INNOVATIVE DIGITAL WATERMARKS AND GREEN SOLVENTS FOR THE RECOVERY AND RECYCLING OF MULTI-LAYER MATERIALS

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Benchmaraking LCA

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2 Executive Summary

This initial benchmarking study forms the fundamental basic component of the process for assessing the long-term sustainability of the proposed new plastics recycling strategies being developed during the Sol-Rec 2 project, and which will consider social, economic and environmental factors. Key overall objectives are to;

- Assess the environmental suitability and impact of the proposed Sol-Rec 2 processes and solvents by both using both Life Cycle Assessment (LCA) and Social Life Cycle Assessment (S-LCA) approaches.

- Determine the economic effects and benefits of implementing the technologies and materials developed within the project, with specific attention to the Life Cycle Costing (LCC).

- Ensure that the new ionic liquids and their processing technology comply with the relevant regulatory, toxicology and health and safety regulations etc.

In order to be able to fully assess the expected benefits and advantages of the ionic-liquid-based recycling processes being developed in the Sol-Rec 2 project, it is necessary to understand the impacts of the end-of-life approaches and recycling treatments currently applied to the types of food and medicine packaging being addressed by the project. In particular, there is a need to accurately define the currently used methodologies and technologies and to determine their related environmental and economic aspects. This will act as a baseline benchmark that can be used as a reference point for the new Sol-Rec 2 technology. A basic understanding of the current state of the art is essential, as it will help to guide the development of the new process elements as they move towards pilot scale delivery and demonstration. When at the demonstration stage, an LCA-LCC of the innovative Sol-Rec 2 pilot plant route will be carried out. Finally, LCA and LCC studies will be completed based on the industrial scale data. These will be the basis of the results for the environmental-economic profile of the Sol-Rec 2 mobile plant and will be compared to the current state of the art industrial scale technologies that are being assessed in this initial examination.

This benchmarking study includes both types of polymer waste being addressed in the project and deals with multi-layer polymer-metal materials waste with a specific focus on;

- Pharmaceutical blister packaging waste, which typically consists of a mixture of polymers and metals e.g., PVC/aluminium

- Laminated consumer packaging pouches containing mixtures of polyolefins, PET and aluminium.

In conducting this study, it has become abundantly clear that it is very difficult, if not impossible at this early stage of the project, to set an accurate baseline from which the new Sol-Rec 2 process can evaluated. This is due to the many complex factors that are described in detail herein and which are inextricably linked to the fact that both pharmaceutical blister packs and laminated food packaging contain disparate material compositions and are currently subjected to a wide range of end-of-life treatment processes. The actual key impacts such as global warming potential and ecotoxicity vary significantly across the large number of products that will form the basic input material to the Sol-Rec 2 process.

However, in compiling this deliverable, it has been possible to identify the key specific factors that constitute critical components of the current treatment and disposal activities. These will be important aspects on which to focus when assessing the benefits of the Sol-Rec 2 process. Where possible, these have been discussed in detail and quantitative data is provided for their specific impacts in the most important LCA categories. As the Sol-Rec 2 process evolves and becomes better defined, it will be possible to focus more accurately on the most important material and process related aspects of current practice and to better define the current baseline.

This document is, therefore, an initial assessment of the factors expected to be important in defining the current baseline and from which to develop a valid reference point. It is planned to issue further updates as the project progresses. The specific data will then also be utilised in comparative LCA work that will be carried out to assess the realistic benefits of the Sol-Rec 2 process.

3 Overall Introduction

Plastics are essential materials that are routinely utilised in everything from food packaging to clothing, motor vehicles, aircraft and electronics. In 2019, global plastics production was around 370 million tonnes, with Europe producing almost 60 million tonnes. This huge amount of material generates a concomitant amount of waste that is becoming an increasingly significant international problem. Consequently, there is growing pressure on the plastics industry, from both consumers and governments, to reduce plastics production and improve the levels of recycling after use. As a result, better waste management infrastructure and protocols have been implemented for the more efficient sorting of different polymer types leading to increased levels of both the collection and recycling of many types of plastic waste. This is demonstrated by the fact that around 9.4 million tonnes of post-consumer plastic waste were collected within the European Union member states in 2018.

However, 7.2 million tonnes of plastic waste still ended up in landfill and, if we are to achieve the circular economy of plastics, zero landfilling will be necessary. The desire within the industry to minimise the quantity of plastics used in consumer packaging has led to the phenomenon of 'light-weighting' which has resulted in the manufacture of soft drink bottles using up to 50% less plastic than previous products, but that are still able to retain the desired impact resistance and gas/moisture barrier properties. However, light-weighting has also led to the wider use of multi-layer materials that employ smaller quantities of virgin materials but at the expense of generating packaging waste that is difficult to sort and recycle. Laminated packaging is an increasingly popular option for lightweight product packaging, comprising multiple thin layers of materials, each with a specific function. Laminates containing polyethylene (PE) and polypropylene (PP) are being increasingly used to store consumer products ranging from laundry detergents and pet food to coffee and breakfast cereals. Such packaging typically consists of five to nine layers of different materials co-extruded or blow moulded to provide the desired barrier properties, with additional tie layers utilised to bond incompatible polymers together. In 2017, over 45.7 billion stand-up pouches were used in Europe, almost 1 billion more than forecast in 2014. A similar situation applies for pharmaceutical blister packs that are used to protect medicines and other sensitive related goods. The global pharmaceutical packaging market size is expected to be valued at almost $220 billion by 2028, and is currently expanding at over 9 % per annum. Blister packaging is a component of this and thus represents a huge amount of waste material that could be recycled.

Life Cycle Assessment is a process for evaluating environmental burdens associated with a product by quantifying the energy and materials used and the wastes and emissions released over the entire life cycle. Relevant ISO standards provide a general framework and set minimum requirements for the execution of an LCA. It is important to analyse the entire life cycle and to assess multiple impact categories. LCA has become a decision-supporting tool in packaging design and interestingly, the first ever LCAs, undertaken in the late nineteen sixties studied packaging. Since then, a large number of packaging LCAs have been published, many of them being comparative. Most studies have focused on the life cycle of packaging alone, without considering the interaction between the packaging and the packaged goods. Also, the first studies were not conducted in accordance with a standardized method and it was not until the nineteen nineties that standardisation took place. Unfortunately, due to different LCA modelling approaches, it is generally accepted that comparability between the results of these studies is often somewhat limited.

Following on from the initial standardisation approaches was the development of EPD (Environmental Product Declaration) systems which had narrower system boundaries and methodologies that allowed for comparability between studies. Another attempt to harmonize LCAs on an international level was The Life Cycle Initiative, hosted by the United Nations Environmental Program, which aims to provide a global forum for a science-based, consensus-building process.

The use of LCAs has been consistently recommended to compare the environmental impact of bio-based and fossil-based polymers and, thereby, to account for the important balances and trade-offs between polymers and their impacts, which is considered a pre-requisite in making sensible material selections. LCAs of products and processes are widely recognised as having two main beneficial features that are related to the 'cradle-to grave' approach, and to the use of a functional unit (FU) that enables comparative evaluations. An LCA is based upon a clearly structured methodology that is ruled by International Standards 14040 and 14044 and is a systematic tool that enables qualification and quantification of the relevant environmental loads and impacts that are associated with the life cycle of a product or service. Preparation of raw and auxiliary materials from resource extraction, transportation, product manufacture, end use and ultimately disposal of the product itself are all accounted for.

LCA has been significantly improved over the past decades, mainly thanks to the development of activities for improvement of currently used databases, integration of quality assurance; improvement of completeness, transparency and consistency of assessments and harmonization of methodological aspects and applications. This has contributed to its emergence as a valuable decision-support tool for both policy makers and companies in assessing the cradle-to-grave impacts of a product or process. Over the years, practitioners worldwide have used LCA to explore relevant environmental aspects in a wide range of sectors including food production and packaging and medicine blister packs.

The most ambitious initiative to harmonize LCA calculations and to improve comparability of results is the Product Environmental Footprint (PEF) initiative by the European Commission. The European Commission published recommendations on the use of common methods to measure the life cycle environmental performance of products in 2013. A number of shortcomings were also evident with this approach, not the least of which was the conclusion that, in reality, it was yet another approach. Whilst this has been refined with different impact assessment criteria, no PEF for packaging has been developed due to the fact that packaging cuts across and accumulates input from many different sectors and product categories.

Establishment of a base-line for both food packaging and polymer blister packs is thus a difficult and complex process, especially considering the various possible collection, treatment and recycling routes and their variability to a certain extent based on national variations that are influenced by 'local' legislation. This deliverable reviews the work that has been undertaken to date and attempts to highlight the key aspects that are important when setting a baseline that can serve as the reference bench mark for the forthcoming comparative LCA that will be used to determine the expected benefits of the Sol-Rec 2 process.

4 PART ONE - Pharmaceutical Blister Packaging

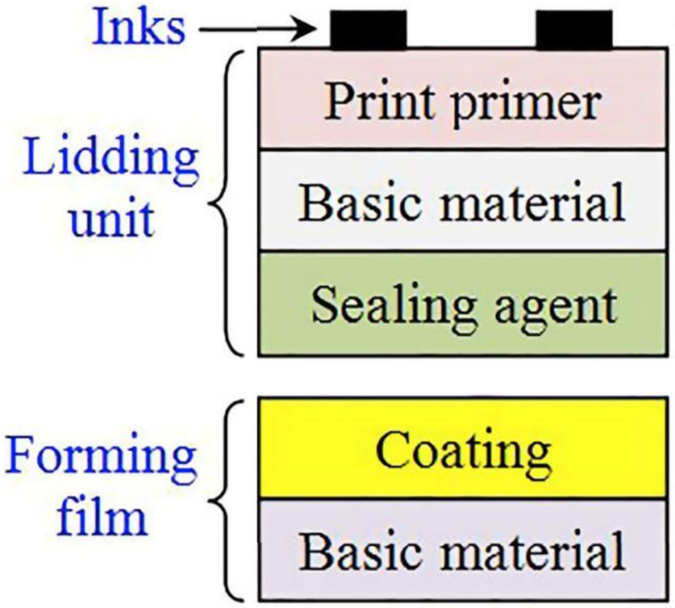
4.1 Introduction

Since the 1960s, so called 'blister packaging' has become the preferred method for packaging solid medicines and related products. This is because the method offers a number of significant advantages over the traditionally used plastic and glass bottles. These advantages include the ability to isolate individual tablets, giving better protection from the atmosphere and moisture, thereby improving the longevity of the packaged products. Additionally, blister packs are also more tamper-proof and give users an indication of the number of tablets consumed. Not surprisingly, therefore, the market for pharmaceutical blister packaging is both large and growing. The blister packaging market is projected to increase in value from $24.1 billion in 2020 to $34.1 billion by 2025, with a compound annual growth rate of 7.2%. In addition, the use of blister packaging is increasingly not limited to pharmaceuticals and there is growing demand for the technology in food, consumer and industrial packaging applications. It has been estimated that around 30% of blister pack applications are non-pharmaceutical.

However, the increased use of blister packaging has also generated an increasing volume of waste material and it is a significant cause of concern because of the difficulty in recycling what is in reality a complex mixture of polymers and metals.

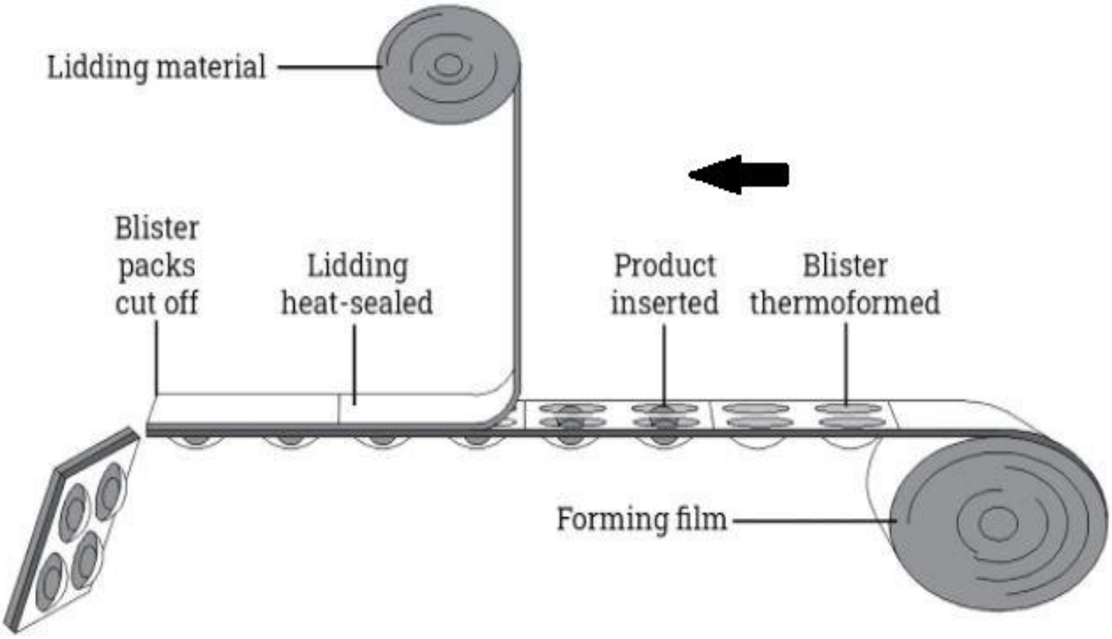
Example of a tablet blister pack

Pharmaceutical blister packs typically comprise a forming polymer film with the actual 'blisters' that contain each individual item and the 'lid' material that seals the package. In addition, there are a number of other materials such as polymer sealants, coatings, printing inks etc, which make the actual package much more complex and also challenging from a recycling perspective. These are outlined in the basic schematic of a blister pack shown below.



Schematic showing the basic structure of a blister pack

The blister component is normally produced using a thermoforming process on polymers such as polyvinyl chloride (PVC), polypropylene (PP) or polyethylene terephthalate (PET), while the lid materials are normally an aluminium foil, which may also have inks and coatings on it. The whole package is thus a complex mix of polymers, metal and other materials which makes economic recycling difficult. This type of packaging typically comprises approximately 80 to 85 wt.% organic (polymer) material and 15 to 20 wt% aluminium foil. The basic blister packaging process is outlined in the following schematic.



Basic schematic of the blister packaging process

As a consequence of the wide range of materials they contain, blister packs have not normally been economically recyclable, leading to the loss of valuable materials, while also requiring their replacement with additional virgin materials for new packaging. This type of approach is becoming increasingly unacceptable and there is growing pressure for the development of new technologies that are able to recover both the polymers and aluminium from blister packs, so that they can be reused in more circular economy type approaches. The key challenges in achieving this objective are in developing a suitable technology that is capable of separating the constituent materials and doing so in a manner that makes the process economically attractive compared to using virgin material. Furthermore, such processes also have to be environmentally benign, or at least show improvements in key metrics compared to the use of virgin materials.

