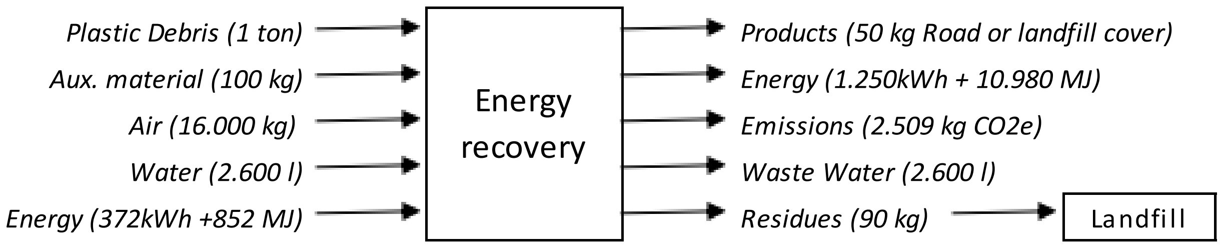

Figure 5.2 LCA option 1: Energy recovery (inputs and outputs)

Because of the combustion, the hot gases are transformed into electricity 1250kWh and heat 10.980 MJ. Although the gases are cleaned after this conversion, there is the emission of CO_2 and CH_4 equivalent to 2.509 kg CO_2, as well as other contaminants such NOx and PCBs.

Regarding residues, about 50kg can be used as a product for road or landfill cover. On the contrary, the other residues (90kg) must be either treated (55kg) and landfilled, or directly landfilled (35kg). Further, wastewater must be also treated.

5.1.3 OPTION 2: FEEDSTOCK RECYCLING

The second option considered is feedstock recycling, and among these techniques, pyrolysis seems more suitable for PD. As mentioned before, pyrolysis consists of a thermal degradation without oxygen and it generates gas, oils and char, and these liquid and gas yields can be used for chemical or energy production.

In this option has been considering both options. On the one hand, the chemicals generated will be about 260 kg of HCV gas and 690 kg of oils, paraffin and olefins, considering that the majority of the plastics are HDPE, LDPE, PP and PET. On the other hand, if these yields are used to make energy, the electrify produced will be around 1.070kWh and the heat about 17.450 MJ.

In both cases, the use of water and energy will be approximately the same: 2600l and 370 kWh and 850 MJ, respectively. Moreover, both situations generate the same char which must be treated and disposed as a special waste (50 kg), and the same emissions during the process (due to the energy consumed), as well as the wastewater (2.600l). However, the auxiliary material used for the gas and oil cleaning is unknown.

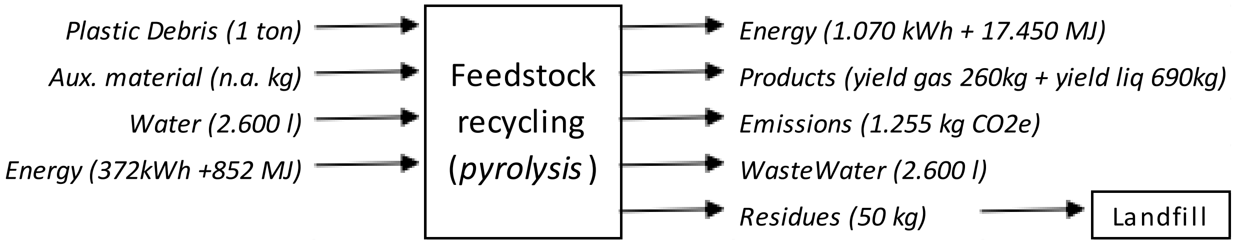

Figure 5.3 LCA option 2: Feedstock recycling - pyrolysis (inputs and outputs)

5.1.4 OPTION 3: MECHANICAL RECYCLING

The third option involves mechanical recycling. As seen before, it is difficult to recycle mechanically non-single-stream and/or contaminated plastics, and Plastic Debris is mixed, dirty and degraded. Hence, the most feasible mechanical option seems to be downgrading to plastic lumber.

