Carbon for Chemicals

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CARBON FOR CHEMICALS

How can biomass contribute to the defossilisation of the chemicals sector?

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The Supergen Bioenergy Hub works with academia, industry, government, and societal stakeholders to develop sustainable bioenergy systems that support the UK's transition to an affordable, resilient, low-carbon energy future. The Hub is funded jointly by the Engineering and Physical Sciences Research Council (EPSRC) and the Biotechnology and Biological Sciences Research Council (BBSRC) under grant EP/Y016300/1 and is part of the wider Supergen Programme.

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Supporting documents and briefings can be found on the **Supergen Bioenergy Hub website: www.supergen-bioenergy.net/output/carbon-for-chemicals**. All enquiries related to this publication should be sent to: **supergen-policy@aston.ac.uk**.

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SUMMARY

Many products in modern society contain carbon: pharmaceuticals, plastics, textiles, food additives, and all manner of ingredients for cosmetics and cleaning products are made of organic, carbon-based chemicals. Unfortunately, most of these carbon-based chemicals are made from fossil feedstocks, meaning that, like fossil fuels for energy, they contribute to global greenhouse gas (GHG) emissions and climate change. The impacts of climate change are already being felt around the world and urgent action is required across all sectors and nations to reduce GHG emissions. The climate impacts of the use of fossil fuels for energy are clear, and thanks to significant efforts and international cooperation, demand for fossil fuels in energy is expected to fall in the coming decades as the world transitions to renewable energy sources. In contrast, the petrochemicals sector is expected to grow significantly in the coming decades, and the issue of how we address the emissions associated with the carbon in our chemicals has received relatively little attention.

Addressing emissions from across the whole life cycle of organic chemicals and materials will require systemic change and a suite of different approaches and technologies. Measures relating to manufacturing processes, energy consumption, renewable energy, and deployment of carbon capture and storage (CCS) have been the focus of attention so far. Although such changes will be necessary and likely have a significant impact on emissions, they will not address the emissions from the embedded carbon in products. The transition to a net-zero-compatible chemical system also requires other changes, including implementation of circular economy principles, steps to address levels of production, and a transition away from fossil feedstocks. Carbon-based chemicals cannot be decarbonised, but they can be defossilised through a transition to renewable carbon sources such as biomass, recycled material (e.g., plastic), or carbon dioxide.

The petrochemicals sector is large, complex, and well established, and the widespread change required to move away from chemicals derived from fossil feedstocks will likely only be possible with government intervention. Like many other countries, the UK does not yet have policies in place that encourage biomass as a chemical feedstock and there is very little clarity around the future of bio-based chemicals. This report presents evidence on bio-based chemicals and materials, to improve understanding, support policy development, and identify evidence gaps and areas where further research is required.

Making chemicals from biomass

Biomass can be used to make a vast array of organic chemicals and materials including plastics and polymers, and fine and speciality chemicals. These bio-based chemicals and materials can replace fossil-based chemicals in a range of applications, such as home and personal care products, packaging, and construction. The molecules comprising biomass feedstocks are carbon-based, but they have different structures and chemical compositions than those in fossil feedstocks. Biomass can be used to make drop-in bio-based chemicals, which are chemically identical to existing fossil-based chemicals, but the unique chemical composition of biomass also lends itself to the production of novel bio-based chemicals.

Using biomass to make drop-in bio-based products can have advantages, in that it results in no change to the end user product and in some cases reduces the need for new technologies and infrastructure. However, the chemical industry has evolved and optimised around the use of fossil feedstocks, meaning drop-in bio-based chemicals often struggle to compete. A more disruptive approach that supports novel bio-based products demands the scale-up and deployment of new technologies and the development of new markets, but it could result in a chemical system that is better suited to using biomass feedstocks. Novel products would also expand the variety of valuable organic chemicals and materials beyond those we are familiar with today, with some offering useful new functions or opportunities for safer and less toxic alternatives to problematic fossil-based chemicals.

There are many examples of bio-based products being made commercially and a vast array of products have been demonstrated at lab scale. However, to date, bio-based chemicals and materials account for just a small proportion of the organic chemicals and materials we use. There are challenges that must be overcome to increase the use of biomass in the chemical industry. Many of these challenges stem from the fact that bio-based chemicals must compete with products of the established incumbent petrochemical sector. Other challenges include uncertain sustainability impacts, high costs and capital requirements, the difficulties associated with scaling up new products and processes, and the lack of a supportive policy landscape.

