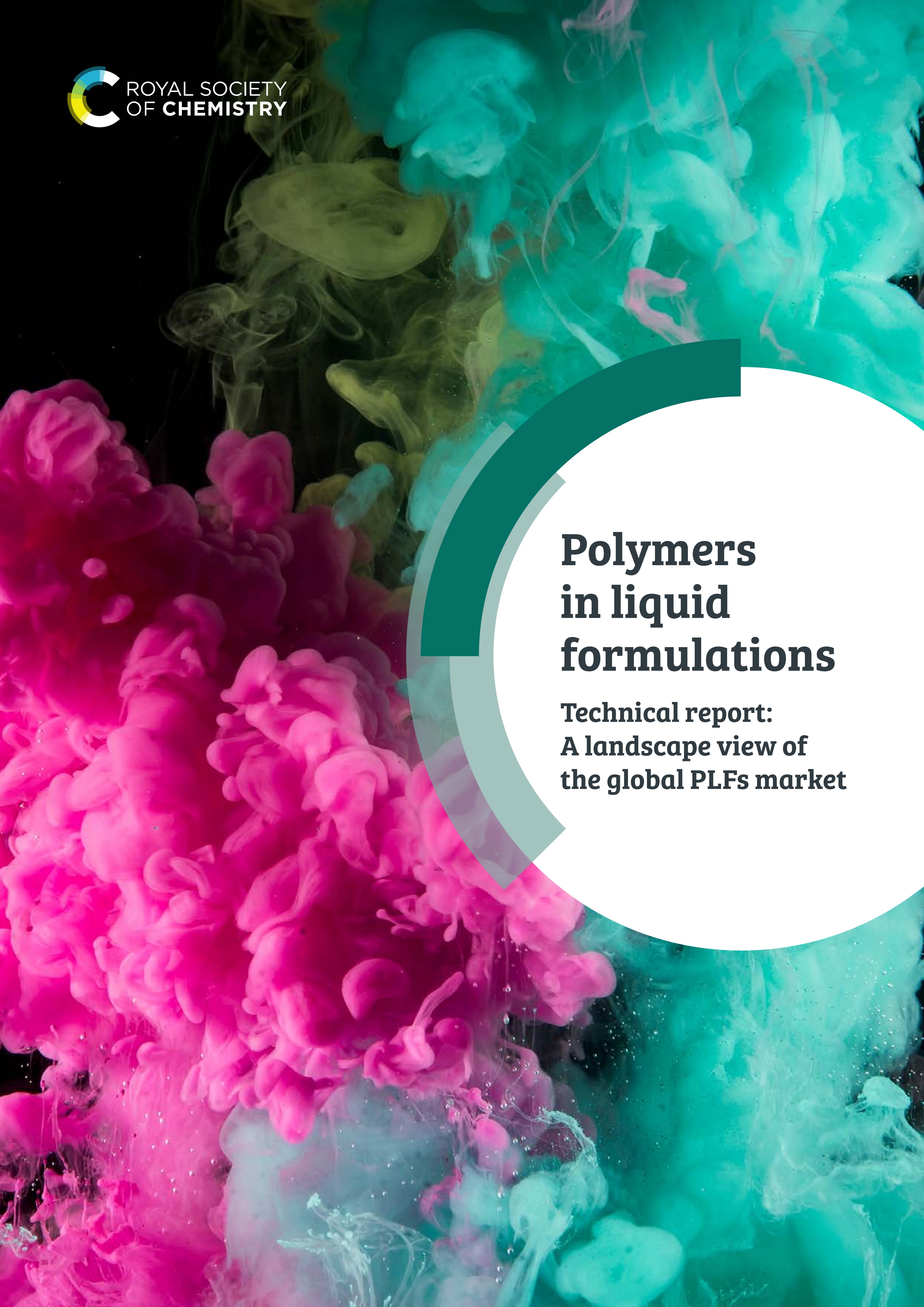

ROYAL SOCIETY
OF **CHEMISTRY**

Polymers in liquid formulations

Technical report: A landscape view of the global PLFs market

CONTENTS

1 About this report

This report was produced from an investigation into PLFs commissioned by the Royal Society of Chemistry and undertaken by CPI. In consultation with industry, the investigation provides a global view of the PLF market and analysis of the current landscape across key markets.

About the Royal Society of Chemistry

We are an international organisation connecting chemical scientists with each other, with other scientists, and with society as a whole. Founded in 1841 and based in London, UK, we have an international membership of over 50,000. We use the surplus from our global publishing and knowledge business to give thousands of chemical scientists the support and resources required to make vital advances in chemical knowledge. We develop, recognise and celebrate professional capabilities, and we bring people together to spark new ideas and new partnerships. We support teachers to inspire future generations of scientists, and we speak up to influence the people making decisions that affect us all. We are a catalyst for the chemistry that enriches our world.

This work was part of our Synergy programme, which brings together businesses working in different industries to tackle complex chemistry topics. Our world is changing faster than ever before. That means businesses are facing new and tougher chemistry-based challenges; often affecting multiple industries and supply chains. We know that collaboration can develop better solutions to these challenges, and faster. That's why the RSC's Synergy programme brings together businesses working in different industries to tackle complex chemistry topics. Through the programme, businesses develop new ways of working collaboratively to reduce risks, cut costs and bring solutions to market faster.

We would like to thank the project team at CPI: Colin Graves, Trevor Hinchcliffe, Nick Johnson, Dan Noakes and Sarah Williams for working with the Royal Society of Chemistry to deliver this important project for the chemistry community. We are also grateful to Afton Chemical, Anglian Water, Ashland, Croda, Lucite International, P&G, PRA world, Safic-Alcan, Scott Bader, Syngenta and Unilever for their contribution to workshops and interviews. We are particularly grateful to Ian Bell, Anju Brooker, Mark Cooper, Chris Lindsay, Gang Si, Laura Pilon, Paul Price and Rebecca Wood for their guidance throughout the project.

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2 Executive summary

Polymers in liquid formulations (PLFs) are a high value, critically important class of speciality chemicals worth **$125.2 billion*** to the global economy. They play a vital role in our society by improving food productivity, treating wastewater, protecting buildings, infrastructure and transport, as well as creating consumer products that promote health and wellbeing.

Despite their importance to the global economy, and in contrast to the strong recent focus on the sustainability of plastics, there has been very little attention on the sustainability of PLFs. This report is an important first step in addressing this issue.

PLFs markets, production and use

More than **36.3 million metric tonnes**† of PLFs are produced each year (equivalent to over **14,500** Olympic sized swimming pools) for agrochemicals, adhesives, coatings, cosmetics, household cleaning products, inks, lubricants, sealants, paints, personal care products and water treatment chemicals, which have a combined annual global value of **$1.27 trillion**. A significant proportion of the global volume of PLFs sold each year, over 31 million tonnes, are sold into paints, inks and adhesives, and sealants markets.

The PLF market is technically diverse and complex, comprising hundreds of different polymer types within the categories of acrylic, epoxy resins, polyesters, polysilicones, polyurethanes, radiation curable, vinyl, water-soluble and other low volume polymers.

In this report, we provide an overview of the PLF landscape and offer a qualitative assessment of PLF sustainability in each market by considering their production, use and environmental fate.

Manufacturers produce PLFs from a variety of raw materials including natural, bio-based and fossil-derived monomers. Synthetic PLFs are the most commercially significant because of their availability at high volumes, their competitive cost and the highly specialised properties that they deliver. As the global population grows, demand for PLFs will increase. The Organisation for Economic Co-operation and Development (OECD) stated that the global consumption of materials will double by 2050 and annual waste generation will increase by 70%.[1] Without PLFs, key industries like construction, utilities, automotive and aerospace would face enormous challenges in operating the way they do today.

In order to ensure that the PLF industry is economically and environmentally sustainable in the future, new approaches to PLF production, use and end-of-life treatment will be needed.

Within the PLF value chain, PLFs are used in formulations that are either liquid, which remain liquid on application and throughout use, or curable, which form solids on application and remain solid in use. This report finds that these formulation systems can explain key differences in the use and environmental fate of PLFs across different markets:

- PLF products in **liquid formulation** systems are predominantly found in personal care and cosmetics, household cleaning, agrochemicals, lubricants and water treatment markets. They are generally in use for short–medium timeframes and are likely to enter the environment as they pass through wastewater treatment plants at the end of their life.
- Adhesives, inks, coatings, paints and sealants use PLFs in **curable formulation** systems, which protect, join and seal other materials. They form solids on application and provide durability over much longer timeframes than other markets. Their chemical and mechanical resistance means that they may remain on substrate materials and enter waste streams at the end of their life or enter the environment through wear during use.

* All amounts quoted in this report are in US dollars unless otherwise stated

† Tonnages are expressed as metric tonnes throughout unless otherwise stated

Making PLFs more sustainable

Our analysis of the PLF landscape across the eight markets confirms that these materials currently follow a linear take-make-dispose model. Formulators select PLFs in the design of formulations based on the specific properties and effects that they deliver. However, PLFs are typically just one ingredient in a product and the value that the PLF brings is likely to go unnoticed by consumers and industrial end users. This factor also makes these materials difficult to collect, which means that they are likely to enter landfill or the environment as waste at the end of their life.

This report identifies a significant role for chemistry in developing solutions and describes three key opportunities to make PLFs more sustainable in the future.

Innovation

Developing novel PLFs from **bio-based feedstocks**, which are derived from food and agricultural waste or **other secondary raw materials (from waste)**, are potential routes to reducing the industry's reliance on fossil-derived feedstocks. **Biodegradable** PLFs could be a particularly important solution for liquid formulation systems that enter the environment as waste at the end of their life. Novel PLFs that **degrade under controlled or triggered processes** also represents an opportunity to improve the recyclability of substrate materials and reduce the potential risks of microplastics. This investigation also uncovered an opportunity to develop **higher performance and more efficient PLFs**, as well as biodegradability and stability testing to quantify technical improvements.

Circular economy principles

This investigation identified an opportunity to create a growing circular economy for paints and coatings **by scaling up existing take-back schemes** and extending them for other markets. **Digital track and trace** for paints and coatings and specific PLFs like polyacrylamide (PAM) could improve industry's understanding of supply risks and help develop more sustainable practices. Developing technology **to create secondary raw materials from waste PLFs** could reclaim monomers and create a sustainable source of energy for the chemical industry.

Optimising existing waste management infrastructure

Improving existing processes or developing new technologies to effectively remove PLFs on substrate materials could improve the recyclability of materials such as wood and plastic. There may also be opportunities to improve biological processes in wastewater treatment to ensure that organic matter containing PLFs is broken down into safe products before application of sludge onto agricultural land.

Taking action

Developing opportunities for industry to improve the sustainability of PLFs is a significant challenge that no single organisation or market can solve alone. However, this report finds a significant opportunity to bring together science, economics, policy and consumer behaviour to make these materials sustainable. Collaboration of this nature could enable us to move away from take-make-dispose models by investing in applied and discovery research, commercialising promising technology and developing regulation and incentives to promote sustainable practices.

We identified five opportunities to galvanise industry, academia, policymakers and funders into action:

1 **Establish new innovation networks that promote collaboration between academia, industry and policy**

2 **Identify and champion key research themes and priorities that will support researchers and businesses to tackle PLF innovation challenges**

3 **Explore the emerging need for a consistent approach to PLF biodegradability and stability testing**

4 **Investigate opportunities for chemistry-based innovations in developing circular economy solutions in key markets such as paints, adhesives and sealants**

5. **Engage with key stakeholders to ensure that a science- and evidence-based approach is used to develop future policy for PLFs**

The Royal Society of Chemistry will establish a PLF task force, which will convene industry to prioritise and progress these opportunities. We call on manufacturers, formulators and end users of PLFs across adhesives and sealants, agrochemicals, household cleaning, inks and coatings, lubricants, paints and coatings, personal care and cosmetics, and water treatment markets to work with us to catalyse action to develop sustainable solutions for PLFs.

If you would like to work with us to help develop these opportunities, please contact Jenny Lovell, Programme Manager, at **synergy@rsc.org**.

3 Glossary and key principles

Bio-based polymer	A polymer that is produced from biological resources, including chemicals derived from plants and algae. For example, polylactide is produced from sugar, which is harvested from plants like sugar cane
Biodegradable polymer	A polymer that undergoes accelerated degradation by organisms and biomolecules such as enzymes, forming small molecules that are metabolised by natural organisms. Biodegradable polymers should break down to natural materials that can be returned to the environment without pollution or deleterious effects
Carbon capture and utilisation (CCU)	A process that captures carbon dioxide emissions from sources like coal-fired power plants and reuses it so it will not enter the atmosphere
Formulation stability	A key aspect of formulation that defines the period of time over which a customer may expect the product to deliver consistent, optimised and safe performance. It sets a specification for shelf life
Life Cycle Assessment (LCA)	The method used to evaluate the environmental impact of a product through its life cycle, encompassing raw material extraction and processing, manufacturing and distribution, use, recycling and final disposal
Microplastic	Very small pieces of plastic that result from degradation of plastic in the environment or from products. Microplastics are plastic fragments between 1 micrometre and 5 millimetres
Molecular weight	The mass of one mole of a substance and an important characteristic that can determine a polymer's thermo-physical and mechanical properties
Monomer	A type of small molecule that makes a larger chain of polymers
Natural/ biopolymer	A naturally occurring polymer, such as cellulose or starch
Plastic	Plastics are primarily comprised of polymers, along with various additives (such as stabilisers, flame retardants, and plasticisers) that affect the physical properties of the material
Polymer	Polymers are long-chain molecules built from smaller repeating units called monomers. Some polymers contain only one type of monomer building block; others, known as copolymers, may contain two or more different types of monomer
Sustainability	Meeting our own needs without compromising the ability of future generations to meet their own needs. Natural, social and economic resources are the three factors that influence sustainability
Synthetic	A material made by chemical synthesis from fossil-derived feedstocks
Technology Readiness Level (TRL)	A method for estimating the maturity of technologies from an idea to a commercial product

4 Introduction

Polymers in liquid formulations (PLFs) are a critically important class of speciality chemicals that play a vital role in our society by improving food productivity, treating wastewater, protecting buildings, infrastructure and transport, as well as creating consumer products that promote health and wellbeing. The following section provides an introduction into this report by describing PLFs, discussing the wider context of global sustainability and outlining the scope of our investigation.

4.1 PLF definition

Polymers are macromolecules that comprise multiple repeating monomer units.[2] Their use is wide-ranging, from plastics to additives for automotive, medical and building applications.

A **Polymer in Liquid Formulation (PLF)** is a broad group of polymers used in a formulation that is liquid in manufacture or point of application. In use, products that contain PLFs either remain as a liquid or become a solid.

PLFs typically have a relative molecular weight between 1,500 and 10,000 g/mol

Their lower relative molecular weight provides soft, rubbery solids or low viscous liquids with little to no strength, which enables formulators to use PLFs as ingredients in liquid formulations. Some examples of natural PLFs, like polysaccharides, can have significantly higher molecular weights. Contrastingly, plastics have a higher molecular weight, between 10,000 and 500,000 g/mol, which gives rise to solid materials such as polyethylene, polypropylene and polystyrene.[3]

PLFs may be synthetic, natural or bio-based

Categorising PLFs as synthetic, natural or bio-based materials provides an insight into the different methods that manufacturers use to produce them. The following table summarises these types.

Derivation	Description	Example polymer
Synthetic	Monomers are derived from petroleum oil and prepared using chemical synthetic methods	Polyesters
Natural/biopolymer	Occur in nature and can be extracted or are produced by biological action	Gums, polysaccharides and proteins
Bio-based	Monomers are produced from biological raw materials but prepared using chemical synthetic methods	Polylactic acid

Table 1: Summary of synthetic, natural and bio-based PLFs

Synthetic materials are the most common type of PLF, but in some markets, natural and bio-based materials are growing in use. In a similar way to plastics, there can be some confusion between natural/biopolymers and bio-based materials; however, their production methods are clearly different.

PLFs are highly specialised materials that provide a wide range of functions

PLF products comprise several ingredients which include PLFs, solvents or carriers, active ingredients, structural ingredients and other components. PLFs broadly provide two essential functions to a liquid formulation.

- **Formulation integrity**

PLFs can be essential to the structure of a liquid formulation. These materials may be rheology modifiers, emulsifiers or stabilisers to thicken, mix oil-based and water-based substances, or prevent ingredients in the formulation from separating. Polyacrylic acids are rheology modifiers in haircare products that suspend, stabilise and thicken the formulation to ensure that consumers can apply the product and rinse it off after use. Without these PLFs, liquid formulations may not exhibit the correct consistency for application or maintain properties over the product shelf life.