When the plastic is mixed, it is necessary to do separation, washing and preparation of the PSW. In particular, the pre-treatment required for this plastic debris consists of two main steps: (i) separation of ropes and fines with a screen due to the fact these fractions cannot be used for the process; (ii) water-washing and shredding of the remaining fractions to obtain a clean and homogeneous scrap. Finally, these scraps are melted to make plastic lumber which is mainly used for outdoor furniture such as benches.

Considering that ropes and fines go directly to landfill (460kg), this process can produce 540 kg of plastic lumber with one tonne of PD. In addition, this treatment needs approximately 1.345 litres of water to clean the plastic and energy for the process: electricity (11.100 kWh) and gasoil (200 l).

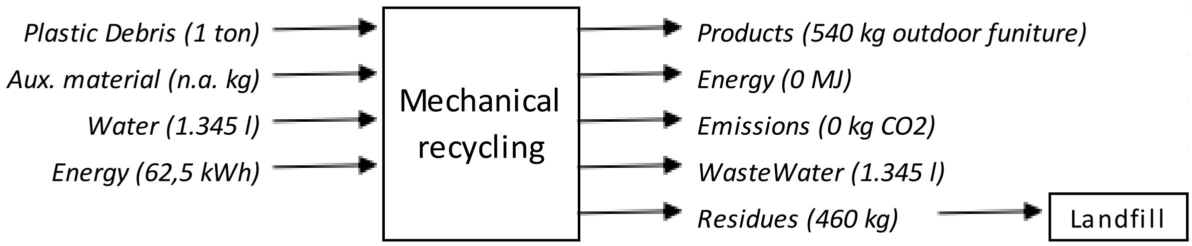

Figure 5.4 LCA option 3: Mechanical recycling (inputs and outputs)

Regarding residues and emissions, about 11.000 kg CO_2e are produced (due to the energy consumed) and 1.345 litres of wastewater (cleaning process). Further, the unused debris goes to landfill (460kg).

5.2 LCA – CLEANING OPERATIONS

As said before, two beach clean-up operations are analysed by means of an LCA. The first one, the collection of debris took place in the remote natural place Svalbard, a Norwegian archipelago in the Arctic Ocean. The second one is the explained removing operation on the Swedish West Coast (see section 4.2.1).

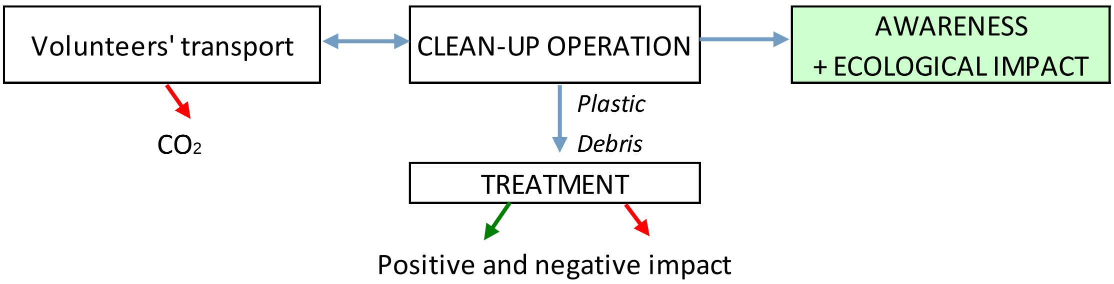

Figure 5.5 Diagram LCA cleaning operations

The clean-up operation is summarised in the diagram above. This process consists of the volunteers' transport to the clean-up operation site (round trip), followed by the clean-up which, on one hand, can create awareness on the people and avoid the ecological impact and, on the other hand, generates debris that must be managed. Finally, the Plastic Debris collected are transported to the waste treatment facility. These facilities are the closest plant that has equivalent treatments options.

Both beach clean-up operations took place in natural protected areas due to its ecological significance, and they also share the procedure followed (5.5). However, the dimension of the collection varies in terms of volunteers and debris collected.