4.2 Types of pharmaceutical blister packaging

As with most types of packaging there are many different blister pack constructions used in pharmaceutical applications, each with its own advantages and disadvantages and unique combination of materials. The preferred type of packaging will be determined by a number of important requirements which are essentially focused around the need to protect the contents, i.e., drugs and medicines, from physical damage, contamination and degradation by the atmosphere or moisture. The packaging thus protects the contents and helps to ensure the required service/shelf life. It can also be used to prevent counterfeiting and to promote a company and its products. Importantly, printing on the packaging can provide useful information such as expiry dates, dosages, date of manufacture, ingredients and other pertinent data.

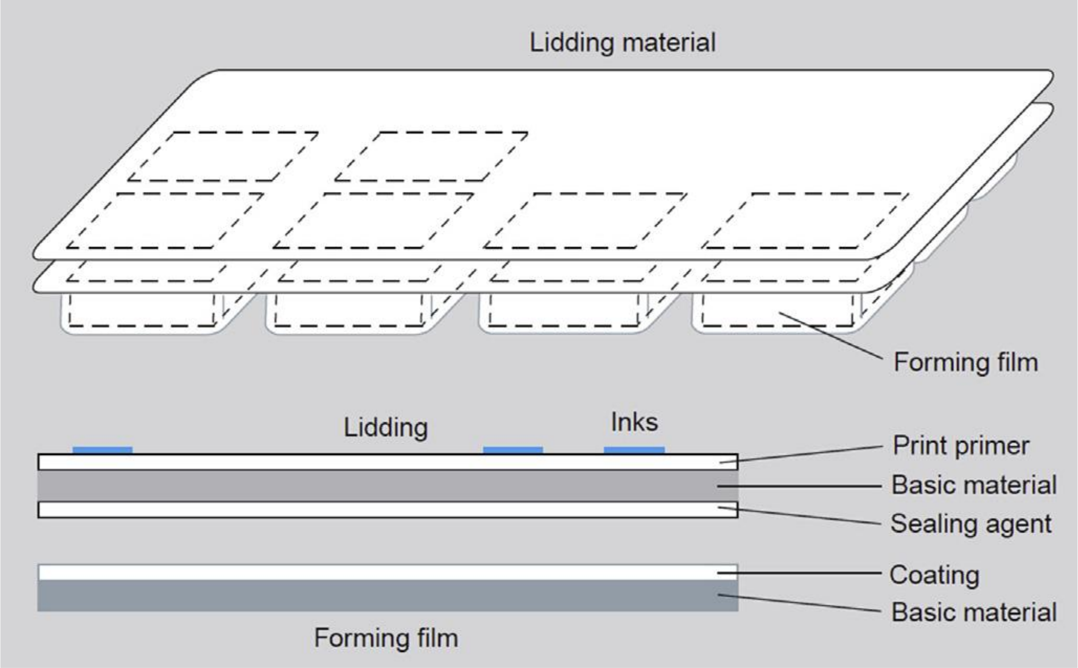
Although there are many types of blister packaging, they are all essentially comprise two key components. These are the materials which contain the pre-formed cavity/pocket and the lid and the two are bonded together. The part with the cavity is normally made of a thermoplastic material while the lid is typically made from a thin aluminium foil. However, it is also possible for other material combinations to be used, i.e., the cavity part itself could be made of aluminium and the lid fabricated out of cardboard, paper or aluminium. There are thus many combinations of materials that can be used and these will need to be individually identified, sorted and processed in any viable recycling and recovery operations.

Even within a specific type of plastic pack there are a range of materials that can be utilised, with each normally being selected because of its suitability for a particular application. For example, in the typical plastic/aluminium foil lid combination, it is possible to find several different polymer types in use. Common examples include polyvinyl chloride (PVC), polyethylene terephthalate (PET), amorphous polyethylene terephthalate (APET), high density polyethylene (HDPE), and acrylonitrile butadiene styrene (ABS), although other polymers are also sometimes used. These materials, and the reasons they are used, are covered in more detail later.

4.3 Materials Used in Blister Packaging

As mentioned above there is a wide selection of materials that can be used in blister packaging. For many applications, polyvinyl chloride (PVC) has often been found to be the most suitable because of its low cost and ease of forming. However, in recent years the use of PVC has become increasingly unpopular and there has been substantial global activity to replace it because of its potential to have a negative environmental impact (57% of the vinyl chloride monomer is chlorine). For example, Greenpeace and several other groups have declared PVC an environmentally unfriendly material and have campaigned for it to be banned.

Despite these issues, PVC has been the most widely used material for blister packaging, occupying around 95% of the blister packaging market. The PVC forming films that are used are rigid, because they are manufactured without any plasticizers or softening agents. PVC is ideal in these applications, as it exhibits both toughness and clarity, which is preferred for protecting products while also providing product visibility. Moreover, PVC films have good barrier characteristics and chemical resistance, both of which are needed for pharmaceutical packaging applications. A typical PVC forming film will have a thickness of between 200 and 300 microns. It is important to note that stabilizers do need to be added to the PVC, because it degrades at high temperatures, in a process known as dehydrochlorination. This produces hydrogen chloride which is highly reactive and clearly undesirable. Since heating is an integral operation in the PVC film forming processes, the stabilizers are added to help withstand the thermal and shear conditions throughout the process. These stabilizers must be formally approved for the specific type of application in which they are being used. Commonly used stabilisers have typically been tin-based but tin-free solutions are also becoming increasingly important.



More detailed section showing the composition of a typical blister pack

Where even better oxygen and moisture protection is required, polyvinylidene dichloride (PVDC) can also be utilised. While PVDC is not used itself as a forming film, it can be applied to other substrate materials such as PVC and aluminium to provide improved barrier properties. PVDC is one of the few coatings that can enhance both moisture and oxygen barrier performance e.g., by 5 to 10 times compared to PVC alone. It is also heat-sealable, with a high gloss, transparency, and flexibility. PVDC is not only applied to the forming film but to the lid structure as well, where it is used on the surface in contact with the product. However, just as with PVC, it can also thermally decompose with the emission of products that can be harmful to both the packaged products and the environment.

Another halogenated polymer that finds use in these applications is polychlorotrifluoroethylene (PCTFE), which has the trade name Aclar. However, unlike PVC and PVDC, PCTFE contains fluorine which make it a fluoropolymer. In a similar manner to PVDC, PCTFE is also laminated to PVC to enhance its barrier properties. PCTFE enables extremely low gas and moisture transmission rates to be achieved, while also being relatively inert to strong chemicals and resistant to UV and ozone induced degradation. PCTFE has high abrasion resistance, along with good transparency and thermal stability. It is often used for pharmaceutical aseptic blister pack laminate structures since they can be heat sterilisable.

While PVC is clearly a very widely used polymer in blister packs, the widespread pressure against the material has led to the increasing use of alternative polymers. For example, polypropylene (PP) is one such alternative forming film to PVC. Its water vapour permeability is comparable to PVDC-coated PVC and it is preferred in some regulated regions since it does not produce harmful chemicals when incinerated. Also, it can be more easily recycled than PVC. However, it has the disadvantage of being more difficult to process than PVC; PP cannot be readily fed into a standard blister packing machine. The range of operating temperatures for thermoforming PP is also very narrow and must be controlled precisely. Warping and post-processing shrinkage can also occur, which decreases the quality of packaging. Another alternative for replacing PVC is polyethylene terephthalate (PET). PET is widely used for packaging food and consumer goods, but is less common in the blister packs used for medicines.

A relatively new class of polymers known as Cyclic Olefin Copolymers (COC) have also been used as alternatives to PVC in pharmaceutical blister packaging. COCs represent a family of fully amorphous polymer resins that can exhibit comparable properties to PVC without the negative effects. They have also been used in multilayer structures for blister packaging and their properties can be varied by modifying the basic chemistry.

Clearly, the wide range of polymers that can be used in pharmaceutical blister packs coupled with the other requisite materials such as aluminium, make their effective recycling complex and difficult. This has prompted work into both new materials and in making blister packs simpler in construction. For example, a Swiss packaging company Amcor has recently introduced its AmSky recyclable polyethylene-based thermoformed blister packaging. This new packaging material has been specially-designed to meet the requirements for pharmaceutical packaging, while also offering a more sustainable alternative. The AmSky blister system utilises a mono-material polyethylene (PE) thermoformable blister and lidding film and thus avoids the use of PVC.

4.4 Current Disposal Methods for Pharmaceutical Blister Packs

Until recently, there had been very little, if any, recycling of pharmaceutical blister packs. This was due to a number of issues that made their recycling relatively complex and thus not economically viable. Also, it is not clear how consumers treat end of life medicines or empty blister packs. In some cases, they will inevitably be discarded with other household refuse which is destined for landfill without any treatment or sorting. Alternatively, the blister packs may be separately collected with other plastics that are destined for separation and recycling. However, it is clear that while some of the plastics collected from households are indeed recycled, others are not. They may subsequently be incinerated, or possibly sent to landfill, having been discarded as unrecyclable.

If pharmaceutical blister packs are to be successfully recycled, it is likely that specific collection schemes will need to be implemented where they can be aggregated as a specific type of waste. Fortunately, there is now an increasing awareness of the need to recycle pharmaceutical blister packs and such schemes are starting to be implemented. For example, in the UK, some pharmacists such as Superdrug, are participating in a scheme, run by the company Terracycle, to collect end of use medicine packaging. Terracycle take the empty blister packets and separate them by polymer type and also clean them (if necessary). Ultimately, the recovered material is extruded into plastic granules that can then be used to make new products. However, in July 2021, it was reported that the Terracycle medical packaging recycling scheme had been scaled back following the unexpected 'high uptake' of the scheme. The Royal Pharmaceutical Society (RPS), explained that the composition and safety requirements of blister packs created difficulties in recycling them and the scaling back of operations was perhaps an indication of the challenges in economically recycling these complex mixtures of organic and inorganic materials. It may also be an indication that the required levels of blister pack recycling are unlikely to be achieved without some form of incentivisation or legislation.

Some of the reasons why they have not been recycled include the following;

- Blister packs are relatively small and light weight, which means that consumers are less likely to individually sort them for recycling and more likely to simply consign them to the domestic household waste which is destined for landfill.

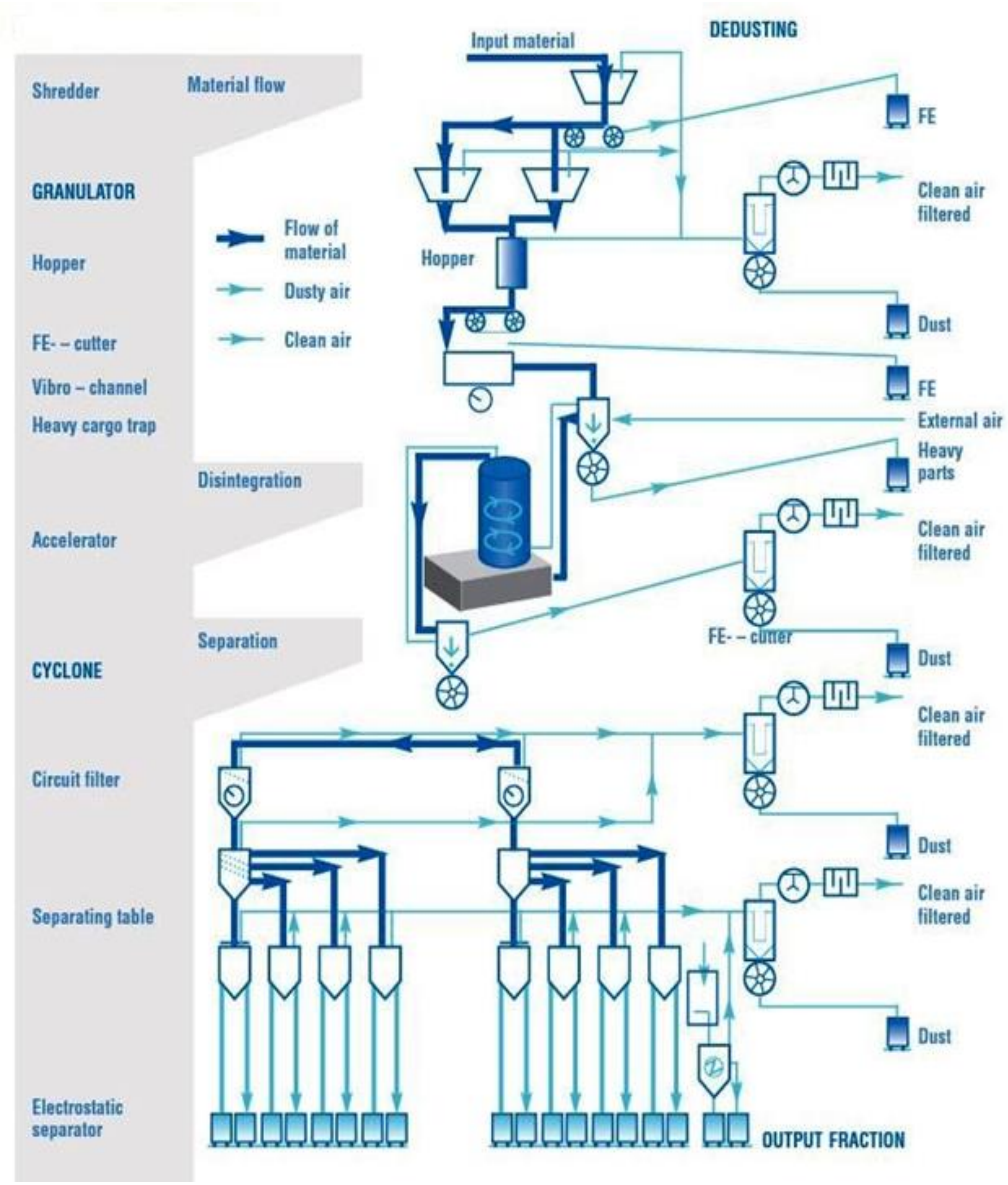
- When discarded, they may contain remaining quantities of unused medicines which could be both toxic and a source of contamination in any recyclate. There are thus important health and safety aspects that need to be considered. At the very least, there will be a need for individual blister packs to be inspected and sorted. Depending on the inspection, it is likely that there will be three outcomes; the pack can be recycled as is with no further treatment required, the blister pack will need to be cleaned before recycling or the blister pack is too contaminated to be recyclable and will need to be safely disposed of in some other manner e.g., by incineration.

- As with all recycling operations, every additional processing stage or intervention in the recycling process adds to the costs and, in this case, also generates a further financial burden in terms of processing the non-recyclable waste that will inevitably be generated.

- Even when empty, the blister packs represent a significant recycling challenge because of their complex material make ups, which include various types of polymers, adhesives, inks and aluminium. Each specific type of blister pack may need to have its own specific treatment requirements and thus there will be a requirement to identify the composition and material types used prior to recycling. At the moment, this requires complex analytical procedures or reference to the manufacturer's information about the packs (if available). Clearly, this is not practical on an individual basis when products have so little intrinsic value. However, the use of digital watermarking on blister packs, as is being evaluated in the Sol-Rec 2 project could lead to their high-speed sorting and thus subsequent segregation for a specific type of recycling process. For example, PVC is currently identified by the recycling symbol 3 i.e.