Examining the sustainability of bio-based chemicals and materials

Bio-based chemicals can reduce GHG emissions compared to the fossil-based chemicals they would displace, sometimes significantly. However, GHG reductions are not universal and so a product cannot be assumed to be lower emission just because it is bio-based. The variation in the climate impacts of bio-based chemicals is the cause of some hesitancy when it comes to deploying bio-based products. However, it would be more beneficial to focus on how technology developers and policymakers can develop or incentivise those products that do deliver the desired GHG savings, whilst avoiding those that do not.

Bio-based chemicals and materials can be a source of negative emissions (i.e., carbon storage) through integration with carbon capture and storage, and potentially through the storage of carbon in long lifetime products. Careful assessment of GHG emissions across the life cycle is required to determine if these truly deliver permanent or long-term removal of carbon from the atmosphere.

It is important to also consider the broader environmental, economic, and social consequences of bio-based chemicals and the feedstocks they are derived from. There can be benefits, but there are also risks, and care must be taken to ensure climate benefits do not come at the cost of significant negative impacts to people or the environment. Policy and regulation will have an important role to play in maximising benefits, mitigating risks, and navigating trade-offs. Evidence suggests biomass can support the transition to a more sustainable global chemical system, and even help to make it a net carbon store, but the optimal approach from a climate and wider environmental perspective will be a system that combines demand management, increased circularity, and a variety of renewable carbon feedstocks, including biomass.

Priority uses of biomass

Sustainable biomass is a limited resource with a plethora of competing applications alongside the chemicals sector. Given that there will not be sufficient biomass to fulfil all these applications in the future, it will be necessary to make decisions about which are the highest priority. From a climate mitigation perspective, the chemical industry should be a priority sector for biomass use because bio-based chemicals can deliver significant GHG emission reductions and potentially negative emissions, and there are limited alternatives for addressing the emissions stemming from carbon in chemicals.

Prioritising certain kinds of bio-based chemicals and materials may also maximise the delivery of different benefits. Some products might deliver the greatest GHG emission reductions, others the greatest benefit to people's health, or to growth and the economy. The best use of biomass therefore depends on what the main objective is.

Bio-based chemicals in the UK

Bio-based chemicals make up only a very small portion of the chemicals and materials used in the UK and examples of bio-based chemicals production are limited. However, the UK is home to significant research expertise in many disciplines and enabling technologies that will underpin the development of bio-based chemicals, and there is a wealth of research happening in this space in both academic and industrial environments. Bio-based chemicals could potentially benefit the UK economy, environment, and people, and support policy objectives such as reduced GHG emissions, negative emissions, safe and sustainable products, jobs, economic opportunities, resource security, and global leadership.

Unlocking the potential benefits of bio-based chemicals for the UK will demand action across society, from policymakers, industry, and academics, as well as cross-sectoral collaboration. Progress should be underpinned by continued research and innovation to address evidence gaps, support decision-making, and develop new technologies and products that meet the needs of society, whilst also being scalable, and economically, socially, and environmentally sustainable. We believe the following actions will be key if policymakers are to address the emissions from carbon in chemicals and accelerate the development of bio-based chemicals in the UK:

- **Now** – Articulate the opportunity and secure cross-government consensus
- **Next** – Develop a roadmap for the transition, and improve sustainability governance and regulation
- **Future** – Implement policy to accelerate sustainable chemicals

INTRODUCTION

Many useful products in modern society contain carbon: pharmaceuticals, plastics, textiles, food additives, and all manner of ingredients for cosmetics and cleaning products are all made from organic, carbon-based chemicals. Unfortunately, most of these carbon-based chemicals are made from fossil feedstocks (i.e., they are petrochemicals), meaning that, like fossil fuels for energy, they contribute to global GHG emissions and climate change [1–6]. The climate impacts of the use of fossil fuels for energy are clear, and thanks to significant efforts and international cooperation, demand for fossil fuels in energy is expected to fall in the coming decades as the world transitions to renewable energy sources [7]. In contrast, the petrochemicals sector is expected to grow significantly in the coming decades, and the issue of how we address the emissions associated with the carbon in our chemicals has received relatively little attention [1, 8–12]. The impacts of climate change are already being felt around the world and urgent action is required across all sectors and nations to reduce GHG emissions and limit global temperature increases [7].