- **Application-specific**

PLFs may also provide an application-specific function. For example, acrylic polymer resins used in paints for automotive topcoats act as a binder to help the paint stick to the surface of the vehicle and to form a stable thermoplastic or thermoset film when it dries. Another example is polysilicones, which provide aesthetic properties by improving the feel of hair and fabrics through a protective film on hair and fabric strands.

PLFs are found in eight high value markets

PLFs are a critically important class of speciality chemicals that are used in a wide range of applications, markets and sectors. This investigation focuses on eight key market segments that have a combined, estimated global market value of **$1.27 trillion** (see Table 2).

Market segment	End user	Example PLF products	Global market value ($ billion)
Adhesives and sealants	Industrial, some consumer	Transportation, construction, consumer DIY	64 [4]
Agriculture	Industrial	Pesticides and herbicides, seed coatings, soil conditioners	213 [5]
Household cleaning	Consumer	Laundry detergents and softeners, dishwashing and household cleaning, handwashing	164 [6]
Inks and coatings	Consumer, some industrial	Packaging, publication printing, digital and coatings that protect inks on products	39 [7]
Lubricants	Industrial, some consumer	Engine oils, hydraulic fluids, manufacturing lubricants	146 [8]
Paints and coatings	Consumer and industrial	Automotive, marine, architectural and decorative	151 [9]
Personal care and cosmetics	Consumer	Face and body care, haircare, cosmetics*	455 [10]
Water treatment	Municipal	Flocculants used in water and wastewater treatment	33 [12]

Table 2: Summary of key PLF market segments and their global market value

*Cosmetics market accounted for $246.3 billion in 2019 [11]

4.2 Context within global sustainability

PLFs are essential to global markets worth more than $1 trillion. However, wider global sustainability themes will influence these materials and their markets in the future. This section discusses three sustainability topics that are likely to affect PLFs, highlights the frameworks that are driving global action to improve sustainability, and the opportunities they may offer PLF manufacturers.

In this century, the global economy largely works by creating value from producing and selling products. The linear economy (Figure 1) refers to a system where industry manufactures materials like PLFs from raw materials and transforms them into products that consumers buy, use and discard at the end of their life. However, society widely accepts that this take-make-dispose model is unsustainable for both its resource consumption and waste production.

PLFs contribute to three significant global sustainability challenges:

- **Reliance on fossil-derived feedstocks as raw materials for producing PLF products**

The chemical sector relies on fossil-derived feedstocks to produce a wide range of products that contain PLFs and other ingredients and is responsible for approximately 7% of greenhouse gas emissions generated from human activity.[13] As the global population rises, the demand for these products and raw materials to produce them also increases. This could lead to price rises and competition with other industries and future supply risks. Half of greenhouse gas emissions and more than 90% of biodiversity loss and water stress comes from material, fuel and food resource extraction and processing, so increased demand could put greater strain on the environment.[14]

- **Waste production from PLF products that are disposed of at the end of their life**

In 2018, the United States Environmental Protection Agency found that more than 27 million (US) tons of global plastic was entering landfill.[15] In a similar way to fossil-derived feedstocks, as population increases more and more products that contain materials like PLFs will be disposed of at the end of their life. PLFs products will likely contribute to increases in waste generation, which the OECD estimates will rise by 70% by 2050.[16]

- **Pollution from PLF products in the environment**

In addition to waste, the volume of pollution entering the environment is another key sustainability challenge. Studies show that the volume of plastic waste entering the ocean is occurring at an approximate rate of 11 million tonnes a year, where it is harming marine life and damaging habitats.[17] PLFs and a wide range of other materials are also likely to contribute to pollution and urgent action is needed to reduce the volumes entering the environment.

The world is taking action and countries are making several commitments to tackle these sustainability challenges:

- In 2015, the Paris Agreement was set up to strengthen the global response to climate change by keeping temperature rises below 2° C.[18]
- The EU launched the Green Deal, which is an action plan to become climate neutral by 2050 through efficient use of resources by moving to a circular economy, restoring biodiversity and cutting pollution.[19]
- In 2019, the UK was the first major economy to set targets in law to bring all greenhouse gas emissions to net zero by 2050. As a result, clean growth is one of the four grand challenges in the UK's industrial strategy, which is driving research and innovation towards low carbon technology.[20]

There are also several examples of organisations that are putting frameworks and initiatives in place to stimulate action. The United Nations established the Sustainable Development Goals (UNSDGs) as a blueprint to achieve a more sustainable future – it is estimated that they could generate $12 trillion in business savings and revenue by 2030.[21]

Countries are adopting a range of approaches, practices and concepts to move towards more sustainable practices. The waste hierarchy, for example, ranks waste management options according to risk to the environment.

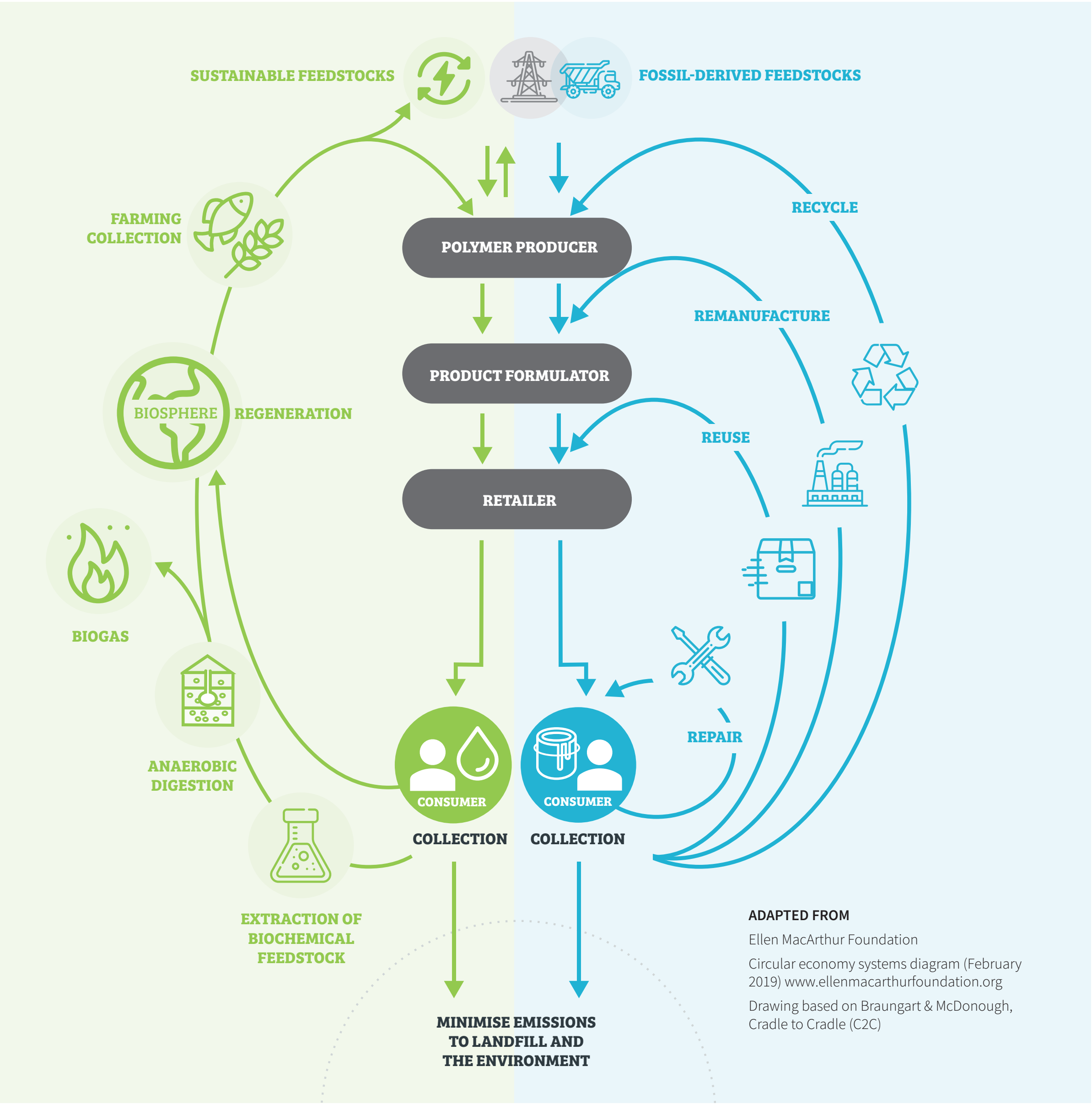
Figure 1: The linear economy

Figure 2: Waste hierarchy

The most impactful solution is rethinking and redesigning products to make them resource efficient. The waste hierarchy also draws attention to reducing consumption of products in the first place. There are plenty of examples of this approach in industry. Personal care brands, for example, are designing durable and refillable packaging alongside direct-to-consumer refill-and-reuse models as a way of reducing the amount of plastic used in their products.[22]

Although recycling is a widely implemented option for materials like plastic, glass and paper, it is not as sustainable as reducing or reusing options. This because energy is still required to turn waste into new products. Recovering energy through anaerobic digestion, incineration and gasification and disposing products to landfill are final resort options if other approaches are not possible.

In 2011, the UK government outlined guidance for businesses on how to apply this waste hierarchy; however, no guidance is given on specific ingredients like PLFs.[23]



ADAPTED FROM

Ellen MacArthur Foundation

Circular economy systems diagram (February 2019) www.ellenmacarthurfoundation.org

Drawing based on Braungart & McDonough, Cradle to Cradle (C2C)

Figure 3: A circular economy

The circular economy is an example of a transformative approach that could offer an alternative way of managing products that contain PLFs. This concept focuses on regenerating natural systems, designing out waste and pollution and keeping products and materials in use. The Ellen MacArthur Foundation promotes a global transition to a circular system, which could save $700 million in annual material costs for the fast-moving consumer goods industry, and generate a 48% reduction of carbon dioxide emissions by 2030.[24]

Figures 1-3 highlight the differences between a linear and a circular economy, and emphasise implementation of the waste hierarchy to reduce, reuse and recycle materials and products to minimise waste production at the end of their life.

There are several initiatives that are stimulating a transition to a circular economy:

- The New Plastics Economy, an initiative backed by 500 organisations, is an example of how industry, UK governments and the public are working together to transition plastics to a circular economy.[25]
- McKinsey management consultancy's ReSOLVE framework outlines six actions to help businesses implement circular economy principles. Shifting to renewable energy and materials, peer-to-peer asset and product sharing and increasing product performance and efficiency are all ways that businesses can improve sustainability.[26]
- The EU has adopted its own Circular Economy Action Plan that uses policy to improve the sustainability of products placed on the EU market. Specific focus will be for sectors that use the most resources and where the potential for circularity is high, such as electronics, textiles and packaging.[27] McKinsey estimates that this could generate a net economic benefit of €1.8 trillion by 2030.[28]

4.3 Opportunity for PLFs and work to date

Governments, businesses and other key organisations are establishing commitments and driving new approaches to improve sustainability on a global scale. Specific action on plastics, for example, will see new mandatory requirements for recycling content in the EU, with special attention on microplastics and more focus on bio-based and biodegradable materials.[27] However, to the best of our knowledge there are currently only limited, uncoordinated examples of these in the PLF industry. Without new approaches and collaboration between UK governments, industry, academia and wider society, there is a risk that the PLF industry will miss opportunities to make these materials sustainable.

Through an ongoing piece of work with industry, we identified an important role for chemistry in developing innovative sustainable solutions for PLFs across multiple markets. We also found an opportunity for greater collaboration between academia and industry to address risky cross-sector challenges that no single market can solve alone. In addition, we recognise a wider opportunity to bring together UK governments, business, academia and the public to invest in research, enable innovation and the commercialisation of emerging technologies and develop future policy to promote sustainable practices.

Through the Royal Society of Chemistry's Synergy programme, we bring together businesses that are facing complex chemistry problems to catalyse collaborative action to develop solutions.[29] In 2018, we conducted an initial exploration into PLFs, which industry highlighted as an important topic for sustainability.

In a series of workshops and interviews with experts from industry, academia, UK government departments and NGOs, we identified the high level drivers for innovation across key PLF markets and cross-sector challenges that these materials pose for industry. Our report, *A Circular Economy for polymers in liquid formulations*, found that industry largely source these materials from fossil-derived feedstocks and they enter waste streams at the end of their life. Through this work, we confirmed that these materials contribute to climate change, waste generation and environmental pollution, though further analysis was required.

Our initial report highlighted four significant opportunities for the development of chemical science-based solutions:

- modification and development of new monomers and polymers
- life cycle analysis, models and methods to design sustainable materials
- manufacturing scale up of sustainable monomers
- recovery and reuse of polymers[30]

The recommendations arising from this initial exploration were to define the scale of the PLF industry and understand the materials currently used so that businesses can progress the four collaborative opportunities described above. After further feedback with industry, we conducted an in-depth study into the PLF landscape with the Centre for Process Innovation (CPI) to satisfy these recommendations.

Further information about the scope of the investigation and methodology that we used is detailed in Section 9.1. In this report we:

- provide an overview of scale of the PLF industry and key markets, applications and materials types
- describe the potential indicative environmental fate of PLFs in different formulation systems and markets
- identify key sustainability challenges for PLFs
- summarise potential solutions to make PLFs more sustainable
- outline our plan to galvanise action in academia, industry, government and wider society to develop sustainable solutions

5 PLF analysis

In this investigation, we identified more than 200 different PLFs across eight key market segments. This section offers an insight into the scale of the PLF industry and provides an overview of the key material types, markets and applications. We also discuss the environmental fate of PLFs at the end of their life to uncover key similarities and differences between different markets. This section aims to provide an overview of the current PLF landscape.

5.1 PLF types and formulation systems

PLFs are a diverse and versatile class of materials. In order to simplify the wide range of PLFs available to formulators, this investigation identified nine key types that group materials with similar chemistries and characteristics. These are: acrylic, epoxy resins, polyesters, polysilicones, polyurethanes, radiation curable, vinyl, water-soluble and other low volume polymers.

Table 3 summarises the different types of PLFs and the key markets that they are used in.

Type	Description	Adhesives and sealants	Agrochemicals	Household cleaning	Inks and coatings	Lubricants	Paints and coatings	Personal care and cosmetics	Water treatment
Acrylic polymers	Prepared from acrylate monomers	X	X	X	X		X	X	
Epoxy resins	Contain one or more epoxide or oxirane group	X			X		X		
Polyesters	Contains ester functional group in their main chain	X			X		X		
Polysilicones	Contain an inorganic silicon–oxygen backbone	X	X	X	X		X	X	
Polyurethanes	Composed of organic units joined by carbamate (urethane) links	X			X		X		
Radiation curable	Polymers that are cured when exposed to ultra violet (UV) or electron beam (EB)	X			X		X		
Vinyl polymers	Prepared from vinyl monomers and have an extended alkane chain	X			X		X		
Water-soluble	Polymers that dissolve, disperse or swell in water	X	X	X	X		X	X	X
Other, eg phenolics, polyamides and polyolefins	High importance, low volume polymers	X	X		X	X	X		X

Table 3: Key polymer types and markets

Table 3 shows that acrylic polymers, polysilicones and water-soluble polymers are key types found across several PLF markets. The 'other' category represents PLFs that are highly important but used in lower volumes, predominantly in lubricants. This type is also common across other PLF markets, which emphasises the diversity of the PLF landscape and that there is no perfect way of categorising these materials. Adhesives, sealants, inks and coatings, and paints and coatings have a similar polymer profile, with examples from all polymer types.

Most of these polymer types share similar chemical structures. However, water-soluble polymers are an exception because they include a wide range of chemistries and polymers derived from synthetic, natural and bio-based materials. This category groups materials that use water as the main solvent carrier often found in formulations for agrochemicals, household cleaning, personal care and water treatment.

This investigation also identified two different formulations systems for PLF products, which brings further clarity to this class of materials. Analysis of PLFs across the eight markets identified:

- **liquid formulation systems** that remain as a liquid on application and in use
- **curable formulation systems** that form solids on application and in use

Table 4 describes these systems and summarises the key markets, polymer types and primary functions.

Five key markets use liquid formulation systems and encompass products that are used in consumer, municipal and industrial products and processes. Curable formulation systems, however, incorporate adhesives, sealants, inks and coatings, and paints markets and typically use a wider range of PLF types.