There are also more general issues and concerns about the recycling of PVC, which is found in the majority of pharmaceutical blister packs. PVC has traditionally been the one major class of polymers that has not been recycled, despite the fact that it is one of the most widely used. A key issue with the recycling of PVC is its high chlorine content, but there can also be problems caused by the additives that are used to provide the requisite final material properties. PVC must therefore be separated from other plastics before recycling.

However, despite these issues, there has been much work recently, especially in Europe to develop new and improved methods for the recycling of PVC. For example, the European VinylPlus scheme has been working to develop mechanical recycling processes that consider the quality of the waste materials collected, along with the further processing requirements and those of the recycled products. As part of this activity, a number of companies have been investigating the development of novel or improved waste separation techniques. There have been attempts to separate a mixed waste into streams that can be handled by conventional mechanical recycling. A good example of this type of approach is that developed by Neidhardt Recycling GmbH in Germany. A schematic of the process is shown below;



Schematic of the Neidhardt process for recycling PVC/aluminium blister pack materials

In their process, the input material is the PVC-aluminium composite material used in pharmaceutical blister packaging. The process relies on a clean supply of the polymer-aluminium composite materials which is first shredded into 20 mm pieces. The shredded pieces are then transported by a conveyor belt to an acceleration rotor where it is ends up in the air stream between the rotor and the stator. The aluminium and PVC are delaminated as a result of the high-rotation speed and the process transforms the aluminium sheet into balls, whereas the PVC sheet remains flat. The delaminated mixture is then sieved into a range of sub-1 mm fractions and the metal and polymer are subsequently separated using an electrostatic device.

As a result of this separation, the PVC fraction can then be used to make new products such as pipes etc, while the aluminium is supplied to metal foundries for use in special applications. However, it should be noted that this type of recycling method, where mechanical grinding is used to separate aluminium from PVC in laminate material waste can still be problematic. For example, the resulting separated aluminium can contain up to 10 % residual PVC, which prevents it from being directly used as a recyclate. A subsequent, thermal post-treatment of such recycled aluminium is need to pyrolyze the PVC and this requires expensive waste gas scrubbing to remove the hydrogen chloride gas generated. It has also been stated that the aluminium produced by this route can have a much poorer quality compared to primary aluminium.

To address this issue Neidhart GmbH have been working with the Fraunhofer IVV to develop a new type of approach for the innovative separation of aluminium and PVC. The method utilises a modified version of the so called Creasolve extractive recycling process that was initially developed by the Fraunhofer IVV to recycle polystyrene. The Creasolve process comprises five key stages:

1. Pre-treatment; where the waste plastics are cleaned, ground and mixed

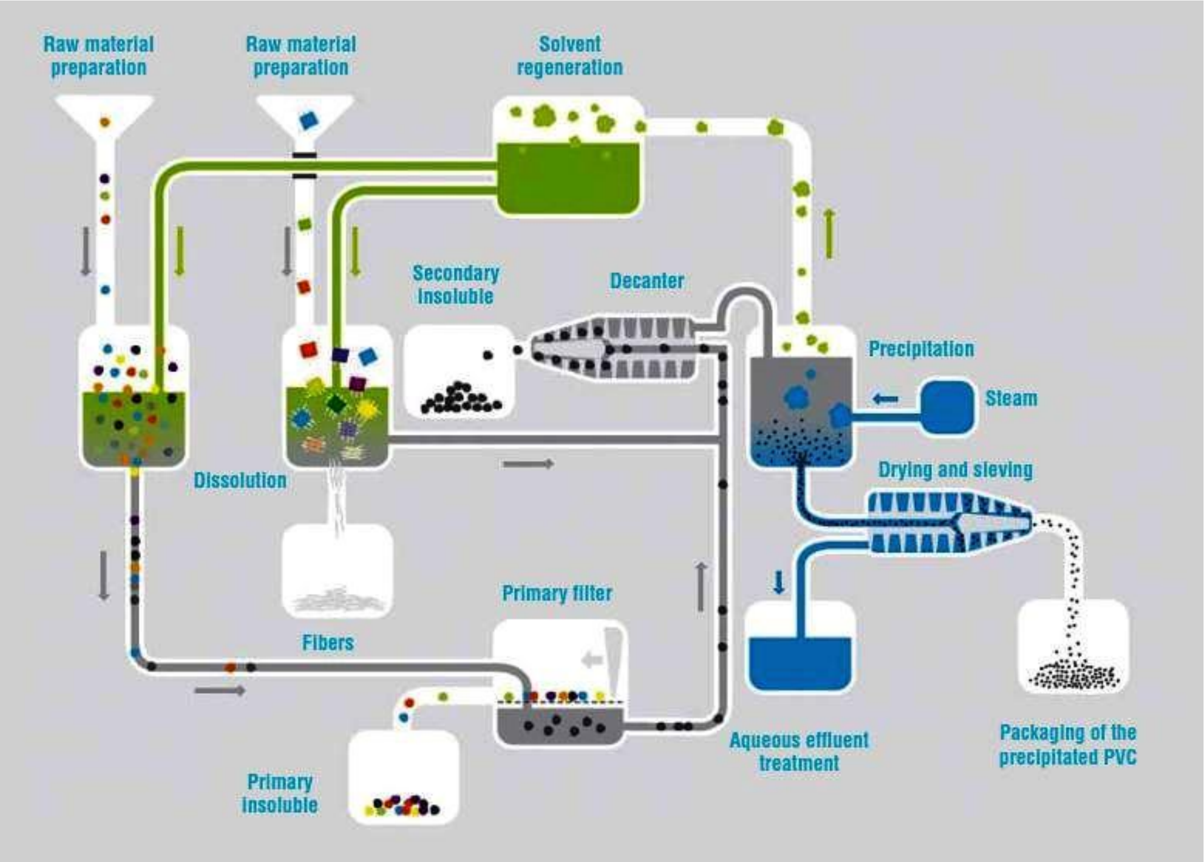
2. Dissolution; where a specific solvent is used to selectively dissolve the PVC compound in a closed loop process where the solvent is continuously recovered/regenerated

3. Filtration and removal of any non-soluble components. These are separated using an initial primary filtration stage followed by use of a centrifuge. (The resulting secondary materials are washed with pure solvent to dissolve any remaining PVC compounds)

4. Precipitation of PVC. The dissolved PVC is recovered in a precipitation tank, where steam is injected to evaporate the solvent and precipitate the PVC

5. Drying; after recovering excess water from the slurry, the wet PVC progresses to a dryer. The PVC compound precipitates as micro granules.

A schematic of the Creasolve method as applied to PVC recycling is shown below;



Schematic of the Creasolve method as applied to PVC recycling

The approach aims to achieve the total removal of the PVC using selective green solvents (e.g., non-hazardous, non-VOC). These biodegradable solvents are also used in a closed loop manner that enables their return to the process cycle. The objective is to produce high-purity, secondary aluminium and a hard PVC that can be used by the plastics industry. There is a fully operational commercial plant in Ferrara, Italy that is able to handle 10,000 tpa of PVC scrap. This approach therefore has some similarities to the approaches being proposed in the Sol-Rec 2 project.

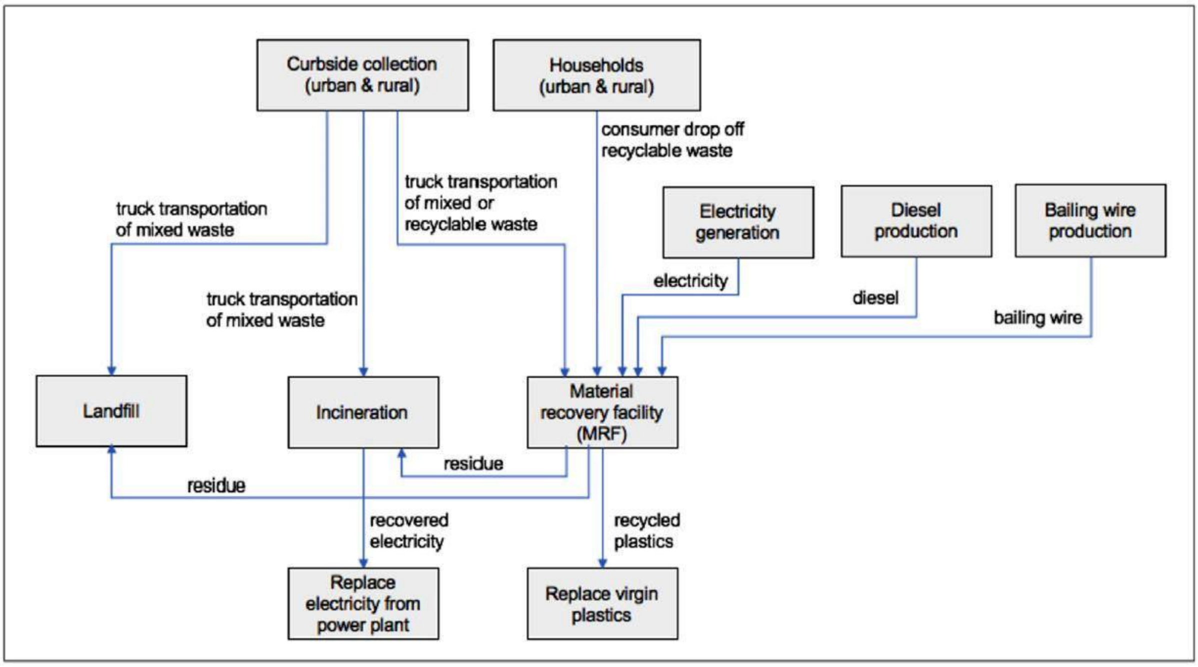
4.5 Life Cycle Assessment of Pharmaceutical Blister Packs at End of Life

As detailed above, the recovery and recycling of the materials used in pharmaceutical blister packs is difficult to undertake economically because of the complex multilayer structures used. Consequently, they have typically not been recycled, with consignment to landfill being the simplest and lowest cost method for handling such waste. However, this is far from ideal, as it represents a waste of valuable resources and because both the aluminium and polymeric components of the packaging can lead to soil acidification (Yousef et al., 2018). In addition, in the case of aluminium, this 'use once and dispose' approach ultimately means that increased production of primary aluminium from bauxite ore is needed, which requires high energy consumption (Frees, 2008). The need for the separation and recovery of polymers and aluminium from waste pharmaceutical blister packs has thus become an increasingly important issue, while also presenting an opportunity for package manufacturers due to the potential for lower costs and reduced environmental effects if they can utilise recycled aluminium instead of virgin material.

In order to assess the viability of the Sol-Rec 2 proposed blister pack recycling process using an ionic/liquid deep eutectic solvent-based approach, it will ultimately need to be more efficient than alternative recycling methods (which realistically don't exist at the moment) and better, using a number of assessment criteria, than what currently happens, i.e., landfill or incineration. Ultimately, however, in order to be successful and widely implemented, the process will need to either be financially viable or, if not, mandated by legislation or incentivised in some other way. It should be noted that it is often more attractive economically, to simply landfill or incinerate materials of this type, as is the current practice. Without suitable legislation being in place, the situation is unlikely to change, especially as the Sol-Rec 2 process uses a range of chemicals in a multi-stage process, each with a concomitant energy demand and the likelihood of additional waste generation. Nevertheless, there has been success in other areas via the introduction of legislation, with a good example being the WEEE Directive, where waste electrical and electronic equipment is now increasingly successfully recycled. There is also growing global pressure to both reduce the use of plastics in packaging and to encourage the recycling and reuse of such materials.

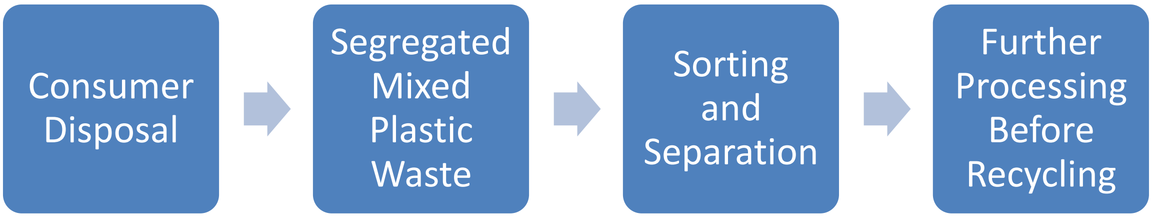
Clearly, even if the recycling of blister packs is mandated by legislation, it will be important to use processes that have less of an environmental impact than the current landfill or incineration routes. It is, therefore, important to assess the impact of current end of life processes i.e., landfill or incineration, so that these can be used as a baseline from which to carry out a comparative Life Cycle Assessment evaluation with the newly developed Sol-Rec 2 process. Some elements of the pathway following user disposal and the generation of new products will be the same, but there will also be additional process stages when adopting a recycling approach. Although, at the time of writing of this initial report, the Sol-Rec 2 process had not been finalised, the basic process flow and any additional treatment stages could be outlined and compared to the current methods. At the very simplest level, the current end of life methods are outlined in the flow diagrams below. The first two represent current practice, where the blister packs may simply be disposed of in domestic refuse. This is quite likely to result in the blister packs (mixed with other household waste) being collected and transported to a landfill site, or to an energy from waste plant. In the case of consignment to energy from waste, there will probably be some basic sorting of the incoming waste in order to maximise the calorific value.

However, even these basic current disposal routes are multistage and contain numerous important elements that need to be considered from an LCA perspective. The process flow of such a post-consumer plastic film treatment system has been summarised in the diagram produced by Ping et al and this is shown below;



An example of a process flow diagram for a post-consumer plastic film treatment system (after Ping et al)

Given that consumers are now required to separate their waste and, in some cases, to isolate plastic waste, it is likely that a proportion of the blister packs disposed of will be disposed by consumers with other plastic waste. However, as many blister packs may be disposed of while still containing some medical products, it is more likely that these will be found in the general domestic waste stream rather than with the mixed plastic waste. (The presence of part-used blister packs could present a potential contamination problem when recycling such materials, but this would not be an issue with incineration, and less of a problem with landfilling.)



Assuming that the public can be persuaded to dispose of their empty blister packs with their other plastic waste, it may be possible to separate them from other plastics for recycling. This could include separation by polymer type, especially if the Sol-Rec 2 digital water marking approach can be implemented to help identify the polymer types present.