Carbon-based chemicals cannot be decarbonised, but they can be defossilised through a transition to renewable carbon sources such as biomass, recycled material (e.g., plastic), or carbon dioxide (CO2) [1–3, 7]. The petrochemicals sector is large, complex, and well established, and the widespread change required to move away from fossil-based chemicals will likely only be possible with government intervention.

This report focuses on carbon-based chemicals (including materials derived from organic chemicals, such as plastics) made from biomass feedstocks. Not only is biomass a renewable source of carbon for chemicals, but the transition to a bioeconomy could also offer a myriad of environmental and societal benefits, such as safer products, biodegradable materials, resource security, green jobs, and income for rural economies. However, like many other countries, the UK does not yet have a policy that encourages biomass as a chemical feedstock and very little clarity exists around the future of bio-based chemicals. The 2023 UK Biomass Strategy did little to resolve this and highlighted several ongoing questions about the potential role of biomass in the chemicals sector [13]. The reality is that this is a complex topic and evidence around the risks and benefits of bio-based chemicals is often varied, which is a significant challenge for those trying to make decisions and develop policy.

This report presents evidence and scientific thinking on bio-based chemicals and materials, to improve understanding, support policy development, and identify evidence gaps and areas where further research is required. It explores questions such as:

- What does the current chemical system look like, and what are its climate and environmental impacts?
- How is biomass converted into bio-based chemicals?
- What does the bio-based chemicals sector look like now, and how might it develop?
- Are bio-based chemicals more sustainable than fossil-based chemicals?
- Is there sufficient, sustainable feedstock to supply the chemicals sector?
- What is the best use of biomass within the chemicals sector?
- What opportunities could bio-based chemicals provide for the UK, and what action might be needed to unlock them?

This report was developed using evidence and information gathered from published material (e.g., peer-reviewed academic literature, reports, and other online information), as well as through workshops, and consultation with academic and industrial experts from across our stakeholder community. It was reviewed and approved by members of the Supergen Bioenergy Hub and Biomass Biorefinery Network management boards with relevant expertise and experience.

PART 1: PETROCHEMICALS AND THEIR IMPACTS

1.1 The petrochemical industry

The chemical industry is the world's second-largest manufacturing industry, making hundreds of millions of tonnes of chemical products each year, including thousands of chemicals ranging greatly in volume and application [8, 11, 14]. The outputs of the chemical industry include both organic (carbon-based) and inorganic (non-carbon-based) chemicals, the former of which is the focus of this report. Organic chemicals are used in a vast array of downstream products, such as agrichemicals, pharmaceuticals, home and personal care products, textiles, and construction materials (Table 1) [9, 10, 14]. So, carbon-based, industrially produced chemicals are ubiquitous in modern society.

Currently, organic chemicals are almost entirely derived from fossil feedstocks (e.g., coal, oil, and natural gas), and so they are often referred to as petrochemicals[1] [1, 8, 15]. The value chain for organic chemicals and materials is depicted in Figure 1. After they are extracted from underground reserves, fossil feedstocks are processed in refineries. Most of the products of these refineries are used for energy applications. However, they also yield feedstocks for the chemical industry, such as naphtha (a liquid mixture of hydrocarbons produced from crude oil) and ethane (a simple hydrocarbon produced via natural gas or petroleum refining). The chemical industry converts these feedstocks into primary chemicals via processes such as steam cracking and catalytic reforming. These primary chemicals are then transformed into a vast array of organic chemicals and materials via numerous processes and intermediates [8, 11, 16]. More than 90% of organic chemicals are derived from ammonia[1], methanol, ethylene, propylene, and BTX aromatics (i.e., a mixture of benzene, toluene, and xylene) [9, 11, 14]. Organic chemicals and materials produced by the industry range from polymers and plastics, which account for almost a third of the chemical industry's outputs, to fine and speciality chemicals such as dyes, surfactants, and therapeutics (Figure 1 and Table 2) [10, 15].