	Liquid	**Curable**
Description	Formulations remain as liquids in use and are key ingredients in consumer, municipal and industrial products and processes	Formulations form solids on application and primarily protect, bond and seal substrate materials
Key markets	Agrochemicals Household cleaning Personal care and cosmetics Lubricants Water treatment	Adhesives and sealants Inks and coatings Paints and coatings
Main polymer types	Water-soluble Acrylic polymers	All types

Table 4: Summary of key formulation systems

5.2 Global market values and volumes

The polymer types and formulation systems discussed in the previous section provide a high level overview of the PLF landscape across the eight markets. This section estimates the global market values for the nine key polymer types described in section 4.1 and offers an approximation of production volumes through two methods, bringing greater clarity to this class of materials.

According to various market reports, the estimated total global value of PLF ingredients is **$125.2 billion**. We also used two approaches to estimate the production volumes of these materials.

Top–down approach

This investigation used published market reports and data for each polymer type to estimate the global production volume for PLFs at **29 million tonnes per year**. Table 5 provides a breakdown of these values and a unit value for each polymer type. (No information was available for acrylic polymers; further detail on how these figures were determined is described in Table 14 (see page 29).

Bottom–up approach

The top-down approach provides an approximation of production volumes without considering the different markets. We also used a bottom–up approach to provide further clarity on the volumes of PLFs used across the eight key markets. We used the following information:

- published data on global market volumes and global polymer spend
- data on key polymers used in specific markets
- estimates of % polymer weight
- market knowledge to estimate the volume of PLFs used in the eight PLF market segments

This approach estimates the total global volume of polymer ingredients in these eight PLF market segments to be **36.3 million tonnes per annum**. This figure includes acrylic polymers, which could account for an estimate that is seven million tonnes higher than the previous approach.

Table 6 summarises the volumes and concentrations of key polymer ingredients in each market. These figures were calculated based on assumptions from the best data available (further detail on how these figures were determined is described in Section 9).

Estimates in Table 5 suggest that water-soluble polymers have the greatest global value and highest volume at $44.1 billion and eight million tonnes respectively. Three of the highest value PLF markets – agrochemicals, household cleaning and personal care and cosmetics – use this significant and important subset of PLFs in liquid formulation systems. The relatively low volumes and concentrations of PLFs in these three markets highlighted in Table 6, further suggests that water is used in high volumes as the main solvent or carrier.

The market volume of acrylic polymers was not available. However, since both acrylic and water-soluble polymers have high global market values and they are found in similar markets, we assume that their volumes are similar. Despite the similarities in markets that use liquid formulation systems, we also highlight some key differences.

Table 6 shows that agrochemicals is a high value market with a relatively low concentration of PLFs in products. Manufacturers often sell formulations as concentrated products for farmers to dilute at the point of application which could explain this observation.

Personal care and cosmetics and household cleaning markets also have high market values and use water-soluble polymers. Experts highlighted that PLFs provide both structural and application specific functions to high value products. Unlike agrochemicals, consumers play a significant role in influencing innovation in these markets.

Polymer type	Global value of polymer ingredients ($ billion)	Global market volume (million tonnes)	Unit value ($/kg)
Water-soluble	44.1 [31]	8.0 [31]	5.6
Polyurethanes	22.2 [32]	8.0	2.8
Acrylic polymers	15.9 [33]	Figure not available	N/A
Other	15.0	6.3	2.4
Polysilicones	8.2 [34]	0.7	11.7
Epoxy resins	7.0 [35]	3.0 [35]	2.5
Polyesters	5.2 [36]	1.1	4.7
Radiation curable	3.1 [37]	0.8 [37]	6.0
Vinyl polymers	4.5 [36]	1.1	4.1

Table 5: Breakdown of global value and volumes according to polymer type

This may provide formulators with a greater choice of PLFs in order to target specific customer requirements. For example, Table 5 shows that polysilicones have a global value of $8.2 billion, but manufacturers only produce 0.7 million tonnes each year. One of their main functions is as an aesthetic ingredient that consumers may be willing to pay a premium for, which may account for their particularly high unit value of $11.7/kg.

Similarly, Table 6 indicates that the volume of polymer ingredients sold into the lubricants market is also low compared to its high market value. The main polymer type used in lubricants is 'other', which describes highly specialised low volume PLFs and emphasises the essential role that these materials play in these products.

Paints and coatings also represent one of the highest polymer volumes, with 21.6 million tonnes sold into this market each year. Table 3 shows that unlike other high value markets, liquid formulations in this market use PLFs from all nine types. The inks and coatings, and adhesives and sealants market segments are also similar. Although the global demand of these products is significantly less than paints and coatings, the volumes and concentrations of polymers in these markets are much higher than the top three PLF market segments.

With a global value of $22.2 billion, polyurethanes are a key polymer type used in these applications. Although the global value of these materials is half that of water-soluble polymers, the global production is also eight million tonnes per year. Paints and coatings, along with other lower value markets, use this polymer type at relatively high concentrations of 2% to 100%. Experts in this market highlighted the drive towards low Volatile Organic Compound (VOC) systems that use less solvent due to EU regulations.

The water treatment market is also a low value market. Experts highlighted that this highly regulated municipal service significantly relies on polyacrylamide, a water-soluble polymer used as a flocculent agent in treating wastewater.

5.3 Key applications and functions

This report has provided an insight into the nine key polymer types used in eight key PLF markets at volumes ranging from one million to 20 million tonnes each year. Further analysis of the polymers used in each of these market segments offers a high level overview of their applications and functions. The following section summarises the main applications and functions of the key polymer types in each market, in descending global market share.

5.3.1 Personal care and cosmetics

Personal care and cosmetics has the largest global market value of $455 billion each year. The three main polymer types sold into personal care and cosmetics are acrylic polymers, polysilicones and water-soluble polymers. Table 7 summarises the main functions in this market.

Market segment	Global market value ($ billion)	Polymer types	Global market volume of PLF ingredients (million tonnes)	Concentration (%)
Personal care and cosmetics	455	Acrylics Polysilicones Water-soluble	0.8	1–10
Agrochemicals	213	Acrylics Polysilicones Water-soluble Other	2.1	<1
Household cleaning	164	Acrylics Polysilicones Water-soluble	0.4	1–10
Paints and coatings	151	All	21.6	20–100
Lubricants	146	Other	0.4	1–2
Adhesives and sealants	64	All	7.8	20–100
Inks and coatings	39	All	1.7	2–100
Water treatment	33	Water-soluble Other	1.5	<1

Table 6: Global market volume of polymer ingredients for each PLF market segment

The personal care and cosmetics market comprises synthetic and natural polymers. Synthetic water-soluble polymers are the most widely used PLF, but natural and bio-based polymers are growing in demand due to greater consumer preference for environmentally friendly ingredients.

PLFs in this market are multifunctional. Polyvinylpyrrolidone (PVP), for example, is a tablet binder, stain remover and opacifier in hair and dental care formulations. However, over 20 examples of both homopolymer and copolymer forms are commercially available at varying molecular weights from several suppliers. This provides formulators with freedom to select polymers with properties that fulfil the increasing list of specific customer requirements. As a result, the personal care and cosmetics market offers a wide range of products, including premium and personalised formulations, enabling businesses to react rapidly to changing consumer demands and trends.

Table 7 highlights that PLFs play a critical role as rheology modifiers in this market; dispersing and stabilising ingredients in formulations for shelf lives of up to two years. Since water is the main solvent carrier in these liquid formulations, acrylic polymers and some natural water-soluble polymers, create viscosity by binding or immobilising water. Polyacrylic acid copolymers are the workhorse of the industry, enabling consumers to apply formulations to skin or hair and wash off after use. Another key PLF function is to act as an emulsifying agent. Some acrylic polymers, polysilicones and water-soluble polymers work by reducing the surface tension between water and oil-based ingredients to form a liquid formulation that users are able to apply consistently to the body or hair.

PLFs in this market also play a key role in delivering active ingredients. For example, water-soluble polymers like biopolymer cyclodextrins encapsulate vitamins for anti-aging lotions. These polymers work by releasing molecules to the target area, eg skin, which increase the efficacy and bioavailability of active ingredients. Preservation of active ingredients during formulation, storage and application is another benefit of these polymers, since these molecules may be particularly sensitive to pH, light and temperature degradation over time.

As well as providing critical functionality to liquid formulations, PLFs also improve the feel of products. Formulators add polysilicones and water-soluble polymers like polyglutamic acid as emollients and moisturisers to provide a protective layer to the skin and hair.

Rapid growth in polymer innovation has enabled the personal care and cosmetics market to create a wide range of products that target growing customer requirements, creating a global market worth $455 billion. The concentration of PLFs in this market is typically less than 1% by weight of the formulation and whilst only 0.8 million tonnes of polymer ingredients are sold into this market these highly specialised materials add significant functionality to products in this market.

Function	**Active ingredient delivery:** delivers active ingredients in the liquid formulation via encapsulation or for polymer incorporation	**Emollient, conditioning, moisturising:** traps moisture and forms a protective film to improve hydration on skin and hair	**Rheology, thickening:** stabilises formulations and thickens formulations for storage and application	**Emulsifier, film former:** mixes ingredients in water and oil-based formulations to ensure consistency for application	**Fixative:** forms hard films for haircare and aerosol products
Acrylic	**X** Alkyl acrylates and methacrylates, omega hydroxyalkyl acrylates		**X** Polyacrylic acid	**X** Poly C10-30 alkyl acrylates	
Polysilicones		**X**		**X**	
Water-soluble	**X** Dextrins	**X** Polyglutamic acid, cationic cellulose and guar	**X** Eg Starch, cellulose gum, alginates, pectin	**X** Polyethylene glycol/PPG copolymers, xanthan gum, agar, chitin, chitosan	**X** Vinyl acetate

Table 7: Summary of PLF types, functions and examples in personal care and cosmetics

5.3.2 Agrochemicals

Agrochemicals is the second largest PLF market with a global annual value of $213 billion and comprises four main polymer types: acrylics, polysilicones, water-soluble and other polymers. PLFs are predominantly an essential component of bulk formulations such as fertilisers, but there are also examples of polymers in specialised formulations: soil conditioners, wetting agents and seed coatings.

Table 8 summarises the main functions in this market.

One of the key functions that water-soluble and ‘other’ PLFs share is to act as dispersing and viscosity agents in bulk liquid formulations. These suspend active ingredients in oil and water-based formulations and generate larger droplets for spray application. This property is especially important for drift control to limit liquid droplets run-off into adjacent fields causing potential contamination. PLFs that provide this functionality also prevent sedimentation in concentrated forms of agrochemical formulations. This property ensures that when farmers dilute agrochemical formulations at point of application, they are at the required viscosity for effective spray application.

Another key function of water-soluble PLFs is the slow or controlled release of active ingredients. PLFs encapsulate macronutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) and micronutrients such as boron (B), chlorine (Cl), cobalt (Co), copper (Cu) and iron (Fe), delivering them directly to plants, whilst reducing the potential of agrochemical contamination and bioaccumulation. We found examples of synthetic water-soluble acrylamide-based polymers for this application, as well as natural polymers including chitosan and starch.

Formulators also use ‘other’ PLF types for these applications, but they are likely to use curable formulation systems. For example, polyurea resin encapsulates solid fertilisers by forming a cross-linked solid polymer film around the active ingredient on application. In a similar way, PLFs are also used for coating seeds. Polyvinyl acetates and polyvinyl alcohols are excellent film formers for specialist formulations, helping to keep ingredients on the seed to maximise their productivity. Experts highlighted that PLFs in these applications have high mechanical strength and durability.

The main application of acrylic polymers in this market is specialist applications for soil conditioning. In their cross-linked form they create superabsorbent polymers (SAP), which absorb large amounts of water. This makes them ideal as nutrient and water carriers for improved irrigation.

Experts highlighted that the concentration of PLFs in bulk liquid formulations is less than 1% by weight. However, since 2.1 million tonnes are sold into this market each year, PLFs in this market are considered essential to improving soil and crop efficiency for global food productivity.

Function	**Soil conditioner**: improves the water retention and aeration capacity of soil	**Dispersant and viscosity control**: suspends active ingredients in water or oil-based formulations for effective application	**Slow/controlled release**: delivers active ingredients into soil to fulfil nutritional needs of plants	**Wetting agent**: enables faster water penetration to soil and improves the ability of soil to retain moisture	**Film former**: coats seeds with active ingredients such as nutrients or disease prevention
Acrylic	**X** Alkyl acrylates and methacrylates, omega hydroxyalkyl acrylates				
Polysilicones				**X**	
Water-soluble		**X** Polysaccharides, xanthan gum	**X** Polyacrylamide-based gels, chitosan, starch		
Other		**X** Ethylene oxide propylene oxide	**X** Polyurea resins	**X** Polyoxyethylene, alkyl polyglucoside	**X** Polyvinyl acetate, polyvinyl alcohol

Table 8: Summary of PLF types, functions and examples in agrochemicals

5.3.3 Household cleaning

Household cleaning is another key PLF end-market with a significant global market value of $164 billion. Like personal care and cosmetics, the main PLF type used in this market is synthetic water-soluble polymers. Table 9 summarises several PLF functions used in household cleaning applications.

This analysis found that formulators in this market have a smaller selection of PLFs to use compared with personal care and cosmetics, which could be because consumers have a less wide-ranging set of requirements. However, the key polymers – polyacrylic acid homopolymers and copolymers and polyvinyl pyrrolidone – are similar.

One of the main functions of PLFs in this market segment is as dispersing agents, reducing the impact of water hardness ions. Acrylic polymers have hydrophilic and hydrophobic properties, which mean that they inhibit crystal growth, keeping them dispersed in water and inhibiting redeposition on surfaces. Polyvinylpyrrolidone (PVP) homopolymer and PVP copolymers are dye transfer inhibitors: as highly polar materials they play a key role in scavenging free dye molecules released from fabrics during the washing process.

PLFs also act as soil-release and anti-soil redeposition agents. Both polyester and polyethylene glycol copolymers improve the release of soil from synthetic fabrics. Acrylic polymers, like anionic polycarboxylates based on acrylic acid, account for a significant proportion of PLFs in this market as they suspend soil and minimise redeposition onto fabrics.

The volume of polymer ingredients sold into this market is 0.4 million tonnes and the concentration of polymers in cleaning and washing products is less than 1%. Even though PLFs in this market are established, there is a trend towards an expanding range of polymers to meet customers' growing desire to be sustainable. For example, there are examples of polymer products targeted towards lower temperature washing and bio-based polymers dedicated to the detergent industry.

5.3.4 Lubricants

Lubricants represent a key PLF market with a global market value of $146 billion. Similar to other high value global market segments, the volumes of polymers sold into this sector are relatively low at 0.4 million tonnes each year. Our analysis shows that PLFs in this market play a critical role in product areas such as automotive, industrial, metalworking fluids, process oils, marine and grease.

Formulations in this market are a mixture of base oil and additives, which reduce or minimise friction to moving parts by providing a thin layer of film between components. Refined crude oil typically provides the base of the formulation, but additives including PLFs provide additional functionality and extend the lifespan of the products.

Function	**Dispersing agent:** reduces the impact of water hardness ions and enhances the performance of surfactants	**Soil anti-redeposition/soil repellency**: improves the release of soil from synthetic fabrics and suspends soils to minimise redeposition	**Dye transfer**: scavenges free dye molecules released from fabrics during washing	**Rheology, thickening**: stabilises formulations and thickens formulations for storage and application	**Flocculent**: coagulates floating particles for removal	**Softening**: after treatment giving fabrics a soft feel
Acrylic	**X**	**X**				
Polysilicones						**X**
Water-soluble		**X** Polyethylene glycol, polyvinyl alcohol, styrene maleic anhydride polymers	**X** PVP, polyvinyl imidazole, polyvinyl pyridine betaine	**X** Cellulose based polymers, Poly (2-dimethylamino) ethyl methacrylate methyl chloride quaternary	**X** Polyacrylamide	
Polyester		**X** Non-ionic polyester				

Table 9: Summary of PLF types, functions and examples in household cleaning

The main function of PLFs in this market is viscosity modification. Some lubricants, like engine oil, must have low viscosity at low temperatures to assist in cold starting and high viscosity at high temperatures to maintain load-bearing characteristics. Polymeric viscosity index (VI) improvers enable viscosity changes at different temperatures.

This highly specialised function is primarily provided by PLFs that belong to the 'other' category of PLFs and include polyolefin copolymers, polyalkylmethacrylates and hydrogenated poly(styrene-co-conjugated dienes).[38] As well as viscosity modifiers, PLFs also assist in dispersion, liquid flow, anti-foaming and corrosion inhibition.