The preferred approach would be for consumers to isolate their blister packs and to dispose of them separately somehow. Unless a suitable collection scheme can be adopted by those already collecting household refuse, it seems likely that some type of disposal collection scheme will need to be established. This could for example be based in local pharmacies or doctors' surgeries, where people passing by, attending appointments, or collecting new medicines/prescriptions could drop off their old blister packs at the same time. From an LCA perspective, this will add an additional transport component related both to the drop off stage and the subsequent collection that will be necessary to take the blister packs to a sorting and processing facility. Any transportation using vehicles is likely to impose several negative environmental impacts, e.g., air pollution from emissions (unless electric vehicles exclusively utilising renewable energy are employed). Nevertheless, the manufacture, maintenance and material disposal of such vehicles will also contribute to the emissions, energy and raw materials consumption that must be considered. It should also be noted that there may be additional negative impacts associated with collection schemes, such as the need for cleaning of packaging waste by consumers prior to disposal and the manufacture and maintenance of the special collection containers likely to be associated with any collection schemes. It is also worth noting that, in related plastic recycling method appraisals, it has been found that approaches where consumers take their waste to a drop-off collection point had the highest environmental impacts because more journeys were required to collect the same amount of waste compared to collection by a dedicated pick-up vehicle. This could of course be negated by encouraging the public to only drop off used blister packs at a collection point such as a pharmacy when they were making that journey anyway i.e., to collect new medicines prescriptions etc. Otherwise, such approaches would not be preferred from an environmental perspective and should only be used when no new journeys were needed. Methods such as segregated curb side collection using dedicated vehicles powered by renewable energy would probably be the most advantageous.

Importantly, the fact that there are different types of pharmaceutical blister packs used means that there are important LCA considerations to be considered even before the packs are discarded. Some types of blister packaging use aluminium to provide the requisite gas and moisture permeability requirements, while others rely on PVC alone. A previously completed comparative energy balance study found that blister packaging with aluminium consumed 63% more energy than PVC blister packaging throughout its life cycle. Additionally, the global warming potential of aluminium blister packaging was 70% greater than that of PVC blister packaging. Overall, the study found that the environmental performance of PVC blister packaging was better than that of aluminium blister packaging, as the PVC blister packaging performed better in nine out of eleven impact categories. The aluminium foil manufacturing stage, which included ore extraction, metal production and foil rolling was the least environmentally friendly step and seriously negatively impacted the environmental profile of aluminium blister packaging. This clearly has important ramifications for the Sol-Rec 2 technology, since the recovery of aluminium may need to be a significant and important part of the process from an environmental benefit perspective. Clearly, there would also be benefits if a standard material construction could be adopted for blister packs, based on the best combination from an environmental and a recycling perspective. However, this would appear to be unlikely, and would probably only be adopted by all manufacturers if they were mandated to do so by legislation.

Overall, and based on the results of previously reported studies (e.g., Bjorklund), it seems clear that recycling can offer considerable advantages over disposal via landfilling or incineration. The main environmental benefit for pharmaceutical blister packs is that by recycling both the aluminium and the plastics, the recovered materials can replace virgin materials and thus contribute to reducing their production. The key factor with any recycling and reuse approach is that it maintains these advantages.

4.6 Consideration of Current Disposal Methods

Given that pharmaceutical blister packs are currently disposed of via landfilling or incineration some discussion of each approach, and their associated activities, from an LCA perspective is clearly appropriate, if they are to be used as a baseline for comparison with the new Sol-Rec 2 recycling process. At the very top level, the current and proposed processes can be defined by the top-level process stages shown in the following flow table below.

Current Method: No Separation	**Current Method: With Separation**	**Proposed Method with Sol-Rec 2**
Not separated: i.e. consumer disposal with general household waste	Separated: i.e. consumer separates waste and blister packs are collected with other plastic waste	Dedicated collection scheme for blister packs initiated: e.g. consumer recycles blister packs at local pharmacies and other participating shops etc.
Transport with municipal waste to appropriate facility	Plastic sorted by polymer type etc. Some plastic is recycled, but complex mixtures of materials i.e. blister packs are landfilled or incinerated.	Specialist recyclers collect the blister packs for recycling, or they are shipped to a central sorting and recycling centre
Blister packs are landfilled or Blister packs are incinerated	Transport to appropriate facility	Initial sorting of blister packs into various categories/types: e.g. by material composition and main polymer type
	Blister packs are landfilled or Blister packs are incinerated	Selection of packs for Sol-Rec 2 recycling, other potential processing or rejection for landfill or incineration
		Initial treatment of blister packs; e.g. washing and drying to remove any dirt/contamination/unused medicines etc.
		Further pre-treatment of blister packs; e.g. mechanical treatment to initiate separation by polymer type. Comminution to increase surface area etc
		Main Sol-Rec 2 process stages; e.g. solvent treatment to remove adhesives, polymer dissolution and recovery, aluminium recovery
		Post-process treatment of solvents and ionic liquids for reuse, treatment and disposal of 'sludge' waste e.g. adhesives etc.

The current processes of disposing of plastic waste to landfill or via incineration are the two least favourable options. In terms of the end-of-life hierarchy and indeed the recommendations of the Waste Framework Directive 2008/98/EC, energy recovery i.e., incineration is preferred over disposal to landfill, yet landfilling is still a popular option. In terms of the development of a new plastics recycling process such as Sol-Rec 2 which is aimed at facilitating the recovery and reuse of the individual polymers and aluminium found in medicine blister packs, it is clear that the process should be economically viable as well as offering reductions in important environmental impact factors such as global warming potential and total energy consumption. There have been numerous LCAs and related studies carried out on wide range of polymers and, although the results are often both complex and conflicting, there is a general agreement that recycling is better than either landfilling or incineration. In most of the LCA carried out for common polymers such as PE, PP, PS, PVC and PET, the general finding is that the global warming potential of recycling is less than that of either incineration or landfilling. It is less clear whether incineration or landfilling offers the better option in terms of global warming potential. However, when considering total energy consumption, while recycling is again the preferred option, incineration is almost always better than landfilling. This is perhaps not surprising because of the energy that can be recovered by incineration. The results of an analysis of numerous reported LCAs are nicely summarised in the environmental and economic life cycle analysis of plastic waste management options review reported by C. A. Bernardo et al (Bernado C. A.). In the case of PVC, which is widely used in blister packs, the toxic emission issues around the incineration of the material have been widely reported and are now well known. Of the two options the landfilling of PVC is the best option because the leaching of additives such as phthalates is deemed to be a less serious environmental problem than emissions generated by incineration.

5 Part 2 - Multilayer Food Packaging Waste

5.1 Introduction

As multilayer flexible packaging offers significant environmental advantages in respect primarily of minimising raw material usage, it is important to note the value of LCAs in being able to give focus to the areas of address required to elevate such products to a true element of a circular material approach. In broad terms, the advantages and disadvantages may be set down as follows and the quantification of these within the scope of an LCA can only serve to enhance the potential to address zero impact.

5.2 Advantages/ Positive Factors

Multilayer flexible packaging is superbly designed for first-life offering minimized content spoilage, long shelf-life, reduced costs, consumer convenience and easy opening.

Less material is used than with other formats (the minimum possible) and much less packaging waste - only 2 % of municipal solid waste is considered to be flexible packaging

Less energy is needed for production and transport, thus lowering costs

It offers lower environmental impact (LCA) and carbon footprint (GHG emissions) than other packaging formats

High barrier protection keeps products fresh for longer, reducing product waste, and enhancing flavours. Barrier properties are tuneable to meet the product and shelf-life needs. They can be retorted and hot-filled to replace glass and metal.

It can be tailored to a specific product and size with continual development of new and improved designs, e.g., with resealable tabs, handles, zips, spouts, dispensers.

It can be readily printed, decorated and coded without the use of separate labels, allowing instant changes.

Flexible Packaging Europe reported that if all non-flexible packaging were replaced by flexible, it would save 26 million tpa packaging entering the waste stream, providing about a 77 % reduction in total weight recycled or landfilled.

Flexible packaging provides the same functionality as many other formats but uses far less resources. Its resource efficiency will be even further increased by optimization of end-of-life recovery.

5.3 Disadvantages/ Negative Factors

The main disadvantages are those associated with the problems of disposal, littering, ocean pollution, reuse and recycling. This is largely because of the:

- lack of recycling infrastructure, which is largely due to problems of collection, sorting and recycling of films and multilayer laminates, particularly for barrier packaging and post-consumer waste
- difficulty in economically mechanically recycling multilayer structures, so that they generally end up in landfill or are incinerated to recover energy content

- problems with common food waste contamination, often between 10 - 20% of the total package weight
- slow environmental degradation of many of the materials used
- continuing visibility challenge with flexible packaging, even though it uses much less material than other formats

Prior to a consideration of LCA studies on the subject of multilayer plastic food packaging and indeed any form of food packaging, it is as well to consider the shortcomings of LCAs in such regard and the consequences in respect of food packaging policies.

LCA studies have become increasingly deployed as a decision-supporting element in food packaging design and there has been a growing frequency with which results from such studies have been referenced in plastic packaging industry-led communications with policy-makers. It is, however, clear that LCA studies taken in isolation are unable to define optimal environmental approaches. As a methodology, an LCA has both strengths and weaknesses. The key points to note regarding LCAs and their use in multilayer plastic food packaging include;

- LCA emphasis on greenhouse gas (GHG) emissions (particularly during the production of food and during transport) has resulted in decisions in food packaging design made at the expense of material efficiency, with too much focus on carbon emissions and too little on end-of-life impacts. This has resulted is complex packaging designs, such as pouches, which are impossible to recycle and that lead to 'mixed residues destined for landfill' or incineration.

- Existing LCAs consider waste management scenarios which often ignore environmental leakage of packaging. Assessments could better consider the waste treatment realities of specific markets in order to develop measures to reduce marine litter and other forms of pollution.

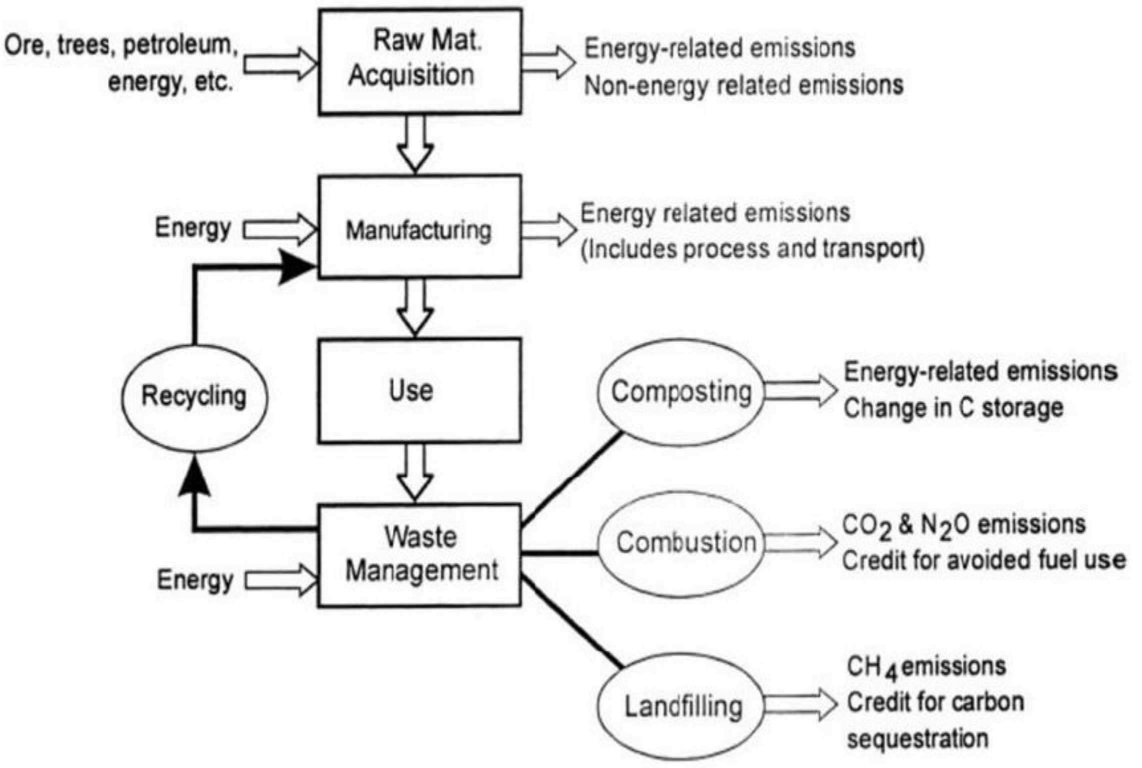
- As the knowledge base on chemical migration from food contact materials grows, these considerations should be better integrated into the assessment of packaging designs and material choices. In the absence of such strong evidence, the precautionary principle should be adopted.

- LCAs should be better combined with knowledge on food waste drivers in order to understand the extent to which packaging can reduce waste of the product itself. Most food waste drivers (e.g., over-purchasing and preparation techniques) are not linked to packaging, and some packaging practices (e.g. trimming and multipacks) can increase food waste.

- Where LCA is applied, greater attention should be paid to the investigation of systemic solutions, such as short food supply chains, package-free retail and reusable packaging.

The ability of LCAs to give a rigorous assessment of every element and process resulting in a final product has led to their extensive use in evaluating the environmental performance of food packaging. In such cases, LCAs are often used to compare alternative packaging made from various materials or designs, in a bid to identify the option with the least impact on the environment, resources and health. Specific impact categories and indicators are defined, weighted or omitted, based on the objectives of the study.

PET, PVC, PE, PP, PS and polyamides are the plastics most commonly used in food-packaging This is because of their good availability, low cost and excellent properties such as tensile and tear strength, being good barriers to oxygen, carbon dioxide and aroma compounds and offering heat sealability etc. However, when they are used as food-packaging materials they are not totally recyclable and, because they are often contaminated by foodstuffs and biological substances, thousands of tons are landfilled every year, increasing the problem of municipal waste disposal. To address these negatively impacting environmental concerns, LCA is a useful technique for evaluating the environmental impact of such materials, considering primarily two fields of interest. The first one is the final destination of post-consumer plastics, comparing recycling with other options such as source reduction, incineration and landfilling, as well as energy conversion and chemical recycling options such as being developed in the Sol-Rec 2 process. The second one is to take into consideration alternative materials such standard glass and/or metal packaging and/or biodegradable polymers that could be recycled or composted. These options must be considered over their entire life cycles and can be summarized in the following figure.



Schematic of food packaging lifecycle considerations

In many cases, LCAs for food and beverage packaging include the packaged product itself, e.g., assessing the environmental impact of the food that is packaged, as well as the packaging. The inclusion of the packaged product in a packaging LCA is a logical inclusion, as the environmental impact of food production and product losses through the supply chain can be significant (Flanigan, Frischknecht and Trisha, 2013).

Most of the studies that have included packaged products in their examination conclude that a specific packaging design is preferable if this can lead to less food waste. Such conclusions are based on the argument that the production of one more unit of food product causes greater environmental damage than the production and waste management of one more unit of packaging serving primarily to protect the food product. However, the increasingly problematic aspects of packaging waste and pollution, alongside persistently high levels of food waste, brings this argument into question (Schweitzer et al., 2018). In the context of policy developments on both food waste and packaging waste, analysis suggesting that packaging can significantly reduce the impact of food waste has the potential to be both politically and industrially valuable. Moreover, media and public communications linked to the food packaging industry commonly focus on the value of plastic packaging in reducing food waste. There is thus a need to better understand how LCA data is used to develop policies on packaging and food waste. A number of non-exhaustive reviews of LCAs on food and beverage packaging, both with and without food waste considerations have been recently conducted, e.g. see Schweitzer, J.-P., Petsinaris, F. and Gionfra, C. (2018).