The Svalbard clean-up is a one-week arctic boat expedition[6] with about 120 participants that was launched in summer 2015 to collect beach trash at that

[6] *The idea behind the* Oceanwide Expeditions *trip was to attract tourists to participate in special clean-up excursions by discounting the cruise price to make a greater effort in cleaning beaches.*

archipelago. As figure 5.6 shows, the participants first travelled to Oslo, mainly by aeroplane, to then fly to Svalbard, where they embarked an arctic cruise vessel. After that, trips from the vessel to the shores were made with several zodiacs in order to arrive at different remote beaches where 500 kg of plastic were collected (Lachmann, 2016).

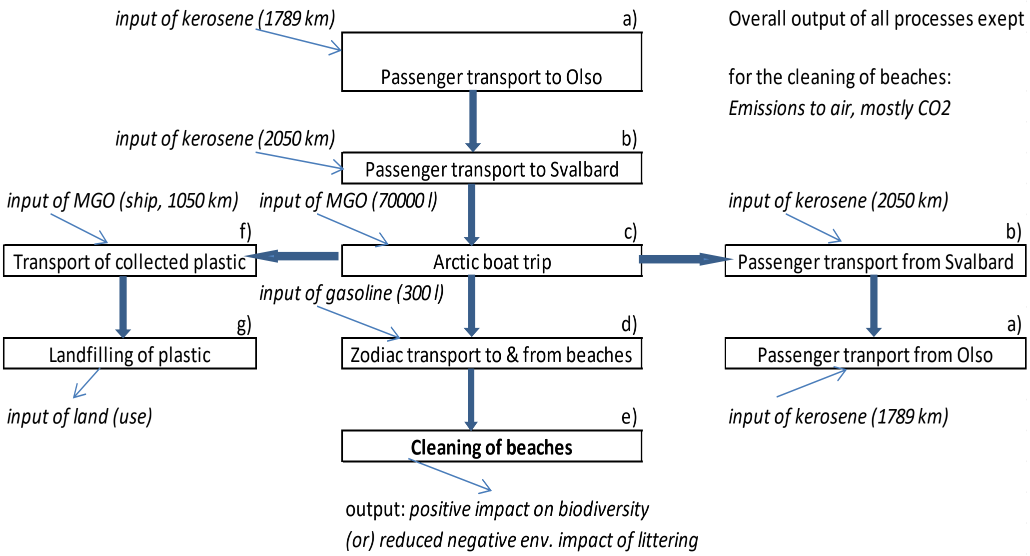

Figure 5.6 Diagram of the LCA for the Svarlbard clean-up Source: (Lachmann, 2016)

On the contrary, the collection performed in the Swedish West Coast had a duration of only one day, was conducted by 3 volunteers, and 4,2 kg were removed from the beach. Further, the participants only needed to travel from Göteborg to Gåsevik beach (110km) using one car.

Another difference is with regards the litter found. Although the litter is similar on both shorelines, the variation resides on the origin. While in Gåsevik was noticed that the debris was mainly from Sweden, the litter found in Svalbard does not come from the settlements at the archipelago but it is transported to the arctic from all over the world by ocean currents.

Considering the similarities and differences of the clean-up operations, the LCA results are analysed in the next chapter. As said before, the LCA unit is one clean-up operation in order to have a holistic approach to the full process. However, due to the disparities between the collections, also it is evaluated the environmental impact per kilogramme of debris to compare both operations.

5.3 RESULTS

The purpose of this section is to present the results of the Life Cycle Assessment (LCA) of the previous point, as well as an analysis of that results. As mentioned above, two clean-up operations are assessed to find the environmental implications, considering four options: landfilling, energy recovery, feedstock and mechanical recycling, making a total of 8 scenarios. The LCAs of each collection are shown in the tables 6.1 and 6.2, respectively. In that assessment has been considered only the air emissions of the transport, energy process consumption and the avoided releases by the production of energy or products (indicated as negative).