The petrochemical sector is large and very complex [8, 11, 17]. Fossil feedstock refining and primary chemical production tend to happen in a small number of very large, centralised facilities, but further down the value chain the sector becomes more diverse, with a huge variety of products, manufacturing plants, and companies. Many of the supply chains are interconnected, and they often involve numerous international border crossings due to the global nature of the chemical system.

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[1] Not all petrochemicals are carbon based. Though most of this report focuses on organic, carbon-based chemicals, it is hard to disentangle these from the wider petrochemical industry and so some discussions of the sector may refer to the petrochemical industry in general. For example, ammonia is an inorganic nitrogen-based molecule that is made using hydrogen derived from fossil feedstocks [8,10]. Ammonia is a petrochemical and is used in the production of many organic chemicals, so it will be included in general discussions about the petrochemical industry here, but it is not discussed in detail in this report because ammonia itself is not a carbon-based molecule.

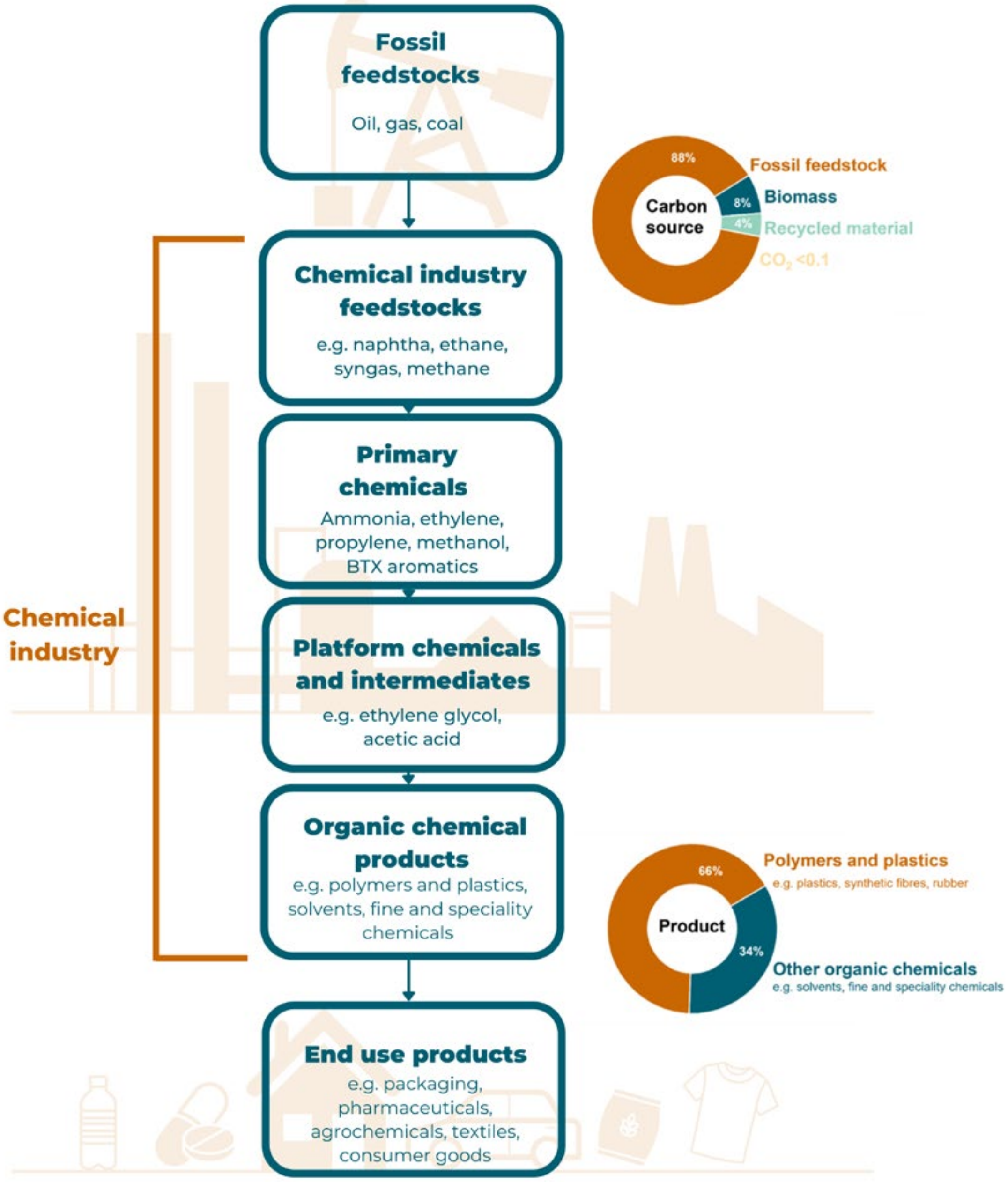

Figure 1. Production of organic chemicals and materials from fossil feedstocks. Pie charts are based on data previously published by the Renewable Carbon Initiative [15], and show distribution of embedded carbon in organic chemicals and materials according to feedstock type and product type

Table 1. End use products derived from or containing organic chemicals and materials

END USE PRODUCT	EXAMPLES	EXAMPLES OF ORGANIC CHEMICAL COMPONENTS[2]	TYPICAL LIFETIME[3]	END OF LIFE
Home and personal care	Deodorants, bath and shower products, perfumes, hair and skincare products, sun protection, detergents, home cleaning products, cosmetics	Fragrances, surfactants, solvents, polymers in liquid formulations (PLFs), pigments, other additives (e.g., for fragrance, health, or aesthetic properties)	Short	Dispersive use means the product or what is left after use is often lost to the environment or the water treatment system[4]. Some chemicals will break down or biodegrade but others may accumulate.