Multilayer food packaging is especially under scrutiny as it combines numerous materials such as polymers, paper, aluminium, and organic or inorganic coatings. Considering the environmental impacts measured by LCAs, these packaging solutions are highly efficient. The main problem, however, is that they are hardly recycled in the existing waste management infrastructure, as Europe widely relies on traditional approaches such as mechanical recycling for regranulation processes, which generally means combined processing of materials. The thermal incompatibility of the diverse combined materials is a major obstacle in reprocessing. New technologies such as chemical recycling have shown promising results, but they need further research, development and scale-up. At the moment, much effort is being applied to the redesign of multilayer flexible packaging in order to improve its recyclability within the existing collection, sorting, and recycling infrastructure. Recyclable film solutions based on polyolefins (polyethylene (PE) and polypropylene (PP)) have already been achieved, as packaging waste material streams exist for these films, at least for mixed polyolefin streams. As polyolefins already dominate flexible food packaging, the restriction of the use of certain other polymers such as polyethylene terephthalate (PET) or polyamides (PA), which are not compatible with polyolefin recycling, could be beneficial.

Unfortunately, enhancing the recyclability of multilayer films often results in reduced packaging efficiency; current products have typically been developed to exhibit optimised resource efficiency and product protection. Reducing the complexity of these films may well result in a need for thicker films, meaning heavier packaging would be needed to achieve the same performance. This is contrary to the circular economy goals of reducing resource consumption and environmental impacts.

Multilayer flexible materials account for 10 % by weight of all packaging. This may not seem huge, but at least 40 % of food products utilise flexible packaging.

A consideration of the characteristics of multilayer flexibles, their contribution to sustainability, and their incompatibility with widely applied recycling technologies makes it possible to discuss the future design of this type of packaging. It is clear that further research is necessary to bring recyclability and overall sustainability together in barrier packaging. Material combinations and recycling options offering clear environmental benefit have to be developed. Multilayer food packaging is a tailored solution with the beneficial properties of diverse materials combined into one packaging solution. Flexible packaging such as pouches, bags, and lidding, as well as rigid packaging such as trays, cups, and bottles consist of variable materials, sometimes combined in layers. Through the approach of combining materials, these products can offer technical and systemic strengths but also weaknesses along the life cycle stages, from production to use phase and end-of-life scenarios.

Conclusions from a recent review of recyclability and redesign challenges in multilayer flexible food packaging (Anna-Sophia Bauer, Manfred Tacker, Ilke Uysal-Unalan, Rui M. S. Cruz, Theo Varzakas and Victoria Krauter, published 2021) summarise multilayer flexible packaging as being efficient. It combines the properties of polymers and non-polymeric materials to thin, lightweight packaging solutions for foods with and without barrier needs. The main problem is that it is rarely recycled in the existing waste management infrastructure. This is caused by multiple factors and circumstances including the variability of the discarded materials, the collection infrastructure, the complex sorting processes needed, and high levels of food residues. Additionally, the focus on mechanical recycling through combined processing complicates the situation. New recycling technologies exist but they are not yet available on a larger scale. This leads to a concentration on mono-material solutions to fit into the existing recycling infrastructure and diminishes the material choice to overcome thermal incompatibilities. The maximum tolerated levels of barrier materials are widely discussed and are in the process of being reduced. The substitution of a specific material is challenging, as only a limited number of barriers are available. In relation to the main purpose of packaging, product protection, this could result in negative side effects. A reduction in food shelf-life, higher packaging weights, and the derived increased environmental burden are consequences that need to be considered when taking steps towards the goal of packaging redesign for holistic sustainability.

A study of LCAs for food and beverage packaging was carried out by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) (Flanigan, Frischknecht and Trisha, 2013). The study reviewed 69 existing LCAs of food and beverage products in order to illustrate the value of applying LCAs to address packaging design in the sector. Based on its analysis, the UNEP/SETAC study explained the benefits of LCAs for assessing the impacts of packaging. These were the inclusion of;

- multiple environmental impacts and indicators
- all product life cycle stages
- the packaged product in the analysis

The report refers to some potentially problematic issues in respect of LCA results and the waste hierarchy, the transferability of LCA results to developing countries and the links between packaging and marine debris, without exploring these issues in detail. For example, the analysis questions the potential relevance of LCA for packaging for developed countries, noting the heterogeneity in environmental impacts and losses in the food supply chain between developed and developing economies (Flanigan, Frischknecht and Trisha, 2013). The report argues that packaging can help to reduce food loss in developing economies, in view of the inadequate infrastructure. However, it fails to acknowledge that inadequate infrastructure, such as waste management, will also likely increase the risk of environmental leakage of packaging, as confirmed by research into global marine litter sources (Jambeck et al, 2015). Although the UNEP/SETAC report provides useful insights into the relevance of LCA for packaging, it does not address some of the key sustainability challenges facing the packaging sector, nor does it examine how these can be tackled via LCA methodologies.

The review demonstrates the complexities inherent in capturing all of the environmental impacts of food packaging in a single methodology. The LCAs reviewed were not intended to address all of the relevant aspects necessary to develop comprehensive policies on packaging and food waste, but they nevertheless provide insights into the adaptation of studies for policy discussions in the future. The following sections identify some relevant shortcomings in LCAs undertaken within this sector.

A number of LCA studies have focused on only one or very few environmental indicators, usually climate change in the guise of greenhouse gas emissions. The choice of environmental impact categories is important when analysing different types of materials, as some can be more resource-intensive or polluting during their production. The exclusion of specific indicators may, therefore, impact the results.

For example, the OVAM (2015) report was conducted by an expert group which included experts from the Pack4Food1 consortium. It found that all of the food products considered within LCAs needed to be covered with additional packaging to afford better protection. However, the only impact category considered in the LCA was 'climate change'. While GHG emissions are highly relevant for food waste discussions, other environmental impacts should also be considered. For example, a report from the USA argues that existing studies have focused too much on carbon emissions and too little on end-of-life impacts. The result is complex packaging design, such as pouches which are impossible to reuse and recycle and lead to 'mixed residues destined for landfill', incineration or litter (Merceron, 2015).

A further perceived problem is that, in general with LCAs for food packaging, a selection of packaging options to include is made with the result that a fairly limited range is considered. This may result in an LCA selecting the least-worse option. A good example is the conclusion that a plastic packaging solution may have a lower environmental impact than a glass jar, without consideration of any reusability aspect.

Additional studies have considered such aspects in more detail (WRAP, 2010a; WRAP, 2010b). They identify key determinants of the environmental performance of reusable packaging systems (i.e., materials used, return rates for reuse, transportation distance, time delay between reuse, transport mode, and waste management). One example examined different types of milk packaging, considering plastic (HDPE) containers, returnable glass bottles, cartons with screwcaps, and gable top cartons (mixed materials). It concluded that combining the lightest weight with the recyclability of the packaging was the best approach. However, it is important to note that the focus was on large retailers, and assumed travel distances for milk (including packaging and end of life) in excess of 800 km by road transport (WRAP, 2010a).

Interestingly, although many studies are underpinned by the assumption that the food sector would have a higher environmental footprint without packaging, this has never been comprehensively tested. There is thus a need for LCAs that explore in more detail how Short Food Supply Chains (SFSCs), as well as re-usable and zero-package retailing, have an influence on environmental performance.

The end-of-life disposal of packaging remains a key environmental impact. Studies tend to apply waste management scenarios which suppose given levels of waste treatment (e.g., for landfill, incineration and recycling). Meneses, Pasqualino and Castells (2012) assumed 100 % recycling of aseptic cartons (containing plastic and aluminium), although they stated that separation of the different layers was not a common practice. Similarly, Bø, Hammervoll and Tvedt (2013) concluded that refillable PET bottles generated 18 % more GHG emissions than non-refillable bottles because recycling was assumed to be a highly energy efficient process. The Quantis (2015) study on coffee assumed capsule packaging recycling to be at average North American residential rates, although there was no indication that the selected packaging was actually recyclable. In practice, coffee capsules are acknowledged to be particularly challenging for recyclers due to their small format, multi-material composition, and the fact that the coffee grounds within are not recyclable, a necessity for a separate waste stream (France 24, 2017). It is also clear that more needs to be done to develop waste management scenarios that can reflect the prevailing conditions specific to individual markets.

Assuming the recyclability of small format, flexible or multilayer packaging products implies the existence of waste management infrastructures equipped to deal with these products, but this is unlikely to actually be the case (Denkstatt, 2014). Furthermore, none of the studies attempt to take inappropriate disposal into account which means that analyses assume 100 % of the collected waste streams goes to landfill, incineration or recycling. This is at odds with reality, where a substantial fraction of packaging ends up in the terrestrial and marine environments.

The UNEP/SETAC report acknowledged that marine debris was of 'general public' concern but failed to address how environmental leakage of packaging might be accounted for in decision-making (Flanigan, Frischknecht and Trisha, 2013). Whether or not incorrect disposal can be integrated into LCA methodologies is unclear. It could be argued that some environmental leakage is linked to consumer behaviour, or is accidental, and is thus beyond the remit of packaging designers or LCA design. However, the prevalence of environmental leakage suggests that this conclusion, while convenient, is inappropriate in the context of developing policies on packaging.

Local waste management conditions are clearly important in defining the environmental impacts of packaging available on the market in that location. This is similar to the localised waste treatment capability within some countries where discharge consent criteria are based on the local capability and capacity to treat pollution. Basing impacts on the best available technology for waste management, or ignoring the risk of leakage, is therefore likely to underestimate the environmental impact of a product. LCA practitioners should consider waste management capabilities in the market in which a product is sold.

Eco-toxicity is another environmental impact commonly regularly addressed in LCAs. However, very few food packaging LCAs, including the UNEP/SETAC paper (Flanigan, Frischknecht and Trisha, 2013), considered the impact of exposure to the chemicals linked to food contact materials. Eco-toxicology is relevant for food packaging because any food contact material can result in the contamination of foodstuffs. There is growing awareness of the risks associated with the chemical transfer of contaminants from packaging materials to foods. This can include both chemicals deliberately added to products and non-intentionally added substances (NIAS) formed in the production process.

Common additives to plastic used in packaging such as Bisphenol A are known to pose a potential risk to human health, although uncertainties about exposure and concentrations from chemical migration persist. Further questions arise in respect of recycled materials, where the material content of packaging is less certain and more difficult to determine; as outlined in the Commission Communication on the interface between chemical, product and waste legislation (COM (2018)32).

Attempts have been made to develop LCA methodologies that include the health impacts of chemical exposure from food packaging (Ernstoff et al, 2014). Arguably, eco-toxicity is one such impact that should be considered as part of the decision-making process for food packaging (Ernstoff et al, 2016). As the knowledge base on food contact materials develops, these considerations should be integrated into the assessment of packaging design and material choice.

Food waste considerations are important when selecting appropriate packaging. The UNEP/SETAC study of LCAs of food and beverage packaging noted: 'Whether or not the product and product losses are considered will depend on LCA goals and the practitioner's reasons for carrying out the study. Only if the alternative designs are associated with equal product losses throughout the supply chain may the product and/or losses be unnecessary for inclusion. Including product losses within system boundaries will be important if loss rates are expected to differ among alternative packaging designs, particularly when the packaging's environmental impact is anticipated to be small compared to the packaged product's impact (and therefore small compared to the impact of packaged product losses). Under these conditions, product losses may be the deciding factor in reducing impact rather than the packaging material or design. If product losses are not considered, it is important to justify their exclusion' (Flanigan, Frischknecht and Trisha, 2013). However, the LCAs that included food waste as a factor in their analyses did not discuss the extent to which food spoilage could be avoided through different kinds of packaging, or indeed zero-packaging solutions. Rather, their approach was to compare the estimated environmental impact of production and waste management of one unit of packaging with the environmental impact of one unit of food waste, and by showing that the former was smaller than the latter, to conclude that it was more efficient to focus on food waste than on packaging. This is particularly the case in the OVAM (2015), Quantis (2015), Silvenius et al (2011), and Williams and Wikström (2011) studies, which calculated the number of units of packaging that would be equivalent to a food/beverage unit and then concluded that more packaging could be environmentally beneficial. Their conclusion gives the impression that the amount of packaging has a positive correlation with the food saved from waste. However, in view of the complex drivers of food waste through the food system, such a conclusion considerably simplifies the reality.

Food waste is not only a result of inadequate packaging but can occur at different stages of the value chain, including at household level during and after food preparation and cooking, where packaging cannot protect it. Assuming that all food waste can be addressed with better packaging and extended shelf-life thus ignores the domestic reality. This goes hand-in-hand with LCA's exclusion of packaging-related food waste throughout the supply chain. For example, food may be discarded or trimmed in order to fit packaging design, potentially leading to significant levels of waste (Colbert, Schein and Douglas, 2017). Furthermore, packaging fixes the portion size or the number of units sold, driving over-purchasing by consumers and leading to further waste. Packaging is also used to attract customers, inviting them to buy a product even if it is not necessary to satisfy their wants and needs (WRAP, 2014). Lastly, in some cases food is discarded unopened, still in its packaging (WRAP, 2008).

Although inclusion of the product in LCAs of packaging applications helps to identify the significant environmental impacts linked to the food supply chain, as well as to raise the issue of reducing food waste as one of the primary utilities of packaging, the relationships between packaging and reducing food waste are often simplified. LCAs should be combined with knowledge on food waste drivers in order to better understand the extent to which packaging can reduce product waste. The assumption that policy objectives aim towards a food system which can contribute to both sustainable development and the transition to a circular economy requires that these objectives are reflected in how policies for food packaging are developed.

Relevant LCA studies generally assess packaging options, such as comparing alternative materials and packaging designs. However, analysis demonstrates that optimising packaging design is often contingent on system boundaries and supply chain configurations beyond the packaging itself, such as the length of the supply chain, mode of transport, energy mix, feasibility of reverse logistics, and consumer practices. This was partly noted in the UNEP/SETAC report, which acknowledged that a range of different variables should be considered when assessing reusable packaging, including the frequency of reuse, transport, and cleaning of packaging (Flanigan, Frischknecht and Trisha, 2013).

Many LCA studies have focused on single products or several typical products, mostly in conventional supply chains. As such, these studies adopt typical supply chain lengths with transport and energy mixes and retail practices in their analyses. Alternative approaches to food supply chains, for example those linked to short food supply chains and zero-waste retail, are very rarely included. These studies thus permit a comparison of packaging options under a clearly defined system but ignore potentially preferable and lower impact outcomes within realistic alternative systems. While LCAs have previously been employed to compare, as an example, the relative impacts of local and non-local food (Kneafsey et al., 2013), little has been done to combine packaging analysis with analysis on food systems as a whole.