Table 5.1 LCA results of the clean-up operation in Svalbard (500kg of PD collected)

	Baseline scenario Landfill	**Option 1. Energy recovery**	**Option 2. Feedstock recycling**	**Option 3. Mechanical recycling**
Transport - volunteers				
Volunteers' transport - Oslo	40.836			
Volunteers' transport - Svalbard	35.211			
Arctic boat trip	191.556			
Zodiac transport beaches	695			
Transport - Plastic Debris				
Transport of collected plastic to Tromso	7			
Transport on land	0,025	0,001	56,220	0,000
TOTAL TRANSPORT (tn CO_2)	**268.305**	**268.305**	**268.361**	**268.305**
Waste treatment				
Energy used	2,4	133,6	133,6	17,4
Avoided emissions: Products	0,0	0,0	0,0	-1.837,5
Avoided emissions: Energy produced	-12,6	-790,3	-911,0	0,0
Emissions process	360,0	1254,5	627,3	0,0
TOTAL Waste treatment	399,9	597,8	-150,1	-1.820,1
Total emissions clean-up (tn CO_2)	**268,7**	**268,9**	**268,2**	**266,5**
Total without volunteer transport (tn CO_2)	**1,1**	**1,3**	**0,6**	**-1,1**
kgCO_2 per kg PD	**537,4**	**537,8**	**536,4**	**533,0**
kgCO_2 per kg PD without vol. trans.	**2,20**	**2,60**	**1,22**	**-2,24**

As can be seen in table 6.1, the total emission (GWP) in the Svalbard clean-up is around 270 tonne CO_2 eq. Though, this discharge is mainly due to the transport of the volunteers from their countries to Svalbard. If this value is removed, the clean-up itself (transport to the beach, transport of the waste and treatment) is about ± 1 tonne CO_2 eq. In other words, the emissions will be around 1 tonne for clean-up, if locals performed the collection.

If the four options are analysed, it can be observed that only mechanical and feedstock recycling have a positive impact by avoiding emissions (due to energy or products production). However, the overall result including transport is always a positive GWP, that is to say, an impact to the environment.

Similarly, the LCA from the clean-up in Gåsevik beach, Sweden, (which an overall emission about 30 kg CO2 eq.) shows that the best options are feedstock and mechanical recycling. Again, there is the impact if the transport is included.

Additionally, it has been analysed which will be the result if the collection will be performed by locals (at 10 km from the beach). As can be seen in the last row, both second and third options will have a null or positive impact, respectively.

Table 5.1 LCA results of the clean-up operation in Sweden (4,2kg of Plastic debris collected)

	Baseline scenario Landfill	**Option 1. Energy recovery**	**Option 2. Feedstock recycling**	**Option 3. Mechanical recycling**
Transport volunteers (110 km)	33,0	33,0	33,0	33,0
Transport Plastic Debris	0,025	0,025	0,072	0,013
TOTAL transport (tn CO_2)	**33,0**	**33,0**	**33,1**	**33,0**
Energy used	0,5	1,3	1,3	0,2
Avoided emissions: Products	0,0	0,0	0,0	-18,4
Avoided emissions: Energy produced	-0,1	-7,9	-9,1	0,0
Emissions process	3,6	12,5	6,3	0,0
Total emissions clean-up (tn CO_2)	**0,006**	**0,039**	**0,032**	**0,015**
Total without volunteer transport (tn CO_2)	**0,004**	**0,006**	**-0,001**	**-0,018**
kgCO_2 per kg PD	**1,105**	**7,801**	**6,314**	**2,962**
kgCO_2 per kg PD without vol. trans.	**0,805**	**1,201**	**-0,286**	**-3,638**
Ton LOCALS	**0,005**	**0,008**	**0,000**	**-0,017**

The emissions per kg of PD are compared, in Svalbard it is around 535 kgCO2/kgPD while in Gåsevik beach is between 6-39 kgCO2/kgPD. This large different is due to the transportation from Europe to the archipelago. However, if this transport is not considered, the different is still vast. For example, for the baseline scenario, the GWP for Svalbard is 2 kgCO2/kgPDD, while it is 0,7 kgCO2/kgPD for the Swedish beach. As already mentioned, this is due to the need to transport by boat to remote areas or the archipelago.