Given the relatively high value of this market, the low PLF concentration and their specialist function, lubricants are another example that illustrates the importance of PLF materials.

5.3.5 Paints and coatings

By far the largest market by PLF volume is paints and coatings, with 21.6 million metric tonnes consumed each year. PLFs in this market are important in protecting and extending the life of buildings, assets and industrial components. Unlike the other high value market segments discussed so far, in this market there are examples of PLFs from all polymer types including acrylic polymers, epoxy resins, polyesters, polysilicones, polyurethanes, radiation curable, vinyl polymers, water-soluble and other lower volume polymers.

The main function of paints and coatings is to protect or decorate materials, which can be categorised into two applications:

- household and commercial architectural applications
- non-architectural applications including automotive, marine and industrial uses

The main function of PLFs in these applications is as a binding agent, helping the paint or coating to adhere to a material's surface. They provide their characteristic protective property by forming stable thermoplastic or thermoset films upon application. PLFs in this market therefore play a key role in protecting materials from external conditions such as weather, marine environments and physical wear that would otherwise cause them to degrade over time. In architectural applications, paints and coatings also provide decorative functions, which can extend the life of household materials. Table 10 summarises a selection of PLF functions and properties in this market.

PLFs in this market are multifunctional, but Table 10 highlights several examples of key polymer types in different paints and coatings applications. For example, this analysis found that acrylic, radiation curable polymers and 'other' polymer types are significant in automotive applications, whereas polysilicones, polyurethanes and epoxy resins are found in marine applications. Polysilicones and vinyl polymers are key polymers used in industrial applications because of their specific heat and corrosion resistance.

Water- and latex-based emulsions are examples of paints and coatings used in architectural applications such as home and commercial decorating. Acrylic, water-soluble and polymers like polybutadienes, enable paints, consisting of immiscible ingredients like pigments, synthetic particles and water, to form a miscible liquid for application. On drying, these polymers ensure synthetic ingredients of the paint can coalesce when the water evaporates, providing the protective or decorative layer.

PLFs provide both structural and application specific properties in a wide range of water-based, solvent-borne and high solid paints, as well as powder and radiation cured coatings. The estimated polymer content of both water and solvent-based paint and coatings is 50% by weight. These make up almost

Application	**Automotive**	**Marine**	**Industrial, eg corrosion and heat resistance**	**Varnishes**	**Water and latex emulsions**	**Wood coatings**	**Wood coatings**
Acrylic	X				X		
Polysilicones		X	X				
Polyester							X
Polyurethanes		X		X			
Epoxy resins		X	X				
Other	X				X		
Radiation curable	X					X	
Water-soluble					X		
Vinyl polymers			X				

Table 10: Summary of PLF applications in paints and coatings

half of the total market share.[39] The other half of the market is comprised of high solid, powder coatings and radiation curable systems, which have higher concentrations of polymer (between 80 and 100% by weight), because of their zero or low solvent systems.

Water-based paint and coating technologies are the largest segment within this market, accounting for 28% of the global market.[36]

Experts project that this technology will grow significantly in the coming years due to environmental legislation driving formulators to move away from high VOC coatings.

PLFs in paints and coatings contribute to a global market value of $151 billion each year. The main difference to the other high value market segments that we have discussed is that they form solid films. From our analysis, we found that the polymer toolbox is more diverse than many other PLF markets and the concentrations are significantly higher, since solvents must evaporate on application.

5.3.6 Adhesives and sealants

Adhesives and sealants is another key PLF market that shares similar PLF types and properties with paints and coatings. This market represents one of the smallest markets in this investigation and is worth $64 billion. Synthetic-based PLFs provide a vital role in manufacturing and construction.

The primary function of PLFs in adhesives is high strength for bonding materials together. This occurs by physical hardening (thermoplastics), chemical hardening (thermosets) and pressure.[40] Sealants create impenetrable barriers to gas, moisture or chemicals by filling up a space, joint or gap between materials.[41] PLFs in these products exhibit lower strength than adhesives but higher elongation.

Adhesives and sealants serve a wide range of markets including automotive, paper, packaging, construction, DIY, textile, leather, and electronics assembly.

Application	**Adhesives**					**Sealants**		
	Metals	**Woods**	**Rubber and plastics**	**Glass and ceramics**	**Versatile**	**Exterior**	**Interior**	**Industrial and commercial**
Acrylic	**X**		**X** Acrylic solvent (cement)		**X** Cyano-acrylates	**X** Solvent-based acrylic	**X** Latex-based	
Polysilicones						**X**		**X**
Polyurethanes	**X**		**X**	**X**				**X**
Epoxy resins	**X** Epoxy silicones							
Other	**X** Polyimides, polyamines, polysulfides	**X** Resorcinol, polychloroprene	**X** Acrylo-nitrile butadiene, butyl rubber, styrene-butadiene	**X** Poly-sulfides, polyamines	**X** Natural rubber	**X** Butyl rubber		**X** Poly-sulfides
Vinyl polymers		**X** Polyvinyl acetates						

Table 11: Summary of PLF applications in adhesives and sealants

This market segment consists of five main product types:

- hot melt, acrylic and pressure sensitive adhesives
- polysilicone, polyurethane and acrylic sealants
- cyanoacrylate, anaerobic and miscellaneous adhesives
- epoxy, polyurethane and vinyl adhesives
- butyl, polysulfide, SMP and miscellaneous sealants

PLF types used in adhesives and sealants are diverse because of the range of materials that they bond and seal. Table 11 summarises polymers and different application areas.

Through our analysis, we found that PLFs in adhesives are multifunctional, providing bonding properties by hardening on application as well as additional properties. PLFs like epoxy resins, polyurethanes and acrylics, provide additional flexibility and strength for bonding materials like metals, glass and plastics. Whereas lower volume polymers like polyimides provide temperature, pressure and chemical resistance required for more demanding applications.

Sealant formulations require different PLF properties compared to adhesives. They are generally high solid formulations delivered through a reaction between a polymer base material and an activator. Lower performance sealants used in interior and exterior household applications include natural and synthetic polymers such as polyvinyl alcohol, polyesters, acrylics, and butyl rubber. Higher performance products used in industrial and commercial applications, like construction and aerospace, typically use epoxy resins, polyurethanes, acrylics and polysilicones.

PLFs in both adhesives and sealants are present in high concentrations, similar to those in paints and coatings. Their functionality provides these products with the necessary strength and flexibility to bond and seal materials, which are vital in the creation of high value products like cars, airplanes and electronics, as well as protecting buildings from moisture damage. Whilst this market is not one of the highest in value, adhesives and sealants are significant enablers of other markets and play a key role in manufacturing and construction.

5.3.7 Inks and coatings

Another key PLF market that uses curable formulation systems is inks and coatings, which comprises lithographic, flexographic, gravure, and digital inks. Polymers in this market are used in packaging, publication printing, screens and graphics as well as offset commercial printing. Table 12 summarises the main applications in this market.

PLFs in this market are multifunctional but their primary function is binding. This property ensures that the ink or coating adheres to, and subsequently dries on, the surface of a material. Polyurethanes are key PLFs in this market that provide adhesion, flexibility, elasticity and heat resistance across all ink applications. Other key functions of PLFs include rheology modifiers, dispersants, stabilisers, surfactants and wetting agents, providing durability and printability.

One of the fastest growing application areas is digital print technologies, such as UV inkjet and screen applications, in turn driving reduced demand for traditional offset lithographic inks for commercial printing. Radiation curable polymers are traditional polymer types used in commercial printing and packaging inks, providing chemical resistance, durability and high gloss. Acrylate polymers, including urethane hexa acrylate, epoxy acrylate and modified polyester acrylates, are also key examples used in this application.

An example of solvent-based inks is those used in high volume flexographic printing for applications such as flexible packaging and gravure printing in the publication sector. Typical polymers in these applications include vinyl polymers, such as polyvinyl butyral resin and vinyl chloride-vinyl isobutyl ether, as well as other lower volume types including polyamides, ketone formaldehyde and nitrocellulose. These polymers provide the flexibility, elasticity and heat resistance that is required for these applications.

Nitrocellulose is a key bio-based raw material worth $720 million, which is used for printing inks and varnishes and enables pigment dispersion into solvents.[42] The publication sector uses this polymer for creating thermoplastic printed layers, fast solvent evaporation for high speed drying and compatibility with other resin components. However, this polymer uses high VOC systems and, as with the paints and coatings market, there will be a shift towards water-based systems in the coming years due to legislation. The market therefore expects the demand for nitrocellulose to reduce in favour of lower VOC systems.

Flexible packaging inks are another key application of PLFs in this market. These provide properties including high graphic capability (enabling marketing and branding), as well as resealability, moisture and aroma barrier properties (protecting and extending the shelf life of food).[43] Polyamide resins are key components of flexographic and gravure inks for non-polar packaging films like polyethylene. With a global demand of $1.5 billion, this polymer provides pigment dispersion properties, adhesion and flexibility.[44]

The benefits of PLFs in this market may not necessarily bring societal benefits to the same extent as paints and coatings, but they clearly play a vital role in some key applications such as food labelling and packaging.

Application	**Packaging:** flexographic, gravure with water, solvent- and UV-based systems	**Offset commercial printing:** lithographic and UV lithographic	**Publication printing:** gravure inks in water- and solvent-based systems	**Screen eg graphics and industrial:** flatbed, UV and solvent-based systems
Acrylic	X	X	X	X
Polyester				X
Polyurethanes	X	X	X	X
Epoxy resins				X
Other	X Reactive polyamide, ketone formaldehyde, nitrocellulose		X Gilsonite 300	X Butylated urea formaldehyde, gilsonite 125, tung oil alkyd, linseed oil, isophthalic alkyd, rosin modified phenolic resin
Radiation curable		X Urethane hexa acrylate, epoxy acrylate, modified polyester acrylate, tripropylene glycol diacrylate		
Vinyl polymers	X Polyvinyl butyral resin, vinyl chloride-vinyl isobutyl ether	X Polyvinyl acetates		X UCAR VMCH vinyl resin

Table 12: Summary of PLF applications in inks and coatings

5.3.8 Water treatment

The water treatment market represents the lowest value market. However, our investigation highlights the particular importance that these PLFs play to society and the environment. This market primarily uses PLFs as a flocculant to aggregate impurities and remove harmful substances from wastewater. A lower volume application for PLFs is in creating potable water for drinking.

Municipal water treatment facilities use anionic, non-ionic and cationic forms of natural (starch derivatives, polysaccharides and seaweed) and synthetic (polyethyleneimines, polyamines and polyethylene oxide) flocculants. However, synthetic polymers are the most common, since they offer multiple benefits such as water solubility, resistance to harsh environments and compatibility with chemical properties of wastewater.

This market is highly regulated, which means that formulators rely on polyacrylamide and its copolymer derivatives, which are both synthetic water-soluble polymers. In addition to flocculants, these materials also act as flotation agents, dispersants and thickening agents, which aid other treatment processes such as sludge formation. Our discussions with experts highlighted that several different grades, molecular weights and modifications are available to formulators, but the content in formulations is less than 1% by weight.

Environmental and drinking water protection agencies heavily regulate water treatment companies to ensure that water is safe to drink and wastewater does not cause harm to the environment. Since polyacrylamide is a commodity product in Europe that is used for many other applications, experts highlighted that this may cause a potential risk to supply in the future.

5.4 Environmental fate and end-of-life

Our analysis of the polymer landscape reveals that the eight PLF markets use either liquid formulations systems, which remain as liquids throughout their life cycle, or curable formulation systems, which form solids on application. These two formulation systems simplify the PLF landscape by bringing together similar functions, applications and types of materials. This section provides indicative fates of PLFs in liquid and curable formulation systems to highlight the possible journeys of these materials at the end of their life.

5.4.1 Indicative environmental fate of liquid formulation systems

Liquid formulation systems incorporate PLFs in higher value markets including agrochemicals, household cleaning, lubricants and water treatment. Although these markets use a wide range of PLFs, we make assumptions based on synthetic water-soluble polymers in concentrations ranging from 0.5 to 5%, since this is the most significant PLF used in this formulation system.

Figure 4 shows the indicative environmental fate of PLFs in liquid formulation systems, which suggests that these materials result in air, water and land emissions.

For example, PLFs in personal care and cosmetics, and cleaning and washing products are likely to enter municipal water treatment at the end of their life via household, commercial and surface water entering sewers. PLFs are also key components of chemical and biological treatment products that treat this wastewater.

PLFs entering municipal treatment facilities are likely to enter:

- **Air emissions** – a proportion of PLFs may be responsible for CO_2 emissions to the air through gas slip during biogas formation, which occurs through aerobic and biological treatment processes.
- **Water emissions** – since PLFs are likely to exist in dilute concentrations in wastewater that also contains other materials, some may pass through water treatment without removal and discharge into watercourses.
- **Land emissions** – some PLFs may settle out into treated sludge after biological treatment, which is generally applied to land, including agriculture.

Agricultural products do not enter municipal water treatment facilities; farmers apply these PLFs directly to the land. However, they are still likely to enter the following:

- **Air emissions** – some PLFs may break down over time in soil and react with nitrogen to emit gases like NO_x.
- **Water emissions** – some PLFs may percolate into ground water after application to land, flow through watercourses and eventually be emitted to water environments.
- **Land emissions** – some PLFs are likely to remain on the land, which is particularly likely for PLFs used as seed coatings and in encapsulation, remaining as solid particles after application.

Indicative environmental fate suggests that PLFs may contribute to air emissions arising from gas slip in biological processes used to treat wastewater sludge. Biogas produced from these wastewater sludge treatments can produce power, helping to offset the carbon emissions associated with local electricity consumption. However, household wastewater could be composed of up to 28% petroleum-derived carbon, which increases the previous estimates of total global greenhouse gases from water treatment facilities by 13 to 23%.[45] The amount of gas slip occurring from these processes is unknown. However, these air emissions may significantly affect the sustainability performance of water treatment processes.

PLFs could have high mobility and solubility in water and soil, which could lead to widespread environmental fate. However, a recent investigation on water-soluble polymers in cosmetics indicated that these PLFs are effectively removed from wastewater treatment plants. It concluded that homopolymers and copolymers of acrylic acids, polyethylene glycols and polyquarterniums displayed sorption to sewage sludge and are likely to remain at the site of entry to soil where slow biodegradation is expected.

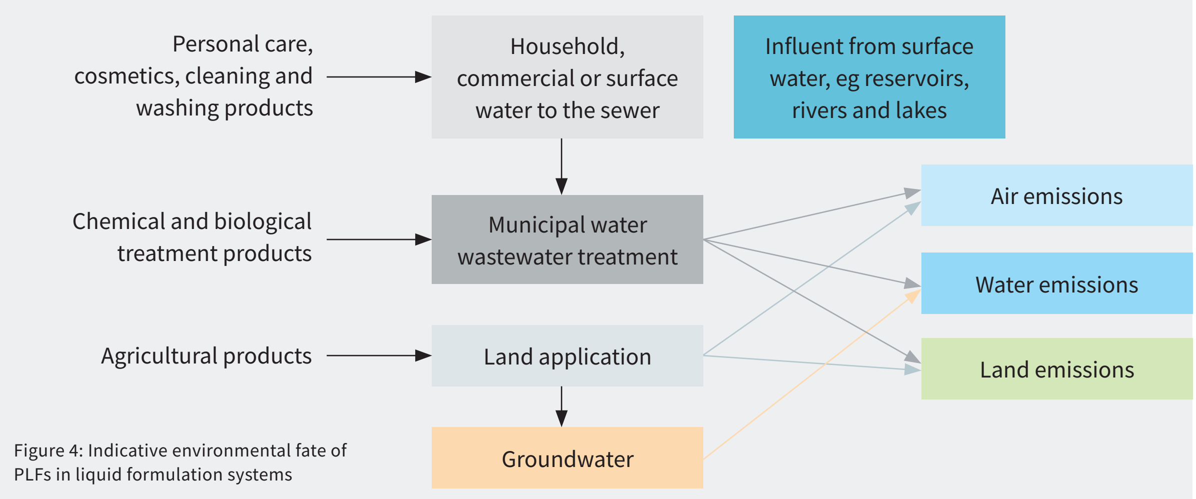


Figure 4: Indicative environmental fate of PLFs in liquid formulation systems

PLFs are likely to be durable by design, but will have varying half-lives, which suggests that a proportion may break down into intermediate materials. For example, research suggests that polyacrylamide has a long exposure time in agricultural applications, which increases the likelihood and degree of photolytic and biological degradation.[46]

It is possible that polymers degrading completely into biomass, water and carbon dioxide regenerate soils and improve productivity. Soil-enriching elements like nitrogen (N), phosphorus (P) and potassium (K) in agrochemical formulations may additionally benefit flora, but in excess these elements can cause eutrophication and algal blooms.