From an industry perspective, LCAs of packaging options in a given supply chain are logical, as they try to optimise and create efficiencies within the spectrum of their own activities. By contrast, policy-makers have the responsibility to support sustainable development in all parts of the food supply chain and economy, including opportunities to better utilise LCA approaches to explore food and packaging more systemically. While LCAs are widely used to inform discussions on food packaging, a majority of the studies considered suggest some potential challenges within the approach. They also demonstrate the complexity inherent in determining the environmental impacts of food packaging in a single approach.

Many environmental impacts, such as environmental leakage and chemical migration, may not be well suited to LCA. Some aspects, however, could be better integrated into studies, such as using real-life waste scenarios, thereby allowing for more realistic representations of the end-of-life of packaging products. This is particularly important when considering the waste management capabilities of locations/countries where not all waste is collected at the end of its life, making the risks of environmental leakage significantly higher. Similarly, changing waste management practices for food waste, including increasing redistribution, or separate collection of organic waste for composting and anaerobic digestion, also has the potential to reduce the impact of waste and LCAs could be used to explore the waste reduction potential of these activities. Overall, many existing LCA results do not support the implementation of the waste hierarchy or vice versa.

Nevertheless, it is quite obvious that multilayer plastic packaging is difficult to recycle and a growing environmental problem, despite the valuable protective properties it offers. As a demonstration of such, a study has been undertaken to examine environmental impacts and recyclability of different representative packaging solutions for bacon in block. Moreover, the study has considered the environmental impacts of the packaged product. The examined flexible packaging included two thermoformed films (polyamide (PA)/polyethylene (PE) and PE/ethylene vinyl alcohol (EVOH)), two vacuum bags (both PA/PE), and two shrink bags (PE/polyvinylidene dichloride (PVdC) & PA/EVOH/PE). A cradle-to-grave LCA was conducted. What was assessed was the recyclability of the different packaging and a comparison of the carbon footprint of the packaging with the carbon footprint of the packaged meat. The environmental impacts were found to depend largely on the packaging weight and on the content of PA. Climate change results ranged from 26.64 g CO_2-equivalents for the PVdC-containing shrink bag to 109.64 g CO_2-equivalents for the PA-containing thermoformed film. Even if the recyclable PE/EVOH film was recycled, its climate change result (51.75 g CO_2-equivalents) was considerably higher than the result for the PVdC-containing shrink bag. Only the PE/EVOH film could be recycled, however, with considerable loss of quality. The carbon footprint of the packaged bacon was, on average, 54 times higher than the carbon footprint of the packaging. Given the relatively low environmental significance of packaging compared to the packaged meat, optimal product protection should clearly be the priority for packaging designers. Weight reduction is preferable to improved recyclability.

LCAs should be combined with knowledge of food waste drivers to better understand the extent to which packaging can reduce product waste, given that many food waste drivers (e.g. over-purchasing, storage and preparation techniques) are not linked to packaging, while some others are (e.g. trimming and multipacks). If food waste is considered (i.e. via shelf-life extension), other drivers of food waste could be similarly considered, particularly where these can be linked to packaging design.

As the knowledge base on chemical migration from food contact materials grows, these aspects should be better integrated into the assessment of packaging design and material choice. In the absence of such strong evidence, the precautionary principle should be adopted. The risks and complexity of identifying chemicals and their toxicity, becomes more complex in recycled products, as identified in the Commission's Communication on options to address the interface between chemical, product and waste legislation (COM (2018) 32). Targets to increase recycling and the recycled content of products will also bring new challenges in how the chemical compositions of food contact materials are managed.

There is a clear an opportunity for LCAs to incorporate assessments of food supply chains which are outside of the conventional food system, including closer examination of short food supply chains, package-free solutions, and reusable packaging. LCA approaches as a means of conducting an environmental assessment of multilayer polymer bags used within food packaging have highlighted some interesting facts, not least of which is that the most impacting phase is the production of the polymer granules. This conclusion has been drawn from an LCA screening of a bi-layer film bag for food packaging comprising films made of a layer of polyamide (PA) and one of low-density polyethylene (LDPE). The system boundaries encompassed cradle to factory gate and included the phases of raw material production and processing for the bag manufacture and delivery of the bag to the food production and packaging plants. The assessment showed that the most impacting phases were the production of the polyamide and low-density polyethylene granules, essentially as a result of the consumption of primary resources such as crude oil and natural gas. The most affected damage category within the LCA was resources, followed by climate change, human health and ecosystem quality.

These assessments are reinforced from other LCA studies. For example, in the study 'Comparative Life Cycle Assessment of High Barrier Polymer Packaging for Selecting Resource Efficient and Environmentally Low-Impact Materials', three types of multilayer gas barrier plastic packaging films were compared with LCAs in respect of resource efficient and low-impact materials selection (ref: D. Kliaugaite, J.K. Staniskis, 2013, Engineering, World Academy of Science, Engineering and Technology, International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering). The first type of multilayer packaging film consisted of polyethylene terephthalate (PET) and low-density polyethylene with an aluminium oxide barrier. The second type of polymer film was PET and a co-extruded film of PE strengthened with EVOH (ethylene vinyl alcohol) as a barrier layer. The third multilayer packaging film comprised PET with the addition of a polyvinyl alcohol barrier layer and low-density polyethylene (LDPE). The

LCAs of these packaging types showed significant impacts regarding resource depletion, because of raw material extraction and the energy used in the manufacture of the different polymers. However, overall impact from the second type of film was some 25 % lower than the other two types. This was subsequently found to be a direct consequence of the impacts being mainly generated from the energy and materials used during raw material extraction and subsequent polymer manufacture. There was little impact attributed to the gas barrier properties of these composite materials.

Food packaging helps to protect food from being lost or wasted, nevertheless it is perceived as an environmental problem. Advanced LCA studies have proposed a methodological framework for the environmental assessment of food packaging. There is general agreement on the definition of sustainable packaging, which has to be effective, efficient, and safe for human health and the environment, but existing frameworks only provide general guidance on how to quantify its environmental sustainability. It is considered that there are three sustainability aspects of food packaging, namely direct environmental effects of packaging, packaging-related food losses and waste, as well as circularity. Such key environmental performance indicators and their associated calculation metrics can be incorporated within an LCA calculation procedures for each indicator. The framework is oriented towards the Product Environmental Footprint initiative and the Circular Economy Package of the European Union. A significant level of work is required on topics such as packaging related food losses and waste in order to accommodate such within an LCA. Circularity, as noted, is also felt to be key in assessing and consequently being able to reduce environmental impact via a life cycle approach.

Numerous LCAs on food packaging have been conducted; however, few consider the interaction between the packaging and packaged food, although it is widely acknowledged that this interaction plays a key role for the environmental performance of food packaging. Various circularity Indicators have been proposed for inclusion within an LCA and comprise factors such as the reuse rate defined by the number of subsequent usages, the overall recyclability assessed via expertise, the final compostability, and the level of renewable energy realisable. The main reason for including circularity indicators in sustainability assessments is that they are highly relevant for the environmental performance of packaging. They represent some of the most important levers for improving packaging sustainability, because packaging producers can directly influence parameters such as recyclability, or the proportion of renewable energy used. Moreover, it has become a legal requirement to make packaging more circular. Nonetheless, the transition towards a circular economy is not a goal in itself; it should deliver ecological goals. Most importantly, packaging designers should always apply life cycle thinking to confirm that, for example., improved recyclability does, in fact, contribute to the overarching goal of reducing the environmental impact.

The circularity metrics proposed in various approaches focus on cyclic material and renewable energy flows. While most of the indicators can be assessed relatively easily, this is not the case for the recyclability assessment. A recyclability assessment requires a good understanding of the available recycling infrastructure and the suitability of a specific type of packaging to be reprocessed into a useful secondary material. For the determination of the downcycling factor, which is required for the calculation of the environmental burdens and benefits of recycling, it is necessary to understand the market situation pertaining to recyclables.

Within LCA reviews in the literature, it is not possible to specifically find ones covering multilayer food packaging but rather food packaging in general, with clearly PET (poly-ethylene-terephthalate) dominating the literature. There is, of course, mention within many reviews of specific multilayer packaging types as exampled in the following which is derived from a review of studies undertaken within the Italian market.

Toniolo et al. used an LCA methodology to analyze two kinds of plastic product; a multilayer plastic tray and a PET tray used for food packaging. For the first product, end-of-life scenarios that included land-filling and incineration were chosen, while for the second product recycling, land-filling and incineration were considered. They studied how an innovative and recyclable packaging material could be environmentally preferable compared to a non-recyclable one, and explained how using recycled materials represented a considerable effort in reducing the environmental burdens. The package produced employing a recyclable mono-material film was more environmentally preferable than the multilayer ones for all impact categories considered.

The results were also tested by a sensitivity analysis and an uncertainty analysis in order to confirm the results of the life-cycle impact assessment. The study was used to demonstrate that the LCA approach was an important tool for assessing how a prevention activity to reduce waste production was actually an environmentally sustainable alternative. It could also provide decision-making support for packaging waste management. During 2014, three directly relevant LCA papers were published: one covered an environmental assessment study of a multilayer material food packaging bag, the second one dealt with an economic and environmental assessment study performed on reusable plastic containers used in the food catering supply chain [46], and the third one was based on the environmental assessment of two packaging materials for poultry products. These were a polystyrene-based tray and an aluminum-based tray (70 wt% primary and 30 wt% secondary aluminum). In the first paper, Siracusa et al. reported an LCA case study on a multilayer film bag made of PA and LDPE, used for vacuum or modified atmosphere packaging (MAP) technology food preservation. A functional unit of 1 m^2 of plastic film was chosen, with a cradle to factory-gate approach, including the phases of the raw materials for bag production and processing and the bag's delivery to both the food production and packaging plant.

Due to the use of crude oil and natural gas, the most impacting phases were the production of PA and LDPE granules. The most affected damage category was 'Resources', followed by 'Climate Change', 'Human Health', and 'Ecosystem Quality' respectively. Reducing the film thickness and using recycled PA granules were proposed in order to reduce the total damage. The results showed that the two proposals allowed the assessed damage reductions to be lowered by ~25 % and ~15 % respectively. In another paper, Accorsi et al. reported that during the last few decades, Europeans have significantly modified their food consumption habits, having increasingly chosen to eat out or purchase take-away foods, thus significantly increasing the amounts of packaging waste. This was at least partly because the food catering supply chain does was not utilise reusable packaging systems. They compared a multi-use system to traditional single-use packaging (e.g., wooden boxes, disposable plastic crates and cardboard boxes), used for an Italian fresh fruit and vegetable catering chain, from vendors to final customers, in order to quantify the economic returns and environmental impacts of the reusable plastic container (RPC). A carbon footprint (CF) analysis was performed for the environmental assessment.

Again, the LCA results demonstrated that the environmental impact associated with the single-use network was mainly due to the manufacturing phase of the large volume of packaging required. The transport phase, along with the different disposal routes, significantly affected the environmental impact and sustainability of the RPC system. Further studies again highlighted a common finding that the greatest environmental impacts came from PS granule production and electricity consumption. A conclusion was that the best way to reduce the environmental impact would be by using renewable energy sources for the PS granule manufacturing.

The major conclusion from the Italian market sector review was that, within the framework of the environmental impact assessments, LCA was a valuable decision-support tool for decision makers, in both political and industrial areas. Consequently, LCA has become an important methodology for identifying the cradle-to-grave impacts of products in a multitude of sectors, among which, polymers are one of the most investigated. The clear message from LCA studies across a wide range of polymers deployed within the food, and indeed the overall packaging sector would appear to be that the greatest single environmental impact arises from the manufacturing phase, i.e., the production of the polymeric raw material feedstocks. This confirms the benefits of recycling such and the consequent associated virgin material displacements.

A recent paper considered four different waste treatment scenarios for plastic films; landfill disposal of mixed waste; incineration of mixed waste; recycling of mixed waste and recycling of recyclable waste. The results from the study demonstrated a considerable advantage of recycling over landfill disposal or incineration. The main environmental benefit was from the recycling of plastics that could substitute for the production of plastics from virgin materials.

6 Dealing with Contaminated Plastic

6.1 Contaminated Pharmaceutical Blister Packs

With the current disposal methods for pharmaceutical blister packs being mainly incineration or land fill there is little, if any incentive to consider post-disposal treatment. However, if the materials are to be recycled and reused, there are likely to be concerns about cleanliness and the possibility of contamination from the drugs or medicines that the blister packs have contained. There could be the possibility of dangerous materials, or degradation products being included in any recyclate, particularly, for example, as would be the case with ageing products that may be well beyond their shelf lives, or that have been subjected to incorrect storage conditions. There is thus likely to be a need to clean the blister packs prior to any recycling operations, especially as there may also be health and safety implications for those handling and processing the end-of-life blister packs. If this is indeed the case, there will be negative environmental impacts aspects, such as the use of water, energy, and waste generation associated with any additional process stages needed to remove or reduce the levels of contaminants present.

While the presence of organic materials from the medicines contained in blister packs is one key area of concern, it is known that elevated levels of metals can also be problematic. In the case of medicine blister packs, it is possible that metals could be introduced via the residual contents but also from the aluminium that is used to limit the moisture and oxygen transmission in such packaging. Recycled plastic samples have been shown (M. K. Eriksen et al) to contain significantly higher aluminium and other metal levels when compared to virgin samples. While most of the metal levels were low and below legal limit values, it is clear that elevated concentrations in reprocessed plastics, aligned with increasing recycling rates, may lead to even higher metal concentrations if the materials are recycled multiple times.

Due to the nature of pharmaceutical blister packs, there is also a distinct possibility that they may still contain medicine and medication residue when they reach the recycler. Clearly, such packs need to be identified since any that contain tablets cannot be recycled and will thus need to be removed and diverted to incineration i.e., energy from waste. In order to be recyclable, blister packs must not have originally been consigned for disposal as clinical or hazardous waste and they must also not have come into contact with biological contaminants e.g., from within an operating or treatment environment.

It seems likely, therefore, that there will need to be an early stage in the Sol-Rec 2 process where some form of automated inspection will be needed in order to identify and remove any blister packs still containing some or all of their original contents. It may be possible to reduce the occurrence of packs that are not empty, if suitable recycling schemes are implemented and the public are specifically advised that only empty packets can be recycled. From an LCA perspective the inspection and removal of packs adds another activity that would not be required if the packs were directly consigned to landfill or incineration. Also, any packs that do still contain medicine will need to be treated separately, which is likely to require additional energy inputs around the inspection, transportation, treatment and safe disposal steps that will be necessary.

6.2 Contaminated Multilayer Food Packaging

As is the case with pharmaceutical blister packs, food packaging is also often contaminated with waste and in this case, it is food. While this in itself represents a waste of valuable resources, the situation at end of life regarding treatment options is also similar to that described above for medicine blister packs. Multilayer food packaging is currently either landfilled or incinerated, so the contamination is less of a problem than if it was recycled. Clearly, any contaminants present during recycling operations will need to be taken into account. At the simplest level, this may mean that the food waste has to be removed and the plastic cleaned prior to entering the recycling process. It is very important that residues are not present in the subsequent recyclate as this can cause a variety of problems and limit the applications available for the recovered material. The Sol-Rec 2 process will, therefore, need to be able to address the presence of food waste and contamination. The result may be the need for cleaning stages prior to the chemical treatment using solvents and ionic liquids. This will require energy, as well as materials and will also generate another waste stream that needs treatment.