To sum up, it is important to optimise the transport of volunteers and do it which locals to try to minimise the impact of the action. Moreover, it was shown that the better recycling options are feedstock and mechanical recycling. Finally, it is important to consider that, even there is an impact, collecting the plastic debris the impacts to flora and fauna are avoided. That is to say, it has a positive impact on the environment. As it was commented before, cleaning the beach is cleaning the ocean too. Moreover, knowing that in shorelines fragmentation is higher, shore washing also can help to avoid the production of more microplastics due to this degradation. Equally important, it prevents the pollution and ingestion of them.

6. DISCUSSION

This project aimed to contribute the knowledge about sustainable solutions for treating the plastic debris after shore-line clean-up and provide different LCA scenarios to analyse the environmental impact. In order to identify appropriate technologies, several aspects have been described; such as waste quantity and properties, as well as characteristics of available methods for handling this material.

One gap found in the literature is the lack of appropriate recycling process for the plastic debris once they have been collected. This report purposed to provide recycling options: mechanical and chemical recycling, energy recovery and disposal. However, this technologies are not always available; while gasification, combustion and landfilling are easily found in Sweden, the mechanical process selected is harder to find, and pyrolysis has only a few pilot plants worldwide. Moreover, there is no data or experiments of the performance of these options with plastic debris.

Another challenge found in the literature is that plastic debris is described by items, and waste management industry cannot use this data for determining suitable treatments. In particular, there was no data on the physical and chemical properties of this waste, thus, this data was found for the PD in the Swedish West Coast providing a starting point for a better understanding of this material. However, only one sample was analysed and it will be interesting to analyse different samples in the same beach in different seasons, as well as in other beaches in the same area. Moreover, more analyses of PD are necessary worldwide.

With regards the LCA performed, it attempts to give an overview of the possible impacts of the different scenarios for two clean-up operations. The scope was further limited to these two case of study; therefore, if other clean-up operations are analysed the results will vary due to the availability and distance to the waste treatment as well as the possible changes on the PD properties. Moreover, the LCA only covers the CO_2 emissions, if the analytic strategy would have hade another focus, the outcome may be different.

7. CONCLUSION

To conclude, this project achieved its aim that was to provide a sustainable solution for treating the plastic debris (PD) after shoreline clean-up. Also, it accomplished to analyse these options from an environmental view.

Plastic waste management and technologies were researched providing an overview of recycling methods as well as actual projects that recycle PD. From this was conclude that the available treatments for this material are: Mechanical recycling (NewtechPoly process, manufacturing plastic lumber), Chemical recycling (pyrolysis, generating high calorific content liquid or energy), Energy recovery (combustion, producing heat and electricity) and Disposal.

The physical and chemical properties data was found for the PD in the Swedish West Coast providing a starting point for a better understanding of this material and helping to select an appropriate waste treatment, as well as, allowing to perform an LCA to evaluate the environmental impact.

Taking into account these recycling technologies and the PD characteristics, the LCA of two clean-up operations were analysed. As a result, it was found that the higher CO_2 emissions in a clean-up operation are due to the transport of volunteers. Therefore, it is important to optimise the transport of volunteers and do it which locals to try to minimise the impact of the action. Moreover, it was shown that the best recycling option is mechanical recycling, due to can avoid CO_2 emissions of the full process by producing plastic lumber.

Finally, it is important to consider that, even there is an impact, collecting the plastic debris the impacts to flora and fauna are avoided, as well as, if volunteer transport emissions are reduced and mechanical recycling is used. That is to say, it can have a **positive impact on the environment**. As it was commented before, cleaning the beach is cleaning the ocean too. Moreover, the clean-up operation can create awareness preventing future littering.