Agrochemicals	Pesticides, growth stimulants, seed coatings, agricultural mulching films	Bioactive ingredients, PLFs, plastics	Short	
Pharmaceuticals	Vaccines, creams, medicines	Delivery vehicles, bioactive ingredients, adjuncts, PLFs	Short	
Packaging	Food and drink packaging	Plastics, additives	Short	Recycling, incineration, biodegradation, landfill, or leakage into the environment. Depends on material, application, and waste management.
Other non-durable goods	Disposable cutlery, bin bags, nappies, solvents, lubricants	Plastics, PLFs, solvents	Short	
Textiles	Clothing, furnishings	Synthetic fibres (natural fibres are common but not discussed here)	Medium	
Other durable goods	Toys, sports equipment, personal electronics, household appliances	Plastics, PLFs (coatings, adhesives)	Medium	
Automotive and transport	Cars, buses, lorries, bicycles	Plastics, PLFs (coatings, adhesives)	Medium	
Construction and infrastructure	Fittings and window frames, asphalt, insulation materials, energy infrastructure (e.g., wind turbines)	Plastics, PLFs (paints, coatings, adhesives), composite materials, bitumen	Long	
Industrial machinery	Industrial machinery	Plastics, PLFs (paints, coatings, adhesives)	Long	

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[2] These often occur in mixtures or combinations in a product. Some are in high concentrations or make up the entire product, others make up a small part of the product, such as components in dilute solution, additives, or coatings.

[3] Refers to length of time in useful service. Short lifetime < 1 year, medium lifetime > 1 year < 20 years, long lifetime > 20 years. Product lifetimes will be a distribution and it is important to note that these are our estimates rather than exact values. Previous publications gave guidance for some applications, particularly for products using plastics and PLFs, but for some data is harder to find [3,18,19]. These principles apply throughout the discussions and tables in the remainder of this document.

[4] It is usually impossible to recycle products that are dispersed in this way during use.