However, in the context of setting the baseline for the currently used disposal practices it is clear that multilayer food waste consigned to landfill may have its own potentially negative impacts. For landfill these examples would be increased carbon emissions (via the methane produced) and the release of pollutants into water courses. Conversely, in the case of incineration, the calorific value of the waste food might be beneficial, depending on the type and composition of the materials present.

The landfilling of plastic packaging contaminated with food waste is increasingly acknowledged as being a big problem, especially as more than 30 % of all food is wasted globally (~1.6 billion tonnes in 2018). Much of this is still disposed of to landfill, which is known to be the most greenhouse gas (GHG)-intensive option, with each tonne of food waste being responsible for emitting almost 400 kg CO_2 equivalent. There are moves by governments to address these issues with, for example, the UK Government already committed to introducing separate household food waste collections by 2023 and to eliminate all food waste from landfill by 2030. One proposed approach is to increase the use of compostable packaging which, if widely adopted, could have significant implications for recycling processes such as Sol-Rec 2. It has been reported that waste food contributes to ~11% of the world's total greenhouse gas emissions, which means that this aspect must be an important consideration for those developing new recycling processes. Ideally, the waste food should be removed from the packaging, thereby enabling optimised approaches to be adopted for each stream. For example, it is reported that sending food waste for anaerobic digestion provided environmental and human benefits for the following typical LCA impact categories; cumulative energy demand, ecotoxicity, eutrophication, global warming potential and human health.

When considering the impact of landfilling plastic packaging contaminated with food waste, it is important to understand that landfilling is a generic term used to cover a range of different technologies. Six of the most widely used approaches are known as; open dump, conventional landfill with flares, conventional landfill with energy recovery, standard bioreactor landfill, flushing bioreactor landfill and semi-aerobic landfill. Given that these are all different, their impacts on common LCA categories (such as global warming, nutrient enrichment, ozone depletion, photo-chemical ozone formation, acidification, and human and ecotoxicity, as well as their impact on groundwater resources, are likely to be markedly different.

When considering the Sol-Rec 2 process for recycling multilayer plastic food packaging that has is likely to be contaminated by food, it will be important to ensure that it enables compliance with any current and emerging legislation. For example, in Europe, recycled plastics that have been in contact with food need to comply with the requirements of Commission Regulation 282/2008 on recycled plastic materials and articles intended to come into contact with foods. This regulation defines the requirements for recycled plastics that come into contact with food. It ensures that recycled plastics can only be used in such applications if they contain recycled plastic produced using a recycling process that is authorised in accordance with the Regulation.

7 Key LCA Benchmarking Figures

For the Sol-Rec 2 project, it is important to compare the performance of the new process with what is currently happening with end of life pharmaceutical and medicine packaging. At the time of writing, the Sol-Rec 2 process was still being developed but it is, nevertheless, possible to undertake some analysis of the impacts of current disposal methods. Although most multilayer food packaging and medicine blister packs are currently consigned to landfill or energy recovery by incineration, there are many variables that significantly influence the overall end of life impacts. These include collection, transport, sorting, and contamination with residual medicines or food. Also, and perhaps more importantly, there is no such thing as a standard type of food or medicine package, both of which can comprise different polymers, as well as numerous other materials including aluminium. In the case of medicine packaging, the two key types are PVC blister and aluminium blister and, as such, they will have very different environmental impacts. For example, it has been reported (Raju G.) that, from an LCA perspective, PVC blister packaging was better than aluminium blister packaging in most of the important impact categories. This was because the aluminium foil production process made a significant contribution to the overall environmental impact of aluminium blister packaging. The loss of the aluminium when blister packs are landfilled means that it is not available for recycling and reuse and thus new virgin aluminium will need to be produced. This factor alone highlights the importance of being able to recover and reuse aluminium in the Sol-Rec 2 process.

One of the simplest end of life scenarios is that the blister and food packaging waste is disposed of by consumers to become part of municipal solid waste (MSW). The actual composition of MSW varies, but it is clear that only a relatively small proportion is plastic. From this low amount, only an even smaller quantity has typically been recycled in the past. For example, in a 2014 report (Themelis N. J. and Mussche C.), plastics only represented around 11 % (39.3 million tons) of the MSW stream considered. Of this amount, ~2.7 million tons (6.8 %) were recycled, 3.9 million tons (9.9 %) were converted to energy and ~0.3 million tons (0.7 %) were used in cement production, while the vast majority (~32.5 million tons (82.7 %) was landfilled. While the recycling and energy from waste figures are likely to have improved over the last ten years, it is clear that there is some way to go in diverting plastic waste from landfill.

If end of life medical blister packs and food packaging could be diverted from landfill to incineration, where the energy could be utilised, there would be significant opportunities to reduce the overall energy consumption.

Typical energy content values for common recycled plastics have been published in the literature and averages of the reported data are shown in the table below.

Polymer	**Energy/MJ.kg^{-1}**
Polyethylene terephthalate (PET)	22.6
High- and low-density polypropylene (HDPE/LDPE)	43.3
Polyvinyl chloride (PVC)	17.0
Polypropylene (PP)	42.9
Polystyrene (PS)	40.3
Typical mixed non-recycled plastic	35.7

The values confirm that many of these plastics contain levels of energy equal to, or even better than, some other common fuel types. Examples from published data are shown in the table below.

Fuel Type	**Energy/MJ.kg^{-1}**
Natural gas	47.3
Crude Oil	42.9
Petroleum Coke	29.6
Coal (averaged, source dependent)	24.5
Wood	14.0
Typical mixed non-recycled plastic	35.7

Thus, it can be seen that, if one example of the baseline is considered to be energy recovery, a good reference figure would be around 36 MJ.kg^{-1} that is available, meaning that 1 kg of waste mixed plastic would be able to replace the use of between 0.75 kg of natural gas and 0.84 kg of crude oil. If the plastic was recovered and reused in the Sol-Rec 2 process this energy would not be immediately available and there would also be the energy inputs for the process itself to consider. However, assuming that at some point, the polymer would no longer be recyclable, the embodied energy would still be recoverable, but at a later stage.

The energy savings that would be available in terms of polymer recycling compared to the use of virgin material can be better appreciated by considering the energy required to manufacture the plastics used in medicine blister packs and food packaging from crude oil. Although there is a wide range in the reported values, presumably depending on the specific process used, operational scale and the specific end product, the data below gives a general indication of the average amounts of energy required to make the more popular plastics (and aluminium).

Polymer	**Average Energy/MJ.kg^{-1}**
Polyethylene terephthalate (PET)	67
High density polypropylene (HDPE)	76 (56-91)
Low density polypropylene (LDPE)	77 (64-96)
Polyvinyl chloride (PVC)	56
Polypropylene (PP)	73 (54-94)
Polystyrene (PS)	90
All plastics range	62-108
Aluminium (from typical 80% virgin and 20% recycled mix	219

Interestingly, and particularly important for the Sol-Rec 2 process, it can be seen that PVC requires significantly less energy than the other polymers in its manufacturing. Another generalization is that it typically requires around two kilogrammes of fossil fuel to produce one kilogramme of plastic. Therefore, for every tonne of plastic that is recycled and reused, there should be a two-tonne reduction in fossil fuel demand (although there would be energy needed for the recycling process itself). The main point to be noted from this data, however is the significant opportunity for energy savings from recycling the aluminium, which on a weight for weight basis offers around three to four times that of the plastics used in blister packs and food packaging.

Given that PVC is a widely used component of medicine blister packs, it is important to understand its global warming potential in both of the end-of-life disposal methods currently in common use, i.e. landfilling or incineration. At the moment, most PVC is consigned to landfill, despite the fact that it can be recycled. PVC recycling and reuse can reduce the amount of virgin PVC that needs to be made, in turn reducing its environmental footprint. Also, the recycling of PVC typically uses just over half the primary energy (~54 %) needed to make the original material and emits less than 40 % of the greenhouse gases. Consequently, recycling results in a significantly lower global warming potential. As the Sol-Rec 2 process will result in the recovery and reuse of PVC, it will enable these benefits to be realised, although the specific benefit level achievable will be influenced by the energy consumption of the process itself.

The impacts of landfilling PVC have been analysed in a number of studies, but they typically refer to specific types of PVC that are different to those encountered in blister pack applications. For example, PVC used in large scale applications such as window frames, often contains a range of formulation additives needed to achieve the requisite polymer properties for each type of application. Materials such as plasticisers and stabilisers are ones that can cause problems with landfilled PVC as, under appropriate conditions, they can leach out of the polymer. Examples of these materials include various phthalates, lead, cadmium and organo-tin compounds. Fortunately, the PVC used for medicine blister packs is different to the more common types of PVC formulations that contain these additives. The PVC sheet used to make such packaging does not contain any plasticizers and it is often referred to as rigid PVC or RPVC. Thus, this type of PVC is, on its own, less likely to be problematic when landfilled than its more heavily formulated analogues. It has been reported that there appears to be little degradation of the PVC polymer itself in landfills and confirmation (ARGUS 2000, Mersiowski 1999) that it is the additives present that diffuse out into the environment over time to cause problems.

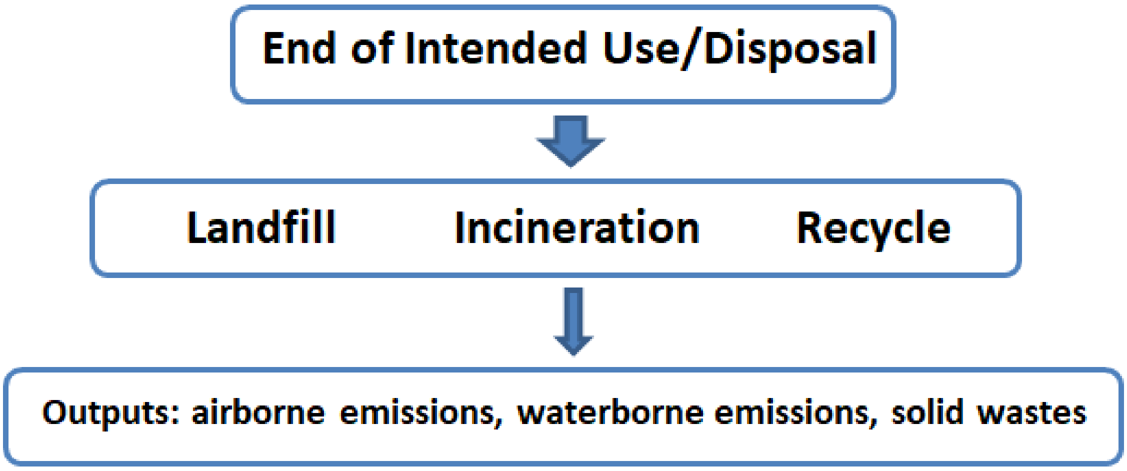
Nevertheless, incineration of the material by, for example, unexpected landfill fires can lead to the generation of toxic halogenated compounds such as hydrogen chloride and various dioxins and furans. The situation can be complicated by the fact that the PVC used for medicine blister packs may be coated or laminated with additional halogen containing polymers to form multilayer films that have enhanced barrier properties. Examples here include polyvinylidene chloride (PVDC) coatings and polychlorotrifluoroethylene (PCTFE) laminates. It is also important to note that PVC-based medicine blister packs may also be deliberately incinerated. This might typically be in an energy from waste plant, but it could also be from individuals burning their household waste in bonfires etc. The combustion of PVC in such uncontrolled conditions can lead to the formation and emission of numerous very hazardous chlorinated species. Open burning of household waste is reportedly responsible for a considerable share of dioxin air emissions. Even in municipal incinerators, the presence of PVC leads to the generation of hydrogen chloride/hydrochloric acid (HCl) in the flue gases. This has to be neutralized (typically by using lime) and removed by scrubbers; a process which consumes energy and generates waste.

Although PVC is still the preferred material for medical blister packaging, there are other materials emerging that offer viable alternatives. These include both virgin and recycled PET, which are readily recyclable.

8 Consideration by LCA Specific Impact Factor/System Boundary

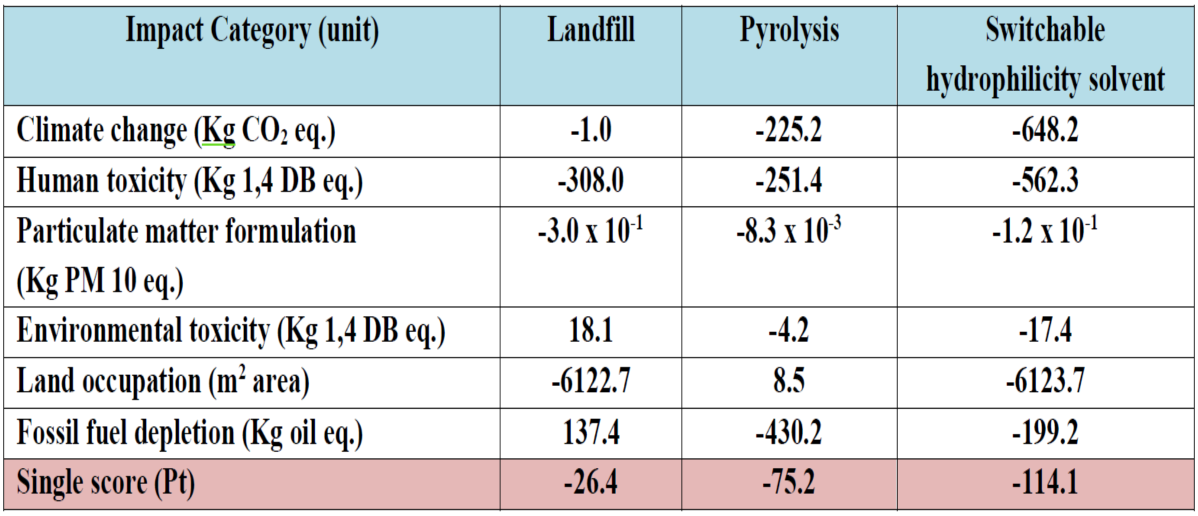
8.1 Overview

According to the standardized procedures for undertaking an LCA, there is a range of clearly defined impact factors that need to be evaluated. While these may cover the whole life cycle of a product, they are each likely to have varying significance at each distinct stage of the lifecycle. For the purposes of this baseline assessment of current practices, the focus is on the current methods of disposal, i.e. what happens at end of life. The aim is to determine how the new Sol-Rec 2 technology compares to current methods after the medicine blister packs and multilayer food packaging have served their purpose. The main area of interest is, therefore, that part of the lifecycle beginning when the packaging is disposed of by the consumer. This will define the system boundary. As it is known that almost none of these complex multilayer materials are currently recycled and that most are landfilled, with some being used in energy from waste plants, the focus will be on these two disposal methods, with the intention of then comparing them with the Sol-Rec 2 recycle process once it is defined.