7.1 OUTLOOK

Although marine pollution prevention and cleaning initiatives are spread around the globe, the question remains for what can be done with the plastics that are already in the oceans. This report attempted to give an initial point on recycling options and LCA of clean-up operations, but further research is necessary:

- Analyse different samples in the same beach (Gasevik) in different seasons, as well as in other beaches in the Swedish West Coast.
- More physical and chemical analyses of PD are necessary worldwide.
- Development of plastic waste treatments such as gasification and pyrolysis.
- Experiments and data of the performance of different treatments with plastic debris.
- More LCAs of clean-up operations worldwide.
- Methodology to calculate the positive impact of the clean-up operation, such as the environmental benefits and the socioeconomics impacts avoided.

7.2 RECOMMENDATIONS

Some recommendations are given to different actors:

- Collaboration between waste management sector and cleaning initiatives in order to achieve the best environmental result.
- Analyse the clean-up operation before hand to avoid emissions (e.g. taking into account the transport of volunteers and the possible treatments near by).
- Review of the monitoring programs to provide useful information for the waste management sector (e.g. adding physical and chemical properties as well as the material components such as PET, PP, PE…).
- Enhance collaboration of the local clean-up initiatives between areas (e.g. Sewdish West Coast).
- Enhance construction of mechanical recycling facilities and the recycling products market.

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9. APPENDIX – TGA ANALYSIS

The purpose of the analysis performent in the TGA 701 was to Know moisture, volatile matter ash and LCV to check availability for combustion processes and feedstock recycling.

The immediate analysis was determined with a Thermal Gravimetric Analyzer (TGA 701). The experiment has a duration of nine hours and consisted of three steps to determine the moisture content, the volatile matter and the ash content, respectively. It included 19 samples of 1g ± 0,05g, where 14 of them were samples of the plastic debris, 2 sampling of each of the 7 categories (ropes, object 1 and 2, plastics objects, films, small plastics and fines), 2 of PE pellets and 3 of RDF. The PE pellets and the RDF had the aim to compare the PD with both a pure plastic and mix waste used for Energy recovery.

Samples ready for the analysis in the TGA equipment

9.1 PARAMETERS AND EQUATIONS USED

Isabel_1: Method Step Parameters

08/03/2017 10:01:00

Step Name	Covers	Start Temp.	End Temp.	Ramp Rate	Ramp Time	Hold Time	Total Time	Max Time	Atmosphere	Flow Rate	Window
Moisture	No	25	105	6	00:13	00:00	00:13	00:00	Nitrogen	Low	3
Volatile	Yes	105	600	20	00:24	00:07	00:31	00:00	Nitrogen	Low	3
Ash	No	450	550	15	00:06	00:00	00:06	00:00	Oxygen	Low	3

Comparator	Final Weight
0.01	At Constancy
100.00	At End of Step
0.01	At Constancy