POLYACRYLAMIDE EXAMPLE

Taking a closer look at polyacrylamide (PAM) further illustrates the potential impacts of polymers in liquid formulation systems. PAM is a synthetic water-soluble polymer used in agrochemicals, personal care and cosmetics, washing and cleaning, as well as water treatment. It provides essential functions such as:

- rheology modification in **personal care products**, increasing formulation thickness and holding together ingredients in solid tablets, as well as for applying and keeping active ingredients on skin and hair
- **flocculation aid** in household cleaning products which helps water softening and inhibits dirt deposition on fibres
- **flocculation aid** in water treatment, producing potable water and dewatering sludge
- **soil conditioning** in agrochemicals, increasing soil stability, infiltration rate and erosion resistance for improved productivity

Water treatment uses high volumes of PAM in processes, but it also enters treatment facilities through the sewer system, from household and commercial wastewater. Experts highlighted a lack of clear evidence surrounding the environmental leakage of PAM since there are limited suitable detection mechanisms in freshwater situations. However, experts in water treatment also highlight that they do not screen PAM during processing. This could indicate that this material settles out into sludge or may be partially present in the final effluent. Indicative environmental fate in the previous section suggests that PAM could enter air, water and land emissions.

The quantity of sewage sludge produced in the UK in 2012 was approximately 1.136 million tonnes, of which 0.8 million tonnes was disposed to agricultural land.[47] Primary research with experts suggests that for every dry tonne of treated sludge disposed to agriculture, 10 kg or 1% is polyacrylamide. This suggests that in the same year 8,440 tonnes of polyacrylamide entered agricultural land in the UK. However, this figure is potentially higher because agrochemicals also use PAM, albeit in significantly lower volumes.

PAM has a half-life of at least 5.4 years,[48] which means that it may accumulate in soils. Experts generally regard PAM as a non-toxic substance: however, it can break down into immediate products such as acrylic acid and acrylamide monomer, which is toxic to most living beings.[49]

Regulation in the water treatment sector ensures that drinking water and effluent water entering the environment is not contaminated. However, there is limited clear evidence surrounding environmental leakage, potentially due to limited technologies that offer suitable detection mechanisms.[50] Although there are some detection technologies emerging, the environmental fate and impact of PAM would significantly benefit from more research.

Lubricants

PLFs in the lubricants market are different to other liquid formulations systems. In 1996, a large industry survey, CONCAWE, indicated that 65% of oil used in engine oils was potentially recoverable. However, as time progressed, further analysis in the UK suggested that half of lubricating oil in engines combusts, is lost through end-of-life components or is removed during servicing.[51] Figure 5 illustrates the indicative environmental fate of engine lubricating oils.[52]

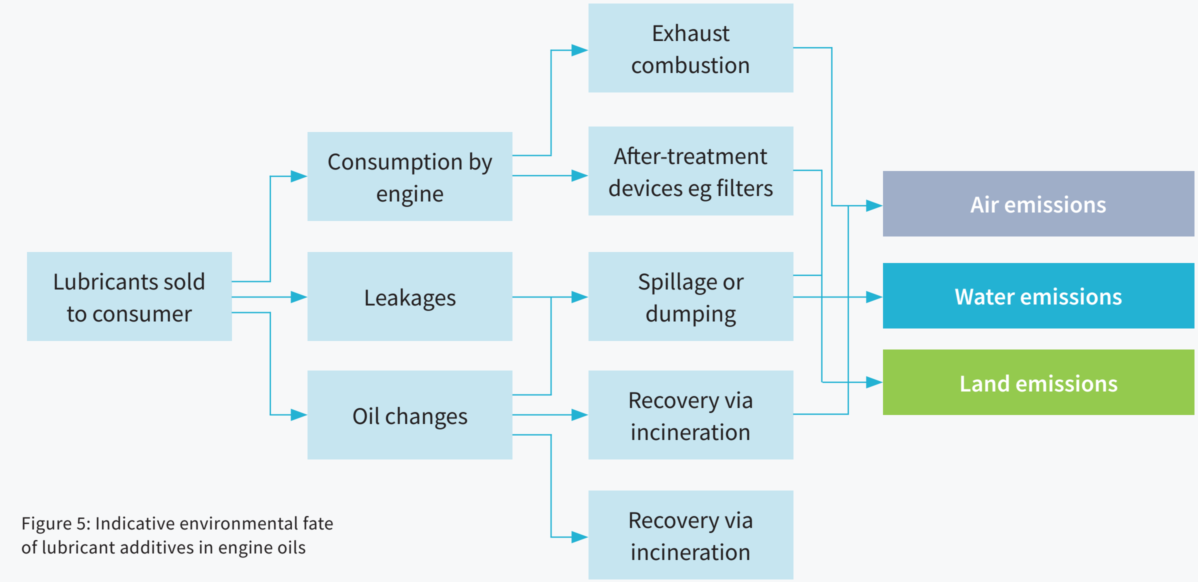


Figure 5: Indicative environmental fate of lubricant additives in engine oils

A proportion of PLFs in lubricant additives will result in air emissions through engine combustion. However, some vehicles may trap PLFs found in incombustible portions of the lubricant, which may enter landfill as part of after-treatment devices. Some leakages may occur through intentional and accidental spillages and dumping which could release PLFs into water or land.

We have only investigated oil use in engines, since little information is available about the environmental fate and possible impact of PLFs in lubricants. Since volumes and concentrations in this market are low, they are not likely to be present in the environment in high volumes, but this market would benefit from further investigation.

5.4.2 Indicative environmental fate of curable formulation systems

Unlike liquid formulation systems, PLFs in curable formulation systems form solids on application. This category primarily brings together low- to mid-value markets: paints and coatings, inks and coatings, as well as the adhesives and sealants market segments. This formulation system includes multifunctional PLFs from all nine polymer types at concentrations, ranging from 2% to 100%, that provide functions including binding, bonding and filling.

PLFs used in adhesives, coatings, inks, paints and sealants form solids after application, which means that it is likely the PLF component will remain on the substrate material at the end of its life. Figure 6 shows collection and flaking into urban areas and the environment as two possible end-of-life journeys:

- **Waste sector collects PLF on substrate materials for recycling, energy recovery via incineration or for landfill**

Air emissions from recycling and energy recovery via incineration: PLFs on substrates collected for recycling may contribute to air emissions in processes designed to remove them, eg melting and burning. This may generate residues, volatiles and potentially cause carbon emissions, eg coatings used in aluminium drinks cans and surface finishes on wood. Similarly, industry may incinerate substrates that cannot be recycled for energy recovery and any PLFs present may contribute to CO_2 emissions.

Air, water and land emissions from landfill: substrates may also enter landfill, particularly if they are complex multicomponent materials eg adhesives on multilayer materials like coatings. PLFs may degrade or slowly break down into intermediate products that may leach from landfill sites and enter treatment facilities through surface water. We already discuss how PLFs may enter air, water and land emissions through municipal treatment facilities in Figure 4.

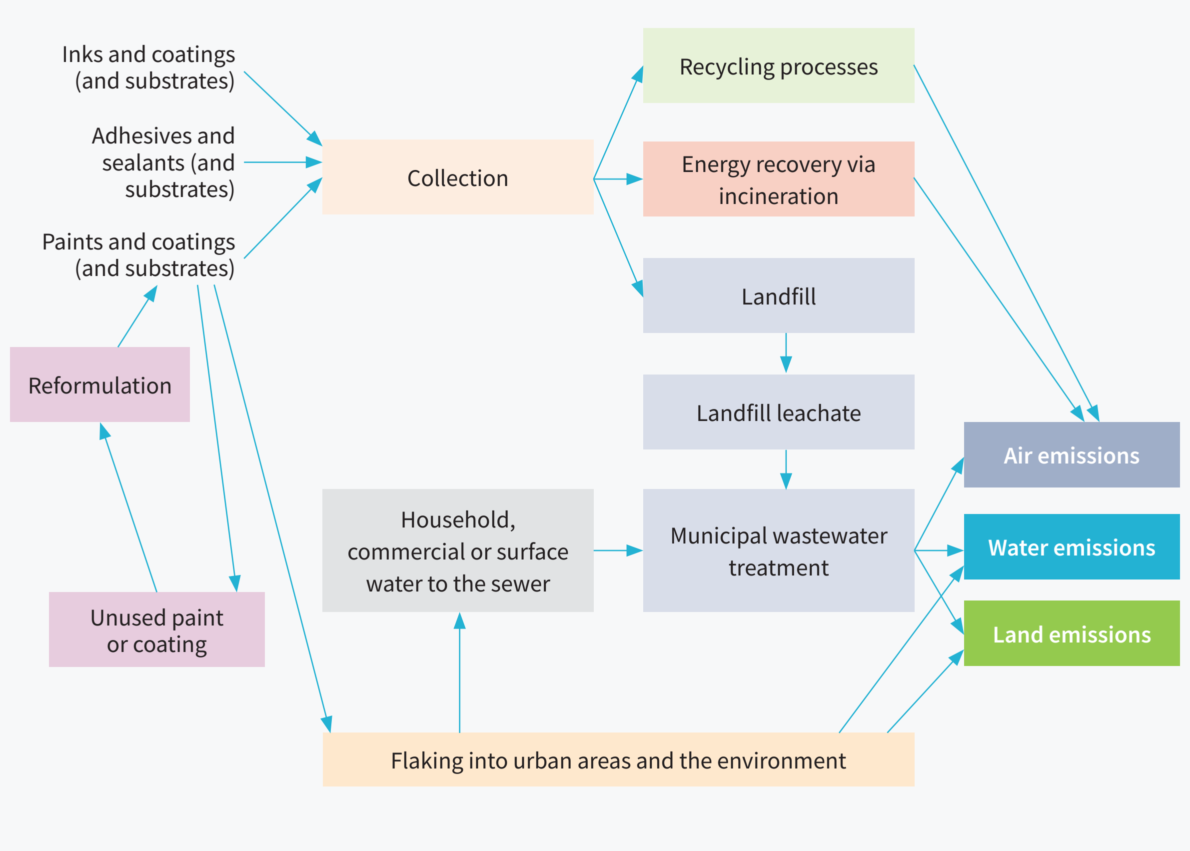


Figure 6: Indicative environmental fate of PLFs in curable formulation systems

- **PLFs flake off through wear or aging resulting in uncontrolled release into the environment or entering municipal water treatment facilities through sewer systems**

Paints and coatings protect and decorate buildings and provide road markings and signage in the built environment. On exposure to UV, water and temperature changes, PLFs may wear and degrade over time, leading to flaking. They may wash directly into land and water environments through surface water or enter sewage systems and water treatment processes, contributing to air, water and land emissions.

Formulations for protecting the hulls of boats and ships may flake off due to abrasion and wear, but in this case could directly enter marine environments.

Consumers may also remove PLFs post-application, eg stripping old paint in redecoration, which may also contribute to materials entering municipal water treatment facilities through landfill leachate or household wastewater.

Discussions with experts identified examples of schemes in place that reformulate excess paints and coatings from manufacturing or unused products into new paint products. However, these circular economy approaches are still emerging and they currently operate on a relatively small scale.

PLFs in curable formulations share some similarities to the environmental fate of liquid formulation systems. However, these PLFs may contribute to air emissions if recycling processes remove them from substrate materials, eg glass and metal recycling, typically use high temperature processes that are not likely to consider PLFs. There is a risk that fossil-derived PLFs removed in these processes could contribute to greenhouse gas emissions. As discussed, adhesives, coatings, inks, paints and sealants form solids on application, which could affect the recyclability of other materials. Multilayer and component materials like composites in aerospace, automotive and wind turbines are more likely to enter landfill or recovered for energy via incineration.

Adhesives and sealant residues could also prevent structural and architectural materials from being recycled at the end of their life, since they may be difficult to remove. For example, PLFs found in adhesives in wood could prevent reprocessing into chipboard.[53] Since PLFs in curable systems serve many products and markets, it is possible that they are responsible for preventing other materials from being recycled and cause knock-on effects on circular economy uptake in wider industries.

Microplastics

The other potential impact of PLFs used in curable formulations is in the formation of microplastics. Abrasion and flaking of paints and coatings due to wear may cause uncontrolled release of microplastics into the environment. Polyureas used in certain agrochemicals for encapsulation may also break down and release microplastics over time in the environment.

A recent review into microplastics in water treatment plants found that 72% of microplastics are removed during the preliminary stage. Primary sedimentation at these stages removes particles that are greater than 27 µm and 149 µm in diameter, which means that the majority of microplastics that are removed are likely to be present in sewage sludge.[54] There is evidence to suggest that microplastics released to the environment from agrochemical products, sewage sludge or surface water run-off may affect the ability of roundworms to regenerate agricultural soils and impact productivity.[55] This emphasises the need for more research and development into effective removal of microplastics in water treatment processes.

In 2019, the European Chemicals Agency (ECHA) proposed a wide-ranging restriction on the intentional use of microplastics to avoid their release into the environment. If agreed, the EU will adopt this restriction in 2022,[56] which may affect the use of PLFs in these markets.

Paint reuse and recycling

In the UK, from a total of 300 million litres of paint sold each year, approximately 55 million litres remain unused.[57] Nearly all (98%) of paint waste goes to landfill, which costs local governments £20.6 million.[58] There are some examples of circular processes in the UK that reuse and recycle waste paints and coatings. The PaintCare initiative is driving change by bringing together industry to create a circular economy for leftover paint.[59] One example is ReColour, launched by AkzoNobel in 2015. The initiative created a paint range based on waste paint that is collected in two not-for-profit paint recycling centres in Cambridgeshire and Merseyside.[60]

Another option is reprocessing waste paints to create products with recycled content. Examples include:

- Newlife Paints Ltd that reprocesses water-based paint back into premium grade emulsion containing 50% recycled content. The first year of operation reprocessed 100 tonnes of waste paint[61,62]
- Paint360 that creates product ranges with over 65% recycled content[63]
- Collaboration between AkzoNobel and Veolia to create Evolve emulsion, which contains 35% recycled paint[64]

Currently, these schemes operate on a small scale, accounting for less than 2% of total UK paint waste. This is because there is no coordinated national waste management strategy in place and little market demand for remanufactured or reusable paint.[58] Experts suggest that at least 40% of waste paint could be recycled into new paint, if reuse, recycle and repurpose schemes are coordinated across the UK and assuming there is sufficient demand.[65] Parliament debated this topic, but there are currently no new government-led initiatives in this area.[66]

POLYSILICONE EXAMPLE

Polysilicone is a key polymer type used in both liquid and curable formulation systems in adhesives and sealants, agrochemicals, household cleaning, and personal care and cosmetics markets.

Polysilicones are primarily synthetic materials comprising of inorganic backbones with alternating silicon and oxygen atoms produced from primary raw materials such as quartz or silica. The polysilicone market is expected to grow to $10.2 billion by 2024.[67] They are high performance materials with good thermal, thermo-oxidative and UV resistance properties.

They are impermeable to water and microorganisms, have high mechanical strengths and low density, making them essential to many sectors including:

- resins, sealants, elastomers and lubricants in the automotive industry
- anti-fouling coatings, adhesives and sealants for structural components for marine vessel manufacturing
- sealants in commercial construction
- conductive adhesives in solar panels and adhesives to bond blades in wind turbines
- wetting agents in agricultural products

Many industries, including personal care and cosmetics, have established the benefits of polysilicones. However, despite their widespread use, the features that make polysilicones very durable may result in their accumulation in the environment after use. Consumers and health activists are becoming more concerned about the safety of these materials and in some markets, like personal care and cosmetics, there is an increasing number of products labelled 'silicone-free'. Despite this, polysilicones remain an area of growing demand and are among the most extensively studied materials used in consumer and industrial applications, which has resulted in more than 1,000 studies to assess their safety.[68]

5.5 Summary of the current PLF landscape

The possibilities in polymer design are almost endless with a huge number of commercial polymer items readily available worldwide and many new polymer technologies in the pipeline to a market worth over **$125.2 billion**.

This section provided estimates for two figures quantifying the global production of PLFs:

- **29 million tonnes per year** (excluding volume of acrylic polymers) by estimating volumes by polymer type
- **36.3 million tonnes per year** by estimating volumes of polymers in each PLF market segment

Since the first polymer value excludes acrylic polymers and may incorporate other markets outside of the scope of this investigation, this report adopts the second polymer volume, 36.3 million tonnes, throughout.