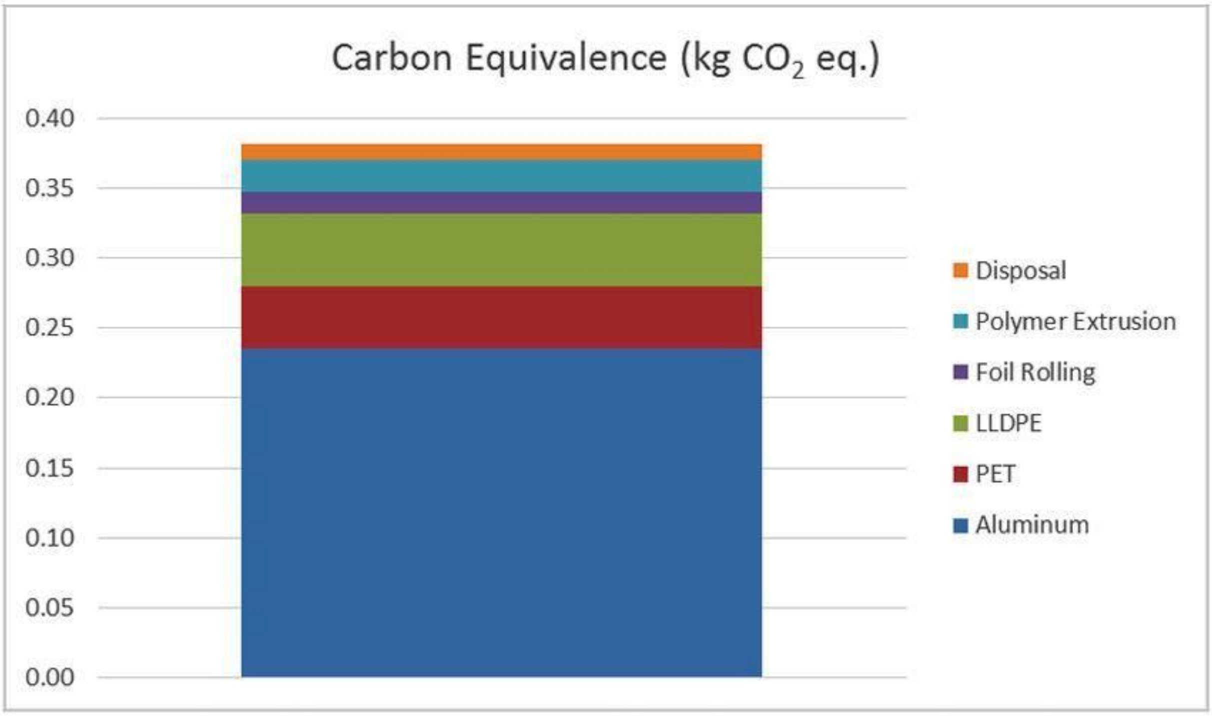
It is also important to identify which of the standard life cycle impact factors has the most relevance in this limited context. For example, global warming potential will be important in terms of incineration, but so will the potential for energy generation. Conversely, methane generation from landfilled products will contribute to global warming. Several of the main impact factors currently identified in, for example, the common standards used by LCA practitioners have been considered in the context of the current end of life treatment methods and the Sol-Rec 2 process (such as is currently known). More specifically, and as defined in the project proposal, the impact categories to be considered are climate change, human toxicity, particulate matter formation, environmental toxicity, land occupation and fossil fluke depletion.

Previous work has already indicated that the proposed Sol-Rec 2 approach of using switchable hydrophilicity solvents has the potential to offer greater environmental benefits than either of the currently practiced landfill and incineration options. For example, by using the ReCiPe harmonized life cycle impact assessment method that was developed in Holland, data from each impact category can be combined to give single score (point, Pt) indicating the cumulative environmental burden of each end of life approach. In each case, the lower the 'Pt' figure the lower the impact and the greater the benefit. From the data generated for multilayer packaging materials, see table below, the advantages of the proposed Sol-Rec 2 process over landfilling and incineration can clearly be seen.

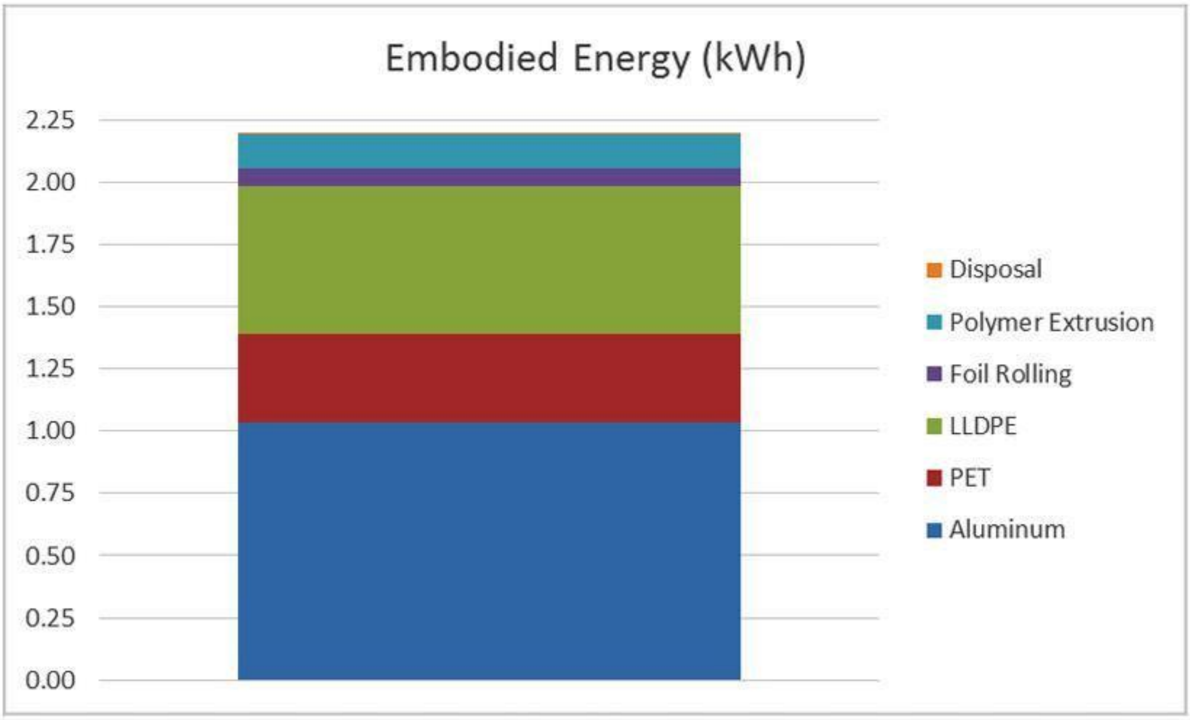


Impact Category (unit)	Landfill	Pyrolysis	Switchable hydrophilicity solvent
Climate change (Kg CO_2 eq.)	-1.0	-225.2	-648.2
Human toxicity (Kg 1,4 DB eq.)	-308.0	-251.4	-562.3
Particulate matter formulation (Kg PM 10 eq.)	-3.0×10^{-1}	-8.3×10^{-3}	-1.2×10^{-1}
Environmental toxicity (Kg 1,4 DB eq.)	18.1	-4.2	-17.4
Land occupation (m^2 area)	-6122.7	8.5	-6123.7
Fossil fuel depletion (Kg oil eq.)	137.4	-430.2	-199.2
Single score (Pt)	-26.4	-75.2	-114.1

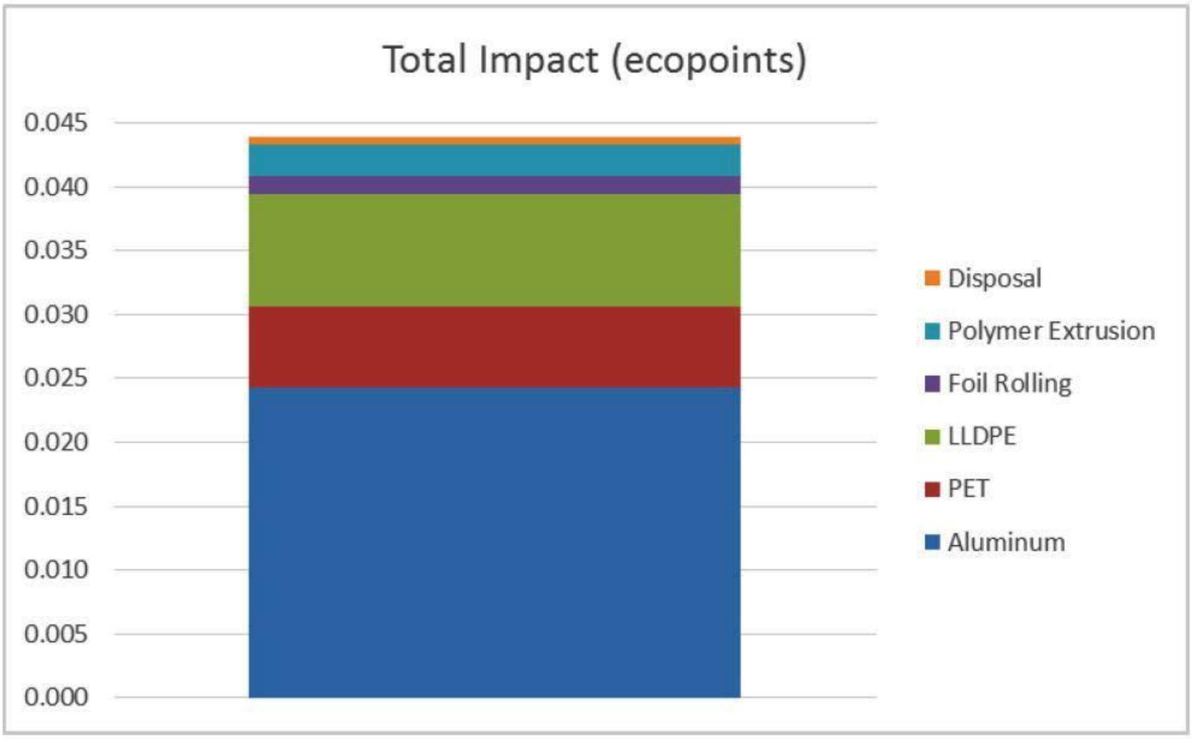
The global warming potential of a metallised polymer film has been reported by Bayus (Bayus J. A., 2015) and the figure below highlights both the significant contribution made by the aluminium and the very small impact of disposal.



Bayus also considered the embodied energy of the films and the results again highlighted the important contribution of aluminium and the small impact of disposal.



Not surprisingly, the overall environmental impact was much the same as indicated for the embodied energy and the global warming potential data shown above. The overall environmental impact was as shown below;



Given the significant impact of aluminium in multilayer packaging at end of life, it is appropriate to discuss this in a little more detail. The following section therefore discusses aluminium.

8.2 Aluminium

One of the common components of both pharmaceutical blister packs and multilayer food packaging is aluminium. This metal is a key component because it has important functions including providing barrier properties to light, moisture and oxygen that result in extended shelf life. LCA studies have confirmed that aluminium in packaging can actively contribute to minimising the overall environmental impact of the product by reducing spoilage, as well as helping to avoid over-consumption.

However, aluminium production requires large amounts of energy to produce it from basic raw materials e.g. bauxite. Consequently, aluminium is widely recycled. Recycling of aluminium differs from other packaging materials. Compared with the production of primary aluminium, recycling only requires 5% of the energy and emits only 5% of the greenhouse gas. At the moment, the aluminium used in food and medicine packaging is not recycled, meaning that there will be a need to produce more energy intensive aluminium from virgin materials. Packaging is mostly landfilled with some being incinerated in energy from waste plants, even though incineration is the preferred method of the two according to the EU Waste Framework Directive 2008/98/EC.

Unfortunately, and unlike the situation with aluminium drink cans for example, the aluminium films found in food and medicine packaging are typically not economically recoverable because they are so thin and thus offer very little material for recycling. The aluminium films vacuum deposited onto the plastics used in these types of packaging are often only between 40 and 100 nanometres thick, as this is generally all that is needed to provide the requisite barrier properties. Many types of packaging will thus contain relatively trivial amounts of aluminium. For example, a square metre of aluminium with a thickness of 70 nm would only weigh 190 milligrams.

As it has been decided that all packaging in Europe must be recyclable by 2030, multilayer laminated plastic film manufacturers are increasingly looking to replace the thin aluminium layers with alternative materials such as other types of polymers or various types of oxide coating. One recently reported alternative for aluminium is to use nanometre thick layers consisting of (one millionth of a mm) thick sheets of aluminium and magnesium hydroxide compounds. These are so thin that they can enable the polymer substrate to be recycled.
However, the key challenge will be in achieving the barrier properties of aluminium that provide the requisite shelf life for a product, without increasing the cost or weight. While consumers might be willing to accept a shorter shelf life in order to enable the packaging to be recycled, such solutions might also lead to increased levels of food waste.

9 Summary and Conclusions

This report has identified and reviewed the main life cycle assessment considerations and criteria that need to be addressed in order to enable a meaningful comparison of the new Sol-Rec 2 process with the current end of life practices used to dispose of pharmaceutical blister packs and multilayer food packaging. It has specifically focused on the impacts of the currently employed landfilling and incineration routes by which most of these materials are still treated. The intention has been to determine the key factors that are important when attempting to set a baseline from which the new Sol-Rec 2 process can be compared. This report has been compiled during the early stages of the project when the exact nature of the Sol-Rec 2 process is still to be confirmed. It has also become clear during the research for this study that the current end of life scenarios practiced for disposing of waste blister packs and multilayer food packaging are both complex and variable. Currently, most of these materials are consigned to landfill, the worst possible option, with only a small percentage being incinerated. Landfilling is acknowledged to be undesirable in the context of many of the key impact factors, yet it is still widely practiced because of the lack of economically viable alternatives and the fact that it is currently not proscribed by legislation.

While the current disposal methods are clearly undesirable, they only make a relatively small contribution to the overall key impact factors when considering the whole lifecycle of these complex materials. It is also clear that the use and subsequent loss of aluminium in these types of packaging is very significant, especially as the current disposal methods result in this energy intensive metal being lost and virgin metal being produced to replace it.

In conclusion, the work carried out in order to prepare this baseline document has highlighted the wide variety of complex packaging materials that are currently being disposed of and thus the wide variations in their specific impacts at end of life. Nevertheless, it has been possible to identify and define the most important aspects that will need to be considered when making comparisons with the new Sol-Rec 2 process. Of course, this in itself is likely to have various process variations that will each provide an optimal approach for a specific type of material waste stream.

As the Sol-Rec 2 process becomes better defined in terms of the specific waste streams and mixtures of materials that will be treated, it will be possible to focus more closely on the aspects of current practice that should be used to define the comparative baseline. It is therefore anticipated that further updates to this document will be made in due course in order to enable a full comparative LCA and related assessments to be made of the new Sol-Rec 2 process.

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