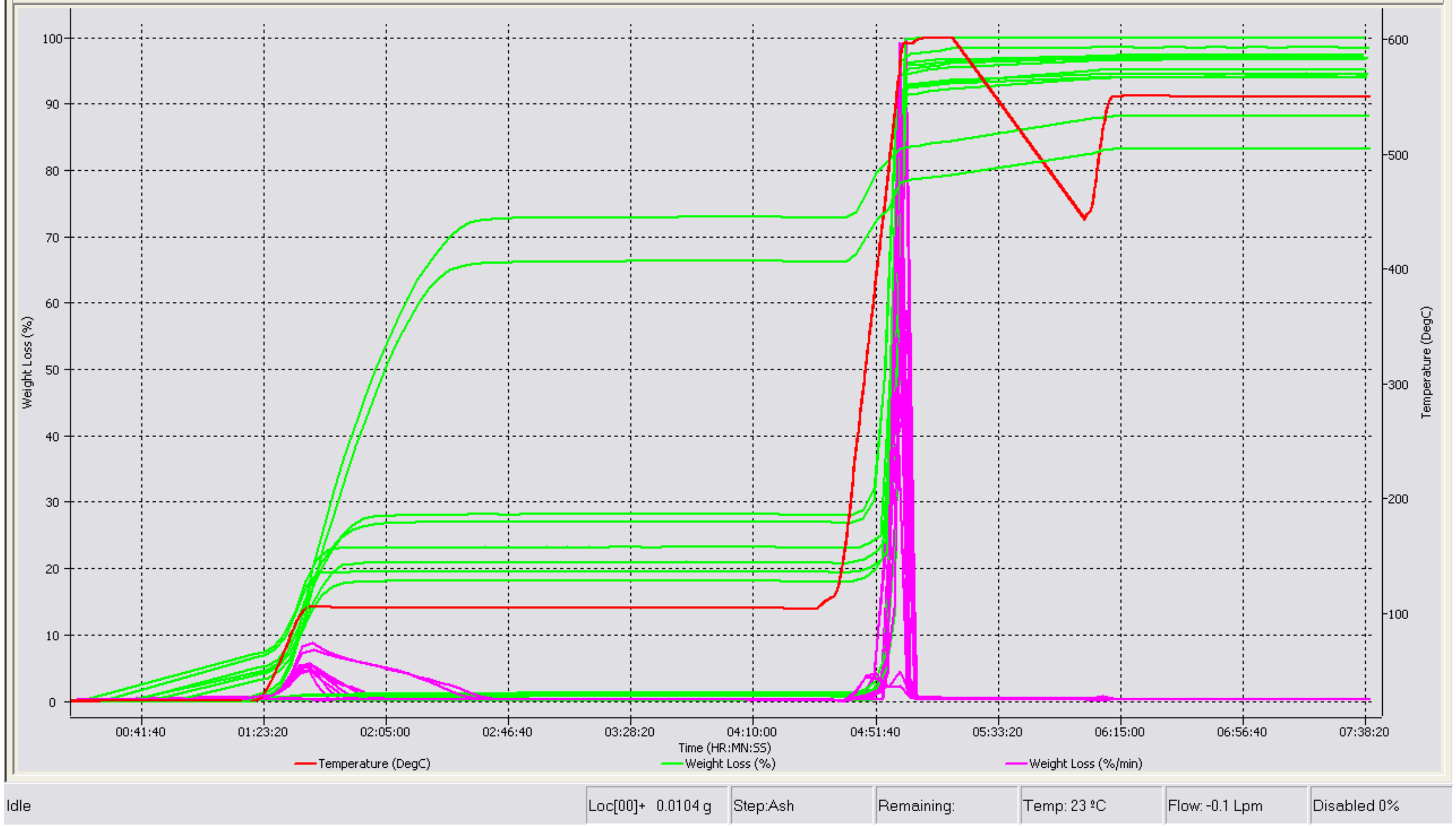
Isabel_1: Method Equation Parameters

08/03/2017 10:03:12

Equation Name	Equation Text	Result Format	Result Units	Description	Calibrate
Moisture	(([Initial Mass]-[Moisture Mass])/[Initial Mass])*100	F4.2			No
Volatile	(([Moisture Mass]-[Volatile Mass])/[Initial Mass])*100	F4.2			No
Ash	([Ash Mass]/[Initial Mass])*100	F4.2			No
Fixed Carbon	100-([Moisture]+[Volatile]+[Ash])	F4.2			No
Volatile Dry	[Volatile]*(100/(100-[Moisture]))	F4.2			No
Ash Dry	[Ash]*(100/(100-[Moisture]))	F4.2			No
Fixed Carbon Dry	100-([Volatile Dry]+[Ash Dry])	F4.2			No

9.2 PROFILE OF THE SAMPLES

n=14	Initial Mass	Volatile	Volatile Dry	Moisture	Ash	Ash Dry	F. Carbon	Fixed Carbon Dry	Fixed Carbon
Average	1.0098	73.88	87.24	20.02	4.85	10.10	0.00	2.66	1.25
Std. Deviation	0.07	29.035	20.015	23.716	4.525	15.778	0.000	4.289	1.216
RSD	6.848	39.30	22.94	118.5	93.27	156.2	0.000	161.3	97.47



9.3 ASH OBTAINED

Colunm 1 (2 samples each):

- PE
- Ropes
- object 1
- Object 2

Column 2 (2 samples each):

- plastics objects
- films
- small plastics
- fines