Comparing these values with known figures for plastics highlights the scale of the PLF industry. Table 13 summarises the market value, volume and unit price for PLFs and plastics.

The figures shown in Table 13 reveal that the market value of plastics is more than three times higher than PLFs. The global volume for plastics is also higher than PLFs, with almost nine times the amount of plastic produced than PLFs globally. However, the average unit value of PLFs is three times as high as plastics.

Market	Global polymer market value ($ billion)	Global polymer volume (million tonnes)	Average estimated unit value ($/kg)
Commodity plastics	420 [69]	320 [69]	1.31
PLFs	125.2	36.3	3.56

Table 13: Comparison of values, volumes and unit value for plastics and PLFs

Over the past century, the plastics industry has grown drastically and produced a wide range of applications from packaging to construction to medical devices. Our investigation concluded that PLFs are a class of speciality chemicals in both liquid and curable formulation systems across eight key markets. In additional to delivering wide benefits for society, this investigation found that PLFs provide a wide variety of functions that many other industry sectors rely upon including:

- producing, packaging and transporting safe food and providing potable drinking water to the global population
- creating high value products for sectors like automotive, lubricants, electronics, personal care, cosmetics and household cleaning
- protecting and improving the longevity of infrastructure

Table 14 summarises the current PLF landscape by bringing together key information in this section, including the volumes and concentrations of PLFs used in producing PLF products, an estimation of their time in use and their likely environmental fate.

It also highlights markets that primarily use curable formulation systems consume higher volumes of PLFs and produce products that contain higher concentrations of polymer ingredients. PLFs in these applications provide durability over medium- to long-term timeframes to protect, join and seal substrate materials.

The previous section suggests that PLFs are likely to enter landfill or incineration at the end of their life. In some applications, they may also contribute to uncontrolled release of microplastics into the environment during use and may additionally affect the recyclability of substrate materials. Although some examples of circular systems were found for paints, these currently operate at small scales and are unlikely to have major impacts on their fate.

Agrochemicals, personal care and cosmetics, household cleaning and water treatment markets that primarily use PLFs in liquid formulations systems have comparatively lower PLF volumes and concentrations. Table 14 highlights that PLF products are in use for much shorter timeframes than curable formulation systems, which in some cases is for just minutes. The likely environmental fate of PLFs in these markets is land and water emissions, which contributes to waste generation in the environment. The lubricants market differs since PLFs are used over medium timeframes and their likely environmental fate is incineration for energy use.

This overview highlights that high value PLFs produced from predominantly fossil-derived feedstocks are lost after use and contribute to waste generation. Although some value may be recovered from PLFs at the end of their life through incineration for energy recovery, the waste hierarchy depicts this as high risk to the environment. There are significant differences between the production, use and end-of-life environmental fate of PLFs in curable and liquid formulation systems, which results in different opportunities to improve their sustainability.

Stage		**Production**		**Use**	**End of life**
Formulation system	**Market segment**	**Production volume per year (million tonnes)**	**Concentration (%)**	**Time in use**	**Environmental fate**
Curable	Paints and coatings	21.6	20 to 100	Medium to long	Landfill, incineration, environment
	Adhesives and sealants	7.8	20 to 100	Medium to long	Landfill and incineration
	Inks and coatings	1.7	2 to 100	Medium to long	Landfill and incineration
Liquid	Agrochemicals	2.1	<1	Short to medium	Environment (agricultural land)
	Water treatment	1.5	<1	Short	Environment (agricultural land via wastewater treatment)
	Personal care and cosmetics	0.8	1 to 10	Short	Environment (agricultural land via wastewater treatment)
	Household cleaning	0.4	1 to 10	Short	Environment (agricultural land via wastewater treatment)
	Lubricants	0.4	1 to 2	Medium	Incineration

Table 14: Summary of sustainability risk in each market

6 Sustainability challenges and solution areas

So far, this investigation has found that PLFs are an important class of materials that provide high functionality in a wide range of applications and deliver many positive societal benefits in markets worth $1.27 trillion. However, PLFs currently follow a take-make-dispose model and there are several sustainability risks currently associated with the production, use and disposal of PLFs that must be addressed.

In considering the wider global sustainability context, our analysis of the PLF landscape and our discussions with experts in industry, we identified eight key challenges that need to be overcome:

1. **PLF markets currently rely on synthetic PLFs for their products**. However, as demand increases for fossil-derived feedstocks, price increases, competition with other industries and increasing environmental strain creates supply risks for the PLF industry.

2. **Natural and bio-based PLFs may not always be ethically or sustainably sourced** and increased demand for these products may lead to unsustainable practices, which could include deforestation and competition for land used for food sources.

3. PLFs in liquid formulation systems entering water treatment plants at the end of their life will be diluted with a wide range of other compounds in household and industrial wastewater streams. **Biological treatment processes are unlikely to remove PLFs and therefore have a high probability of entering agricultural land as treated sludge**.

4. PLFs in liquid formulation systems, especially water-soluble polymers and any breakdown products, will be **highly mobile in soil and water, resulting in widespread environmental fates**.

5. PLFs in curable formulation systems may **produce unintentional microplastics during use** from paint flaking and partial degradation of seed coatings and active ingredient delivery mechanisms. Uncontrolled release of these materials into the environment may be contributing to wider problems with microplastics pollution in marine and land environments.

6. PLFs in curable formulation systems may be difficult to remove from substrate materials at the end of life, especially in multicomponent products. This may **prevent materials like composites, plastic packaging and traditional metal, wood and glass from being recycled**, contributing to the generation of waste in landfill.

7. Biodegradable replacements for existing PLFs must remain stable in the formulation with other ingredients and solvents/carriers. This is especially technically challenging in formulations with high aqueous contents since this catalyses degradation. **Formulators must balance the complete breakdown of PLFs into environmentally friendly products after life and formulation stability, without compromising performance**.

8. **There are significant differences in the way that consumers and industry use and dispose of PLF products across the eight markets around the world**. Factors like consumer behaviour and waste infrastructure will influence the volume of PLF products consumed and their fate.

This investigation also identified three significant solution areas that could address these challenges. These are innovation, adopting circular economy solutions and optimising waste management and recycling processes.

6.1 Innovative materials and formulations

The most significant solution area is innovation. Industry experts highlighted the importance of moving towards PLF production from renewable sources, designing in biodegradation at the end of their life and improving PLF efficiencies in use. Innovation in these areas will reduce the market's reliance on fossil-derived feedstocks and reduce waste generation, whilst maximising the value of PLFs in liquid and curable formulation systems.

This investigation identified four chemical science-based themes that will be important focus areas for academia and industry in developing innovative materials and formulations.

6.1.1 Platform technologies for formulation testing

Formulators face many technical challenges when replacing existing PLFs with sustainable alternatives such as developing drop-in sustainable polymer replacements that have the same or better performance. Novel PLFs are likely to behave differently to existing polymers in a formulation and may alter stability and shelf life. Since PLFs are highly specialised materials with a wide range of functionalities, it is not realistic for formulators to develop sustainable alternatives for every PLF in their product ranges. However, if formulators could understand and ultimately predict the behaviour of novel candidate PLFs and their effects on formulations, it would accelerate the development of innovative sustainable materials.

This is particularly challenging for developing novel biodegradable polymers in liquid formulation systems. One of the key mechanisms for biodegradation is hydrolytic bond cleavage to form water-soluble degradation products. In formulations that contain high water content, formulators must balance polymer biodegradability and formulation stability. These aspects are significant barriers for developing new biodegradable analogues.

OECD guidelines already provide the PLF industry with tests to identify and characterise potential hazardous breakdown products.[70] However, these tests have limited use beyond safety and regulatory purposes. Industry experts highlighted that they employ their own testing to support innovation. The Dow Chemical Company, for example, highlight their use of high-throughput technologies and predictive technologies to accelerate formulation development and optimise performance of PLFs and other ingredients in a range of applications.[71]

However, there is a significant opportunity for industry to develop platform technologies and high-throughput screening methods to rapidly test novel PLFs in different applications. This could help formulators develop the best novel sustainable PLF candidates and provide greater understanding about biodegradation mechanisms, formulation stability and performance for future innovation.

6.1.2 Liquid formulation systems: novel bio-based and biodegradable PLFs and natural alternatives

The indicative environmental fate of liquid formulation systems suggested that synthetic PLFs in liquid formulation systems are likely to enter land and water environments as waste at the end of their life. One solution could be to develop novel bio-based PLFs that biodegrade at the end of their life under environmental conditions. This would reduce the amount of fossil-derived feedstocks in production and ensure that any waste generated has a positive effect on the environment by regenerating living systems like soil.

There are several examples of novel sustainable PLFs in commercial products. This trend is increasing across markets that use liquid formulation systems, especially in consumer-facing products. ISO 16128-1:2016 standard qualifies 'naturally derived' ingredients as those containing at least 50% biomass by weight and provides guidance to businesses innovating in this area.[72] However, drop-in replacements for all existing PLFs are not likely to be a realistic solution. Another opportunity here could be the development of completely natural alternatives for PLFs.

Innovation in this area could help the supply chain transition towards more sustainable practices. A brief review of the research literature revealed some promising examples of novel solutions for further exploration:

Alternative to polyacrylamide flocculants

Early stage research found that chemically modified galactomannans, which are natural storage polysaccharides found in certain seeds, produce cationic derivatives of biopolymer flocculants for use in water treatment processes as a promising alternative to synthetic polyacrylamides.[73]

Other research identified cactus pads, okra seed pods, moringa seeds and mango kernels as promising natural alternatives to synthetic coagulants and flocculants in a variety of water treatment streams.[74] In a similar way, researchers highlighted the use of sesbania seed gum as a coagulant aid in water purification processes. When combined with ferric chloride, this offers an effective way of increasing river water turbidity.[75]

Several researchers identified polygalacturonic acid and galactomannan polysaccharides as the main actives in these materials. The galactose/mannose ratio produces galactomannans with unique properties and since they are biocompatible, biodegradable and non-toxic, they have numerous potential applications in cosmetics and paints, which are other key PLF markets. This may offer a promising area of innovation.

Bio-based PLFs for personal care and cosmetics

Recent research by Nottingham University investigated the synthesis of renewable polyacrylamide from naturally occurring terpene derivatives such as camphene, which can be harvested from pine trees or acquired from paper industry waste.[76]

Investigations into bio-based cinnamate functionalised cellulose found their use as a UV blocker in sunscreen. Combining cinnamate groups with high UV adsorption onto cellulose nanocrystals provided effective formulation stability. Research also highlighted its potential application for UV-shielding polymer films for windows.[77]

Bio-based PLFs for lubricants

Researchers synthesised lubricants from biomass derived 2-alkylfurans and enals as an alternative to bio-ester based lubricants that do not provide comparable lubricity or miscibility with other commercial additives. This material's molecular size and degree of branching is tunable for a wide range of applications.[78] Vegetable oils offer a green option for lubricants, but there are challenges with their oxidation stability. Researchers showed that bio-based multifunctional additives synthesised from biphenols and 4-aminodiphenylamine, improved wear, friction and oxidation resistance.[79]

Despite all of this work, several areas require significant further investigation. Some of the opportunities for chemical science research, development and innovation include:

- mechanisms by which PLFs biodegrade in the environment
- the environmental fate of PLFs and their potential breakdown products in different applications
- sustainable sources of waste product for feedstock at industrial scale and low cost
- bio-based PLF backbones that can be modified to match or exceed existing functionality and performance
- biodegradable PLF backbones that break down completely under environmental conditions

6.1.3 Curable formulation systems: novel bio-based PLFs and triggered degradation

In a similar way, developing bio-based alternatives for PLFs in curable formulation systems could be a sustainable way of producing these materials and reduce reliance on fossil-derived feedstocks. However, PLFs in these applications need to be durable to protect, join or seal substrate materials over long timeframes, so they will require a different approach to liquid formulation systems.

Developing biodegradable alternatives may affect their long-term performance and durability. However, since these PLFs are likely to remain on substrates at the end of their life, developing PLFs that degrade under controlled conditions or by triggering mechanisms could offer a way to:

- effectively remove them in recycling processes so that substrate materials like glass, plastic and multicomponent materials can also be recycled
- eliminate environmental pollution occurring from uncontrolled release of microplastics from paint flaking and degradation of some agrochemicals in the environment
- break down PLFs entering landfill into safe products and prevent potential leaching into the environment

A brief review of the research literature revealed some promising examples of novel solutions for further exploration:

Bio-based polyurethanes for agrochemicals and paints and coatings products

As previously discussed, agrochemicals products use PLFs to improve the uptake of fertilisers by crops and reduce the potential for run-off into the environment. Early stage research has highlighted the potential of bio-based polyurethanes, synthesised from caster oils reacted with a range of isocyanates, as alternatives to fossil-derived polymers for controlled release.[80]

Waterborne polyurethanes are also widely used for paints and coatings. Researchers have synthesised versions of these PLFs from bio-based precursors such as citric acid and glycerol, which have good mechanical properties and are biodegradable.[81] There are also examples of UV curable waterborne polyurethane systems for use as pigment carriers in textiles from acrylated and epoxidised soybean oil, which could also offer an interesting area for further exploration.[82]

Bio-based polysilicones

Researchers identified a promising method of making polysilicones from biogenic silica, derived from sources such as rice hull ash. Over 134 million tons of rice hull ash is produced per year, which contains 90% amorphous silica, making it a highly available raw material.[83] Despite this, significant work is required to generate commercial biogenic polysiloxane alternatives from this process.

As an alternative route to greener polysilicones, many research groups have explored biopolymer and siloxane hybrids as a way to reduce the amount of siloxane needed in functional materials. One area of bio-based siloxane composites that researchers are investigating is bio-waste materials, such as lignin-silicone-based elastomers and composites.[84]

In a similar way, opportunities for further investigation outlined in the previous section for liquid formulation systems, sustainable sources of waste product for feedstock and novel bio-based PLF backbones are important focus areas for curable formulation systems.

Opportunities for further investigation include:

- mechanisms and timeframes by which PLFs degrade in landfill and their likely degradation products
- environmental fate, impact and scale of uncontrolled release of microplastics from areas like paint flaking and agrochemical products
- triggered biodegradation mechanisms for key PLF backbones that have the potential to produce microplastics
- PLF backbones that degrade under controlled conditions such as temperature, pressure and UV for recycling

6.1.4 Liquid and curable formulation systems: improved PLF efficiency and performance

It may not always be possible to develop novel PLFs because of technical feasibility, cost or potential knock-on effects on formulations. However, there may be an opportunity to improve the efficiency and performance of PLFs in both liquid and curable formulation systems through innovation, which could improve sustainability by reducing either the amount of PLF required in a formulation, the product required in use, or the amount of other ingredients required in a formulation.

According to the waste hierarchy (see page 11), reducing the amount of material or product initially used provides some of the best waste management solutions for the environment. Therefore, designing products that maximise the resource efficiency of PLFs may offer a way of preventing excess waste generation. Innovation in this area could not only improve the sustainability of PLF products across all eight key markets, but also create sustainable business models and customer behaviours. Some of the potential opportunities could include:

- improving durability of PLFs in paints to reduce the need for reapplication and reduce customer over-purchasing
- increasing bonding properties of PLFs in adhesives to reduce the amount of product that is required and the frequency of repair
- modifying existing PLFs to create multifunctional materials that reduce the need for other ingredients in a formulation
- improving PLFs to deliver active ingredients more efficiently, reducing the amount of PLF required in the formulation or the amount of product required in use

A brief investigation into relevant research and innovation in these market segments highlighted some interesting examples of PLF efficiency and performance:

Controlled release in agrochemicals

Researchers identified a way of improving the release of pesticide-fertiliser combinations using mesoporous silica polydopamine composites derived from mussel proteins. This approach showed effective control of micronutrients and pesticides through chelating properties.[85]

Increasing durability of polyurethanes for paints and coatings

Harsh environmental conditions can significantly limit the lifespan of roof coatings to two to three years. However, researchers developed a waterborne siloxane modified polyurethane that enhanced durability and almost doubled lifespan that potentially offers a significant reduction in material recycling and waste.[86]

Performance of PLFs in household cleaning products

Industry researchers improved the efficiency of polymeric chelants in automated dishwasher formulations to address the long-term performance and sustainability concerns associated with some amino carboxylate ingredients. They showed improvements in the performance of polymeric chelants through copolymerisation of itaconic acid and sodium styrene sulfonate. These copolymers showed high binding of calcium but low binding for metals like iron, aluminium and gold, reducing metal erosion in decorated dinnerware.[87]

Procter & Gamble – using PLFs for more sustainable 30 degree washing cycles

Washing detergents have contained the PLF carboxymethyl cellulose (CMC) for many years, which is used in quantities of over 100,000 tonnes per year. To maximise the potential for the industry to deliver cost savings and sustainability benefits, P&G has developed an alternative version called blocky carboxymethyl cellulose (BCMC). Many P&G laundry powder detergents around the world now contain BCMC, formulated at levels of 0.1 to 1%, including those sold in Europe, Latin America, Middle East and Africa.