Table 2. Organic chemicals and materials

ORGANIC CHEMICALS AND MATERIALS	GLOBAL DEMAND[5]
Primary and platform chemicals	
The chemical industry converts feedstocks into primary chemicals such as:	
• Ethylene	161 Mt [20]
• Propylene	114 Mt [21]
• Methanol[6]	98 Mt [22]
• BTX	121 Mt [23]
Primary chemicals are transformed into a vast array of organic chemicals and materials via a range of chemical intermediates [8, 11, 16]. A chemical intermediate is a substance formed in between a starting material and the desired product. A platform chemical is an intermediate which, due to its structure, can be converted into many different derivatives [24].	
Polymers and plastics Polymers are long-chain molecules made from many smaller chemical building blocks (monomers) joined together. Additives are often used to create polymeric materials with the desired properties:	
• Plastics: materials with properties ranging from rigid to flexible.	391 Mt [25]
• Polymers in liquid formulations (PLFs): polymers dissolved in a solvent or carrier. Some remain liquid on application (e.g., home and personal care products, agrochemicals, water treatments, or lubricants) and others form solids upon application (e.g., adhesives, sealants, paints, coatings, and inks) [19, 26, 27].	36 Mt [19]
• Synthetic rubbers: elastic materials that are an alternative to natural rubber [28].	15 Mt [29]
• Synthetic fibres: polymers spun into fibres, for example for textile applications.	75 Mt [30]
• Polymer composites: strong, lightweight, and durable materials formed by embedding fillers (e.g., fibres or nanoparticles) in a polymer/plastic matrix material [31, 32].	12 Mt [33]
Other	
Examples include:	
• Solvents: fluids that are used to dissolve other substances [34-36].	28 Mt [37]
• Fine chemicals: often have complex structures and are produced at high purity; they are building blocks for the synthesis of ingredients for things like pharmaceuticals and agrochemicals. • Speciality chemicals: chemical substances where the effect they produce is key (e.g., dyes, fragrances, surfactants (molecules that are used for cleaning applications and to stabilise emulsions and bubbles), and plasticizers (additives used to alter the mechanical properties of plastics)) [38-40]. • Materials such as bitumen and waxes, which are produced from heavy oil derivatives[7] instead of via primary chemicals and chemical industry processes [15].	Individual products tend to be produced in relatively small volumes.

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[5] Figures for annual global demand are annual figures, and the most recent year for which data is readily available varies across the different products discussed. Here, we intend this number only to give an idea of the relative scales of the different markets, so we have presented figures for approximate global demand without specifying a year. All data relates to a year no earlier than 2019, and more information can be found in the references.

[6] Including fuel applications.

[7] Heavy oil fractions are the residues of crude oil that remain after lighter components are removed in refineries. Heavy oil derivatives are carbon-based materials that are relevant to the discussion in the report. However, they tend to be excluded from discussions about the chemical industry and its impacts and the carbon and emissions figures for the chemical industry discussed here do not include these products.

1.2 Greenhouse gas impacts of organic chemicals and materials

The chemical sector is the largest industrial consumer of fossil resources, accounting for 14% of global oil demand and 8% of global gas demand [8, 11]. Some of this is fossil fuels used for energy, but the chemical industry also uses fossil resources as feedstocks, transforming the hydrocarbons in the fossil feedstock into chemical products [41]. This use of fossil feedstocks makes the chemical industry different to other energy and emissions-intensive sectors, and it accounts for roughly half of the fossil resource consumed by the chemical sector [8, 11]. Some of the feedstock carbon is lost during manufacturing as process emissions[8]. The remainder (on average around 70%) is embedded in the organic chemicals and materials until they break down and it is released to the atmosphere as carbon dioxide or other greenhouse gases (GHGs)[9] (Figure 2) [1, 8]. So, carbon which was previously stored underground ends up being released into the atmosphere in the form of GHG emissions whether fossil fuels are used for energy or as chemical industry feedstocks.

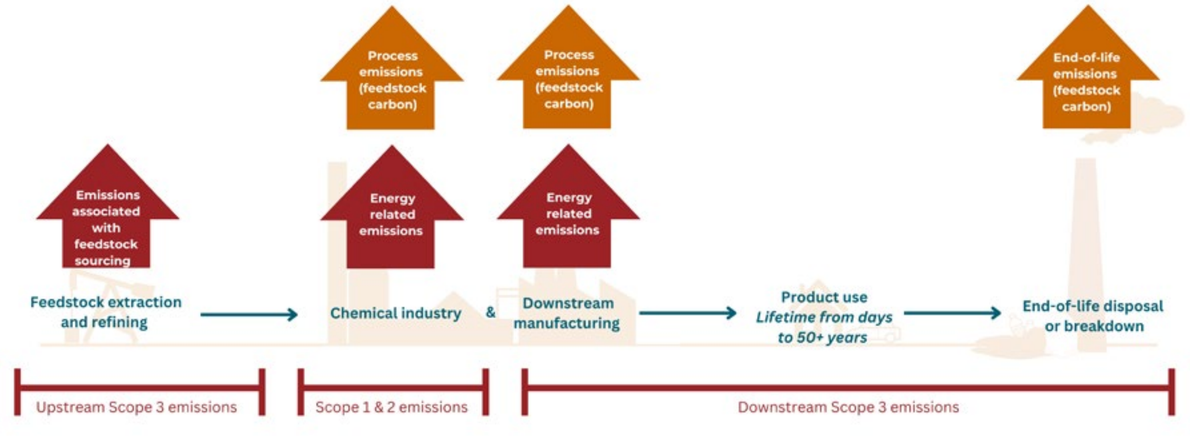

Figure 2. GHG emissions associated with the organic chemicals and materials value chain