The BCMC make fabric and dirt particle surface more negatively charged, so it is better able to repel soil particles from textiles once adsorbed onto cotton fabrics and soil particles. The key innovation during development was the use of regioselectivity in the carboxymethylation process to impart ‘blockiness’ or clustering of the negatively charged groups to free up unsubstituted regions that are able to adsorb onto textiles.

This affects the performance of the detergent in two major ways. Firstly, the increase in fabric surface and dirt particles’ surface charge reduces the redeposition of dirt particles back onto the fabric surface, leading to whites and coloured items retaining their intended colour. Secondly, it modifies the fabric surface to reduce the transfer of dyes between garments during the washing process.

This has enabled washing cycles to be effective at lower temperatures, with the following additional benefits:

- produced by carboxymethyl modification of wood cellulose, it is ~75% bio-based and inherently biodegradable
- there is a fourfold improvement in the efficiency of BCMC compared to CMC, meaning it can be used in lower quantities and reduces environmental impact during transport
- improved efficiency also requires fewer natural resources for the same level of performance
- BCMC can also be used to enable replacement of other non-sustainable PLFs in detergent formulations
- the anti-redeposition and dye transfer inhibition benefits contribute to improved garment longevity by helping to keep clothes looking like new

6.2 Circular economy principles for PLFs

Several circular economy frameworks, including those by McKinsey and the Ellen MacArthur Foundation, offer an approach to improve the sustainability of materials and products. This investigation found only one example of a circular solution for waste paints. To the best of our knowledge, this concept has not been widely adopted for PLFs, which could be because:

- PLFs have potentially widespread environmental fate
- PLFs are likely to be found in low concentrations in products
- PLFs may be technically difficult to remove from substrate materials

In addition to innovation, this investigation identified three possible circular economy-based focus areas for industry to explore for PLFs. These could lead to new business models for PLFs that move away from current take-make-dispose models. They also represent an opportunity for businesses, UK governments and chemical science researchers to work together to develop sustainable solutions.

6.2.1 Digital track and trace across the supply chain

McKinsey's ReSOLVE framework outlined an opportunity for businesses to move towards a circular economy by optimising the supply chain.[88] It is widely recognised that adopting digital processes and automation can improve performance, which can cut costs, maximise resources and reduce waste.

Industry experts also highlighted that they are seeing a greater demand from consumers for product information. According to IBM, 71% of customers indicated that traceability is very important in purchasing products.[89] Subsequently, they outline advice for businesses to provide detailed information about products and ingredients and greater transparency about production methods and traceability of source materials.

This investigation identified a significant opportunity for businesses to improve the sustainability of PLFs by adopting digital track and trace across the PLF supply chain. Better information exchange between producers, manufacturers, formulators, retailers and waste management companies could:

- predict and overcome supply risks
- understand consumer buying behaviour and prevent over-purchasing
- understand scale and impact of waste across the supply chain and at end of life
- implement ways to reduce waste in manufacturing processes
- develop more sustainable end-of-life strategies such as take-back schemes
- identify and develop new markets for secondary raw materials
- improve customer confidence and empower them to make sustainable choices

Digital track and trace is a significant enabler of circular economy business models. This solution could offer businesses with a way to reduce costs and improve efficiency in the short term and develop circular economy business models in the longer term. This investigation identified two specific opportunities that may provide an opportunity for further investigation:

Digital tracking of decorative paints and coatings sales

Businesses that produce decorative paints and coatings have already optimised processes to improve manufacturing yields and reprocess waste streams into saleable products. Section 5.4.2 provided examples of specific products made partially from recycled waste paint. However, customers may over-purchase products that are subsequently stored or disposed of as waste.

Implementing digital tracking, monitoring and reporting of decorative paint and coating sales and returns could help industry identify opportunities to reduce waste. For example, developing services to take back unused products. Since many household recycling centres do not have facilities to collect waste paint, this could also provide more data and evidence for local councils to develop cost effective take-back schemes.

Digital tracking of PAM supply chain

The water treatment industry is heavily reliant on PAM in its processes. However, this investigation identified a potential risk in supply security as well as possible widespread environmental fate. Implementing digital processes to map and track PAM supply chains could increase understanding about the risks to supply and inform decision making for developing alternative solutions.

6.2.2 Converting waste PLFs into secondary raw materials for the chemical industry

This investigation identified two technologies that could offer a way to convert waste PLFs:

- hydrothermal separation and conversion technologies to convert PLFs in activated sludge and on substrate materials into high performance biomass to feed gasification processes
- heat, solvent and hydrothermal separation and conversion technologies to reclaim monomers from PLFs on substrate materials for reuse

One example is Ingelia, a technology-based company in Spain that developed industrial scale hydrothermal carbonisation technology (HTC) to valorise biomass. The process transforms carbon in organic waste streams into solid biomaterial, which can be used as a raw material for industry. The product has high calorific value, low humidity and high performance on combustion with minimal impact to global warming, so it is an effective substitute for fossil fuels.

This technology provides many advantages, including:

- the production of bio-coal that has versatile uses in electricity generation to direct combustion for heat or power
- modular HTC plants that can be adapted to current production processes
- the ability to process wet biomass, which limits requirements for pre-processing and produces clean water as a by-product for irrigation and industrial processes[90]

Technologies like Ingelia could offer a way to transform organic matter that contains waste PLFs, such as sewage sludge and municipal solid waste, into valuable secondary raw materials. At scale, these circular solutions could reduce PLF waste and generate new sustainable business opportunities.

The first HTC reactor was built in the UK in 2018, so Ingelia's technology is not yet widely available. Promising technologies like this may also involve complex processes that require high technical capability to operate or require significant investment to build. Therefore, they may present an interesting opportunity for waste management companies, technology providers and industry to further explore and develop into economically viable solutions.

6.2.3 Scale up take-back schemes for curable formulation systems

As described in Section 5.4.2, there are examples of take-back schemes for leftover and serviceable decorative paint. These schemes provide a way to recycle unused decorative paints that may be stored in sheds, lofts and garages. However, they currently operate on a small scale and in limited locations in the UK.

This investigation found that products like adhesives, coatings, inks, paints and sealants are likely to have high PLF concentrations compared with other PLF products, which may provide an economically viable opportunity to recycle PLFs. Scaling up these schemes at a national level, engaging the public in recycling initiatives and expanding them to other PLF products could offer a way to reduce waste generation and develop new business models based on a circular economy.

This investigation identified three different focus areas for further investigation:

Reusing leftover paint from domestic applications in community-based initiatives

There are already examples where paint manufacturers work with community groups, local authorities and housing associations to collect and redistribute leftover reusable paint. For example, in 2019 Dulux collected over 481,000 litres of paint through a network of 70 paint reuse schemes in the UK.[91] Crown Paints also partnered with social enterprise NIMTECH to provide recycling services across 130 centres in the UK.[92] Increasing the network of reuse schemes and improving public awareness of reuse opportunities could enable a circular economy for leftover paint that would otherwise enter landfill.

Recycling waste paint into premium grade paint

Not all waste paint is in reusable condition. However, innovative companies like Newlife Paints Ltd,[93] Paint360[63] and AkzoNobel[64] have launched new paint ranges with recycled content ranging from 35% to 65%. So far, collaborations with waste management companies like Veolia have enabled manufacturers to recover and refine waste paint feedstock in limited locations. However, scaling these up could increase the amount of waste paint feedstock available and attract manufacturers to explore innovative product ranges based on recycled paint.

Repurpose waste paint into products for other markets

Often, waste paint coalesces and dries out over time, which means that reuse and recycling options are not viable. However, there may be opportunities to repurpose it into products for other markets. Possible examples include:

- **Concrete**: In 2003, Segala combined waste paint with other additives to form Portland cement.[94] Researchers showed that concrete containing up to 20% waste paint, replacing water, provided additional flexibility and durability for construction applications. Since the UK construction industry uses nine million tonnes of cement each year, this market offers a significant opportunity to repurpose waste paint.
- **Polymer-modified concrete**: Using waste paint in polymer modified concrete for specialised applications such as roads and pavements, gave comparable properties to styrene-butadiene. In addition, waste paint reduced the costs of typical virgin polymer additive used. PaintCrete™, an industry collaboration in New Zealand, successfully uses waste paint in these applications, which offers a potential opportunity for the UK.
- **MDF**: Waste paint can act as a binder in MDF manufacture for construction applications. Although New Zealand based company Orica announced the development of a high performance product in 2009, it doesn't exist in the current product line. There may be an opportunity to continue exploring this area as a possible market.
- **Organic and inorganic components**: Another possibility is separating organic and inorganic components for repurposing in other applications. Researchers have suggested the use of pyrolysis in recovering TiO^2 from waste paint and its subsequent reuse in paint formulations. Other opportunities exist to further explore possible reuse markets for paint components.

As previously discussed, the PaintCare initiative is a significant driver of activities in the UK. However, there may be an opportunity to scale them up and expand them to other markets like adhesives and sealants. At scale, these could offer a circular solution for PLF products in curable formulation systems that remain unused pre-application. However, to achieve this will require significant effort and collaboration between UK governments, businesses and consumers.

6.3 Optimising existing waste management infrastructure

Innovation and implementing circular economy principles should offer the greatest opportunity to improve sustainability in the long term. However, these solutions may not be suitable for all PLFs and applications. Optimising existing waste management infrastructure may provide an alternative approach to reduce PLF waste generation. The following section provides two potential focus areas: wastewater treatment facilities and recycling processes.

6.3.1 Turning breakdown PLFs entering wastewater treatment facilities into safe products

This investigation found that PLFs in both liquid and curable formulation systems may enter wastewater treatment facilities at the end of their life. PLFs in organic matter found in domestic and industrial wastewater are likely to pass through primary treatment processes and undergo anaerobic and aerobic digestion. Solid waste that bacteria cannot process settles out into sludge and is subsequently applied to agricultural land. Although microorganisms in these processes break down organic matter into carbon dioxide, methane and water, there is limited understanding about how PLFs behave in these processes. This may mean that PLFs are not completely broken down before release into the environment.

There is an opportunity to implement methods to detect PLFs and monitor their behaviour in wastewater treatment processes. This could increase industry's understanding of the different types of PLFs entering facilities, their concentration and their potential environmental fate. Researchers have already developed a fast detection method for polyacrylamide flocculants in fresh water situations. By using interpolymer complexation between flocculants and a poly(acrylic acid-co-acenaphthylene) probe, this technique was robust against a range of contaminants and capable of detecting levels of flocculant dosing below $1\ \mathrm{mg\ l^{-1}}$.

Further development of detection methods like this could significantly improve understanding in this area. This data could support the optimisation of existing biological treatment processes to ensure complete breakdown of PLFs into safe products prior to land application. For example, optimised aerobic digestion with integrated anaerobic digestion could significantly improve the breakdown of organic matter and produce biogas for heat and electricity generation.

6.3.2 Removing PLFs from substrate materials to enable recycling and circular systems in other industries

Another opportunity to optimise waste management processes is removing PLFs in recycling processes from substrate materials. PLFs in curable formulation systems are durable to protect, join or seal substrate materials. However, these same properties makes them difficult to remove and may prevent substrate materials like wood, glass and plastics from being recycled.

There are some examples where recycling processes effectively remove PLFs, for example, coatings removal from aluminium cans. This investigation also identified a promising technology based on supercritical carbon dioxide removal that may provide an opportunity to remove PLF residues like paints and adhesives. Although this solution may not provide an opportunity to recycle PLFs, they could contribute positively to the circular economy of other industries.

Researchers developed a new approach to remove paint layers on the surface of retired products using supercritical carbon dioxide as a pre-treatment and then wet blasting cleaning to remove residues. Experiments on a small scale illustrated satisfactory paint removal using these two methods. There are likely to be other technologies in development, but they may also be at an early stage. Therefore, further development would be required to develop these technologies on a commercial and industrial scale.

6.4 Emerging technologies

So far, this section has highlighted three possible solutions for making PLFs more sustainable. There may also be examples of promising technologies in other application areas that could provide an insight into developing solutions for PLFs. This section highlights four examples of UK based SMEs with emerging technologies related to this area that could be exploited for PLFs or provide further knowledge and understanding to develop sustainable solutions.

ViridiCO2's heterogeneous catalytic platform for manufacturing sustainable PLFs

ViridiCO2 has developed a heterogeneous catalytic platform to manufacture high value chemicals using CO_2. Using uniquely designed active sites within the catalyst, its technology rapidly activates CO_2 under mild conditions, which subsequently reacts with substrates to produce products like polymers.

The company's carbon capture and utilisation (CCU) technology has the potential to reduce the chemical industry's dependence on traditional fossil fuel processes for producing chemicals, while offering:

- chemical manufacturers an opportunity to use CO_2 as a direct feedstock for products
- other industries a way to reduce their emissions by incorporating their waste CO_2 output into other materials

ViridiCO2's technology is modifiable so one of the main advantages is that it can produce a wide range of chemical products. In order to develop its technology further, ViridiCO2 will work with chemical manufacturers that have existing CO_2 infrastructure to validate its process in an industrial setting. Incentives for corporates that may be early adopters of technologies like these would significantly help SMEs like ViridiCO2 scale sustainable solutions.

Cambond's plant-based resins and composites for industrial adhesives and construction products

Cambond developed an innovative bio-based resin that provides an environmentally friendly industrial adhesive to replace formaldehyde-based resins in products like MDF, particleboard and plywood. Formaldehyde-based resin is an example of a synthetic PLF that is manufactured in a highly regulated process that produces CO_2 and toxic by-products. Cambond's technology offers a direct replacement for this PLF, which is more sustainable. It has also combined its resin with other biomass fibres or polymers to produce biocomposites, which can replace plastics in applications such as sustainable packaging, compostable materials and construction board manufacturing.

This technology is a low cost solution that can be used in existing manufacturing processes. The other advantage of this technology is that it offers a fully circular solution that turns biomass by-products from agriculture into valuable materials, which are readily available in large quantities.

Wasware, Cambond's subsidiary agrochemical business, is also investigating the opportunities to exploit this technology for seed coatings and other household and homeware products such as cups and bowls.

Further investment and UK/European business partners will help Cambond grow its business in scale, develop its manufacturing capabilities and enable the company to explore other promising markets. Additional support to develop UK manufacturing in specific industries would also help SMEs like Cambond that are developing circular economy-based technology.

Naturbeads' cellulose-based microparticles to replace microplastics

Naturbeads is developing a process to manufacture cellulose microparticles to replace plastic microbead exfoliants, binders, abrasives, anti-caking agents and enzyme carriers, which are used in a wide range of applications including cosmetics and paints. Naturbeads' technology could provide further insight into sustainable solutions for PLFs in paints and agrochemicals, which release microplastics into the environment throughout their lifetime. There are current bans on using microplastics specifically as exfoliants in cosmetics due to the potential risks that these materials may have. However, the EU has proposed further restrictions, which encompass a wider range of functions and applications including PLFs.

Naturbeads' technology provides a solution to this problem by producing cellulose beads from a natural biopolymer, which is 100% biodegradable. The main advantages of its technology are:

- the ability to produce particles between 1 and 50 micrometres in size
- the customisation and modification of the mechanical, surface and optical properties to mimic the performance of polymeric microbeads

- the potential to source cellulose from waste products and recycled paper as secondary raw materials

Naturbeads is currently scaling up its process to industrial scale and customising its beads for different applications. Industrial partners and further funding would significantly enable the company to scale its process and test its technology in different applications to bring Naturbeads' technology towards TRL 7 and 8.[106]

Puraffinity's technology to remove target molecules from wastewater

Puraffinity, has developed a molecular binding technology to capture and remove target molecules from wastewater. Using molecular receptors, its technology electrostatically binds to a target compound that would otherwise enter the environment at the end of its life. Target molecules can then be recovered for recycling or reuse.

Currently, Puraffinity is developing solutions for perfluroalkyl substances (PFAS), highly persistent and potentially hazardous molecules used in a range of applications including flame retardants, waterproofing agents and surfactants. However, Puraffinity's platform technology has wider benefits that could make it suitable for recovery of PLFs:

- tailored technology with the potential to capture a wide range of target molecules including inorganic and organic compounds
- a grab and unlock mechanism to recycle and reuse target molecules offers a circular economy solution
- highly efficient and precision tools to capture specific compounds rather than broadly capturing all chemicals

Puraffinity is currently focusing on developing solutions for large engineering installations in wastewater treatment plants to capture target molecules at scale – to date it has successfully scaled up its technology to five tonnes per year in the UK. They are currently running two industrial trials in Germany and the United States for PFAS, which are important technical milestones to validate its technology.

In the future, Puraffinity says it will be able to leverage its platform technology to tackle other targets such as dyes, pharmaceuticals, pesticides and potentially PLFs. It believes that investment in a "cleantech cluster" in the UK to help incubate biotech and cleantech companies could lead to job creation and more effective waste management practices.

6.5 Section summary

This section highlights innovation opportunities, circular economy approaches and possible ways to optimise processes to make PLFs more sustainable. These are:

- **bio-based, biodegradable and more efficient PLFs are likely to drive innovation across the eight key markets. Significant research and development in this area is required to overcome the technical challenges associated with developing novel materials and products**
- **developing platform technologies for biodegradability and formulation testing could also enable the development of novel PLFs**
- **digital technologies could provide businesses with an opportunity to predict possible supply risks and engage customers with recycling options**
- **developing early stage technology to transform waste PLFs into biofuels for the chemical industry could provide a future circular economy solution for waste in sludge and landfill**
- **collaboration between UK governments, businesses and the public may offer a completely circular solution for unused PLFs in curable formulation systems with high PLF contents**
- **detecting PLFs in household and industrial wastewater may provide more information about PLFs entering treatment facilities and aid decision making about optimising biological treatment processes**
- **developing technologies that effectively remove PLFs from substrate materials to improve recyclability in other industries**

These focus areas represent several possible sustainable futures for PLFs. Future solutions need to be sustainable and avoid 'regrettable substitutions' that can happen when new products are developed. Businesses are innovating for sustainability, but they face significant technical challenges in developing novel PLFs and products that make it too risky for any organisation to develop alone. Using consistent life cycle assessment approaches will be important to know if new chemicals really are more sustainable than what they are replacing and ultimately help businesses make the right decisions.

This investigation identified several examples of emerging technologies that could provide additional insight into developing sustainable solutions for PLFs. There are likely to be other SMEs that are developing technologies with potential applications across key PLF markets. The following opportunities would significantly enable SMEs to develop and grow their business:

- incentives that encourage businesses to become early adopters for emerging technologies to help SMEs validate their solutions
- funding pools that specifically help SMEs address the risks associated with developing emerging technologies between TRL4 and TRL8
- establishing links between local UK manufacturing industries to help SMEs develop circular economy-based technologies
- developing mechanisms that help SMEs access skills and expertise that help them develop their business such as business experts, investors and mentors
- developing targeted funding streams to help agile SMEs that are developing urgent technology solutions for sustainability issues such as CCU

Although continued research, development and innovation in academia and industry will be important, it is also necessary to consider other factors that will influence the adoption of sustainable solutions. These include scale and effectiveness compared to existing technology, environmental impact, customer acceptance, regulatory compliance and return on investment for businesses.

7 Opportunities

The solution areas highlighted in Section 6 offer a clear way forward for PLFs. However, improving their sustainability is a significant challenge that no single organisation, market or academic research group can solve alone. This report finds a significant opportunity to bring together science, economics, policy and consumer behaviour to make these materials more sustainable. Here, we summarise five key opportunities to galvanise industry, academia, policymakers and funders into action.

7.1 Establish innovation networks that promote collaboration between academia, industry and policy

The first opportunity that we identified is to establish a series of new PLF innovation networks to help the PLF community address the specific technical, market and supply chain challenges.

Such networks would additionally enable knowledge exchange between different markets, catalyse new collaborations and facilitate the exploitation of emerging technologies to progress sustainable solutions. These mechanisms would also facilitate dialogues between industry, government departments and funding bodies to address wider barriers to innovation.

This investigation identified several possible focus areas for collaborative discussions:

Innovation

- assessing the technical feasibility of biodegradable PLFs as a long-term solution
- approaches to test biodegradability of novel water-soluble PLFs for liquid formulation systems
- life cycle analysis for designing future PLFs for curable formulation systems

Circular economy principles

- digital processes to map the current PAM supply chain
- technologies for reclaiming PLFs for reuse as secondary raw materials for the chemical industry
- investigation into new markets for waste paint in the construction market

Optimising waste infrastructure

- measuring the scale and impact of microplastics generated from PLFs in paint flaking
- measuring the scale and impact of key PLFs on recycling substrate materials like wood, metal and plastics
- opportunities to exploit existing technology to capture target PLFs from wastewater treatment

7.2 Identify and champion key research themes and priorities that will support researchers and businesses to tackle PLF innovation challenges

The second opportunity highlights the need to identify key PLF research themes and priorities across all TRL. Engaging with funding bodies in this process would lead to further support for researchers, SMEs and large businesses working in this area.

This investigation identified several themes where further investment in fundamental and applied research, emerging technology development and large scale research and development challenges would accelerate innovation in this area. These could be a starting point for further exploration with businesses and academia:

Innovation

- development of a standard approach to test biodegradability and its effect on formulation stability of novel PLF candidates
- development of novel trigger systems for degradation of PLFs in curable formulation systems such as adhesives and sealants for easy removal in recycling processes
- development of self-initiated biodegradation for paints at end of life to prevent uncontrolled release of microplastics into the environment
- development of bio-based alternatives to PAM flocculants in wastewater treatment processes

Circular economy principles

- investigation into the chemical loading and behaviour of PLFs in wastewater treatment plants and methods to detect and monitor key PLFs such as PAM
- separation of PLFs from other paint components and investigation of recycling options into new products

7.3 Explore the emerging need for a consistent approach to PLF biodegradability and stability testing

The third opportunity is to further explore the need for a consistent approach to biodegradability and stability testing for PLFs across key markets. In this investigation, we identified this as a significant enabler of innovation, helping industry develop novel polymers and formulations.

Further exploration into the needs and technical requirements across multiple markets in collaboration with key stakeholders would progress the key components of this approach, which are:

- platform technologies for biodegradability and stability testing for key PLF markets
- open access testing facilities for companies of all sizes
- standards to help industry develop innovative bio-based and biodegradable materials

7.4 Investigate opportunities for chemistry-based innovations in developing circular economy solutions in key markets such as paints, adhesives and sealants in the UK

The fourth opportunity is to further investigate the opportunities for chemistry to support the development of circular economy solutions. This investigation identified the potential to scale up existing schemes that reuse, re-purpose and recycle paints at a national level to reduce PLF waste in this market. We also identified a potential opportunity to expand them to other markets such as adhesives and sealants. Further exploration into the following areas would help overcome current challenges:

- chemical science technology and innovation that can support the scale up of existing circular economy initiatives
- integration of digital track and trace across the supply chain to inform future chemical science-based technology and innovation needs
- new markets for secondary raw materials from waste paint

We also identified an opportunity for chemical scientists to support discussions between trade associations, industry and UK governments to develop consistent take-back schemes, collection facilities and infrastructure at a national level. In addition, there is also a role for experts to help the wider public understand recycling options through consistent product labelling and engagement.

7.5 Engage with key stakeholders to ensure that a science and evidence-based approach is used to develop future policy

The fifth opportunity is to engage with key stakeholders including government and industry to develop future policy for PLFs that is based on science and evidence. This investigation identified policy as a significant enabler of innovation and developing sustainable PLF solutions. The following examples represent key focus areas that will be important for UK governments to consider in developing future policy for PLFs:

- consistent life cycle assessment (LCA) approaches to know if new chemicals really are more sustainable than what they are replacing
- communications to the public on the benefits, hazards and risks of chemicals in our lives, so consumer demand drives sustainable product innovation through informed choice
- transparent risk–benefit frameworks to inform whether exposure to a given chemical is acceptable or unacceptable to citizens and wildlife
- open, transparent, evidence-based risk assessment to authorise and restrict the use of chemicals of concern in products and processes
- incentives to support collaboration between academia, SMEs, corporates and citizens to develop sustainable solutions

This investigation identified several existing initiatives looking into this area, which could act as a starting point for further discussion, for example:

- ECETOC is developing a conceptual framework for assessing the safety of polymers to harmonise risk assessment across industry[107]
- the European Commission is leading discussions on available data and potential criteria for polymers in preparation for its registration under REACH[108]

8 Next steps and concluding remarks

It is clear that PLFs are a vital class of speciality chemicals, essential to our society in improving food productivity, treating wastewater, protecting buildings, infrastructure and transport, as well as creating consumer products that promote health and wellbeing. However, despite their importance to society and the global economy, and in contrast to the intense recent focus on the sustainability of plastics, there has been very little coordinated attention focused on the sustainability of PLFs.

We believe this must change. Manufacturers, formulators, end users and waste management companies will face significant PLF sustainability challenges in the future. The aim must be to reduce dependence on fossil-derived feedstocks, maximise resource efficiency and reduce waste generation in the long term. These solutions must be economically viable, available at industrial scale and accepted by the consumer. In addition, solutions must match or improve the performance of existing PLFs across a wide range of applications, perform in a formulation alongside other ingredients and be sustainable throughout its life cycle. There is a significant role for those working in the chemical sciences to make a radical contribution to the development of sustainable solutions.

These factors present a significant technical and business challenge, which is too risky for any one single organisation to solve. Without a coordinated and concerted effort from businesses, researchers, UK governments and the wider public, innovation will be slow, significant knowledge gaps will continue to exist and emerging technologies will not be exploited.

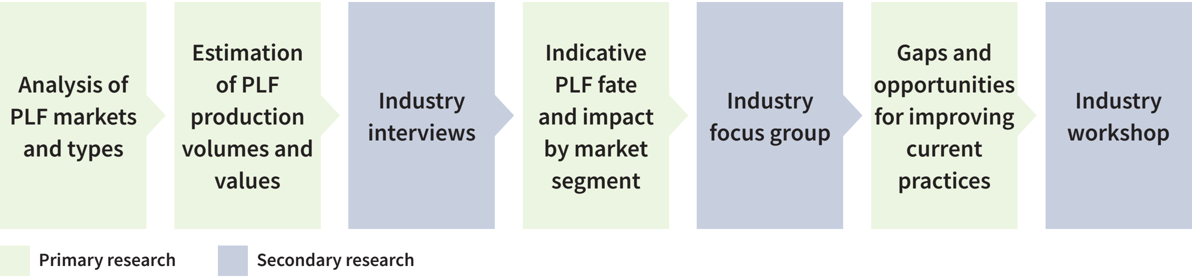
That's why we are establishing a PLF task force to tackle this challenge. The Royal Society of Chemistry will convene industry to prioritise and progress the five opportunities outlined in the previous section through the Synergy programme. We will seek opportunities to engage and collaborate with key stakeholders in academia, industry, UK governments and funding bodies to catalyse action in the UK. Through this work we will raise awareness of this important topic, establish a focal point for the PLF community and harness support for the researchers and businesses working on solutions.

This is not an issue for the UK alone. Stakeholders in other countries should consider the findings and recommendations in this report and explore opportunities to stimulate action, collaboration and innovation to develop a sustainable future for PLFs.

9 Appendix

9.1 Methodology and scope

This investigation used a combination of primary and secondary research to gather and analyse data from trusted sources and validate findings with industry experts. This section describes the approach and the scope. We combined desk research with industry engagement in the following process:



Data sources for primary research included published peer reviewed scientific journals, industry white papers, annual reports, published reports by credible agencies, financial reports and published patents. CPI procured published market reports to obtain key data for polymer value and volume estimations. Secondary research included company interviews, focus group meetings and online workshops with key technical members of leading market companies.

This investigation considered eight key PLF market segments that we describe in section 5. In order to distinguish PLFs from other materials and other ongoing investigations, this research excluded the following areas:

- microplastics at the point of pre-application, eg solid particles of polymer greater than 5 mm and solid particles of polymer from 5 mm down to nanoparticles which are intentionally incorporated into the liquid formulation. Unintentional microplastics generated from liquid formulations post-application (eg weathering of cured paint films and degradation of agrochemicals) are considered in this investigation
- small chain monomeric species and oligomeric materials
- polymers approved for human or animal consumption, eg Food Standards Agency and the Food & Drug Administration (FDA)
- waste streams that are outside of the core manufacturing process of a liquid formulated product, eg process washings that may result in polymer disposal via drains

9.2 Assumptions for estimating polymer volumes

The assumptions made in estimating the global values and volume of polymer types are summarised in the table below.

Polymer type	Assumption
Acrylics	No figures available for volume
Water-soluble	No assumptions made, global value and volume reported in reference
Polyurethanes	Total global market including foams and elastomers is $68 billion with a total volume of 28 million tonnes 8 million tonnes of polyurethane consumption is estimated in PLF sectors mainly from coatings and adhesives segments[32]
Radiation curable	No specific volume data was available for this set of PLFs so an estimated market selling price of $2.38/kg has been assumed
Polyesters	No specific volume data was available for this set of PLFs so an estimated average market selling price for polyester resin of $4.92/kg has been assumed
Vinyl polymers	No specific volume data was available for this set of PLFs so an estimated market selling price for vinyl polymers of $4.30/kg has been assumed
Polysilicones	No specific volume data was available for this set of PLFs so an estimated market selling price of $12/kg has been assumed
Epoxy resins	No assumptions made, global value and volume reported in reference
Other	Market values assumed for phenolics, polyamides and polyolefins No specific volume data was available for this set of PLFs so an estimated market selling price of $2.38/kg has been assumed

Table 15: Summary of assumptions made for estimating global volumes of each polymer type

PLF market segment	**Assumptions made in estimating volume**
Personal care and cosmetics	Estimated global polymer ingredients for personal care products in 2017 is \$3.49 billion[109] There is a higher than average unit value for polymers supplied in this sector; the estimate is \$8.50/kg. Based on this unit value, ingredient spend and an estimate of the polymer volume supplied for personal care products is 0.41 million metric tonnes per annum The global market value is an approximate 50:50 split between personal care and cosmetics, so we assume that the polymer volume supplied for cosmetics products is also 0.41 million metric tonnes per annum
Household cleaning	The volume of 0.41 million metric tonnes per annum is a conservative estimate following primary research with experts of personal care/household cleaning products where the polymer volume quantified for washing and cleaning is said to at least match the volume of polymers consumed in personal care
Paints and coatings	Market reports predict 54 million metric tonnes globally for wet paints and coatings against this market value.[31] Due to the drive towards high solids low VOC coatings, CPI estimates the current average polymer content to be 40%; the assumption is, therefore, a polymer volume of 21.6 million tonnes per annum
Inks and coatings	Global printing ink consumption in 2013 was 3.3 million to 3.6 million metric tonnes in 2023.[7] 3.4 million metric tonnes was assumed for 2019 CPI estimates the average % solids by polymer weight in inks to be 50%
Adhesives and sealants	Estimated market volume for adhesives and sealants is 19,577 K tonnes in 2019 and is projected to reach 23,201 K tonnes by 2023[26] CPI's estimate of % solids by weight polymer is 40% with the remainder being solvent and other materials to generate an estimated polymer volume of 8 million tonnes per annum
Lubricants	Polymers act as viscosity modifiers in lubricant formulations and are generally incorporated at 1% levels or less by weight of the PLF Global demand for lubricants in 2018 was 35 million metric tonnes[30]
Agrochemicals	Based upon primary research with experts in this segment and market reports, 10 million tonnes per annum of agrochemicals globally[5] In terms of formulations the polymer content is generally <1% by weight
Water treatment	Published global volume of polyacrylamides (anionic, cationic and neutral) in this segment is 1.5 million tonnes per annum[36] Validation of high volume/polymer consumption for UK carried out through primary research with the UK municipal water industry

Table 16: Summary of assumptions made for estimating global volumes of polymer ingredients in each PLF market segment

9.3 Organisations consulted in this investigation

The Royal Society of Chemistry would like to thank the following organisations for their input into this report.

- Afton
- Anglian Water
- Ashland
- Croda
- Lucite International
- P&G
- PRA world
- Safic-Alcan
- Scott Bader
- Syngenta
- Unilever

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