The potential emissions due to the embedded fossil carbon in chemical products are substantial: analysis by the Renewable Carbon Initiative showed that 480 Mt fossil carbon is embedded in organic chemicals and materials each year[10], equivalent to over 1.7 Gt CO2 [15]. However, not all of this carbon will be released to the atmosphere in the near term. The timeframe in which such emissions occur depends on the nature of the chemical product and how it is dealt with at end-of-life. The lifetime of chemical products can vary significantly from less than one year (e.g., cosmetic or packaging products) to greater than 50 years (e.g., products used in construction) (see Table 1). At end-of-life, chemical products may be recycled, incinerated, landfilled, or end up in the environment due to waste mismanagement or dispersive use (Figure 2 and Table 1) [8, 9, 19, 26, 42]. Incineration or degradation (e.g., biodegradation) releases the embedded carbon. In some cases, recycling can avoid emissions by locking the fossil carbon up in new products. If organic chemicals or materials end up in landfills or the environment, some degrade quickly, but others have properties that mean they persist for extended periods. It is estimated that more than half of the carbon embedded in organic chemicals and materials across the system is released relatively quickly due to incineration or degradation after a short product lifetime [1, 6].

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[8] Process emissions occur due to reactions during manufacturing that release carbon dioxide because of the difference in carbon content between the feedstock and the products [8,43].

[9] There are also non-carbon dioxide GHG emissions associated with energy, process emissions, and the breakdown of chemicals containing other elements, such as the significant emissions associated with the breakdown of ammonia-derived fertilisers during use. These are not discussed in detail in this report.

[10] This figure does not include products derived from heavy oil fractions such as bitumen.

The chemical industry produces a huge variety of chemicals that are used in products with different lifetimes and which are dealt with differently at end-of-life. This, coupled with the complexity of the global chemical system and a lack of detailed publicly available data on the chemicals sector and its supply chains, makes it challenging to quantify its GHG impacts [5, 11, 43]. Several interesting studies have attempted to do this in different ways, often focusing on plastics rather than the entire chemical system [2-6, 10, 43-45]. Estimates of the direct emissions of the entire chemical industry (e.g. inorganic and organic chemicals) range from 1.7 to 2 Gt CO2 per year (Figure 3) [14, 46]. Direct emissions are those occurring within the chemical industry or associated with purchased energy, sometimes referred to as Scope 1 and Scope 2 emissions[11]. Though estimates of direct emissions are often used to describe the impact of the chemical industry (e.g., at national or global level), this does not provide the whole picture. Emissions occurring upstream and downstream of the chemical industry (e.g., during resource extraction and refining or at product end-of-life) are estimated to contribute an additional 1.5 – 2.5 Gt CO2 eqv a year (Figure 3) [46]. Upstream and downstream emissions, which are often referred to as Scope 3 emissions, occur beyond the bounds of the chemical industry and some contribute to the emissions accounting in other sectors such as waste management or agriculture [11, 41, 46, 47]. Once again, the temporal aspect of the emissions stemming from the embedded carbon in chemicals must also be considered, as even figures for Scope 3 emissions do not include emissions that will occur in future due to the release of embedded carbon in longer lifetime products.

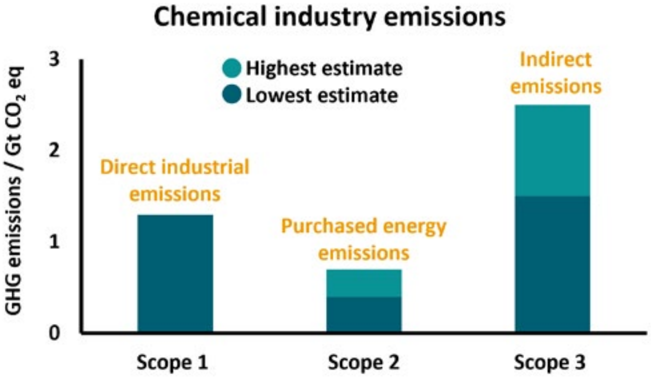

Figure 3. Estimated chemical industry emissions based on data summarised in reference [46]

Despite the complexity of the global chemical system and the challenges quantifying its GHG impacts, its significant contribution to climate change due to the use of fossil fuels and fossil feedstocks cannot be ignored. For the chemical system to be compatible with net-zero, the whole-system emissions, including those stemming from the carbon embedded in organic chemical products, must be addressed [2, 10, 43, 47, 50, 52].

1.3 Transitioning to a net-zero chemicals system

Fossil fuel demand is expected to decrease in the coming decades as the world transitions to renewable energy sources [7]. In contrast, the petrochemicals sector is expected to grow significantly and many oil and gas companies are now looking to expand their petrochemical businesses in the hope of more resilient incomes [8, 10, 49, 50]. Emissions from the chemical system will therefore greatly increase unless sufficient abatement measures are implemented [3, 10]. Whilst negative emission technologies may be able to balance some residual emissions, the feasibility of deploying these technologies on a large scale still needs to be determined [51]. It is, therefore, crucial that changes are made to significantly reduce chemical system emissions rather than relying on negative emissions from elsewhere in the economy to balance out business as usual. Emissions from across

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[11] Scope 1, 2, and 3 are classifications used to define emissions. See [43].

the whole life cycle of organic chemicals and materials must be addressed, including energy-related emissions and those related to the embedded carbon [1-7, 45, 46]. This will require systemic change and a suite of different approaches and technologies; no silver bullet exists (Table 3) [1-6, 10, 17, 45, 46]. Measures relating to manufacturing processes, energy consumption, renewable energy, and deployment of carbon capture and storage (CCS) have been the focus of attention so far. Although such changes will be necessary and likely have a significant impact on emissions, they will not address the emissions from the embedded carbon in products. The transition to a net-zero-compatible chemical system also requires the implementation of other measures, including a transition away from fossil feedstocks [2-6, 45, 46].

Table 3. Strategies for reducing chemical system GHG emissions

RENEWABLE ENERGY	Direct emissions could be significantly reduced by transitioning to renewable sources of electricity, heat, and steam [4, 6, 12].
LOW-CARBON HYDROGEN	Hydrogen is a feedstock for many chemical processes but it is mostly derived from fossil feedstocks [10, 12, 56]. A transition to low-carbon hydrogen[12] could reduce chemical sector emissions [10, 12, 57].
ENERGY AND MATERIAL EFFICIENCY IN MANUFACTURING	The chemical industry is already well integrated and efficient but there are opportunities for further improvements to efficiency, for example through improved catalysts, industrial biotechnology, application of green chemistry principles, and digitalisation [9, 11, 43].
CARBON CAPTURE AND STORAGE (CCS)	CCS can reduce emissions by preventing release of fossil carbon to the atmosphere at point sources such as refineries [8, 12]. It may play an important role in capturing emissions that cannot otherwise be avoided, but it comes with trade-offs and cannot be used to fully mitigate release of embedded carbon in chemical products [2-4, 10, 58, 59].
CIRCULAR ECONOMY	Circular economy principles guide minimal extraction of raw materials and production of waste, through material efficiency, product reuse and durability, recycling, and waste valorisation [9, 60]. These practices can reduce demand and so decrease the amount of feedstock required, as well as allowing carbon to be retained in the system rather than lost when products reach end-of-life [4, 5, 10].
MANAGING LEVELS OF PRODUCTION AND DEMAND	Reducing, or at least limiting increase in, levels of organic chemical production through supply side interventions will limit the associated emissions. Behavioural and societal changes could also reduce demand for petrochemical products.
RENEWABLE CARBON FEEDSTOCKS	Carbon-based chemicals cannot be decarbonised but they can be defossilised through a switch to renewable carbon sources such as biomass, carbon dioxide or recycled materials [8, 14, 61]. These carbon sources are considered renewable because they do not rely on extraction of carbon from underground reserves, instead relying on carbon that is already in products or that has come from the atmosphere [1]. In the case of biomass, the carbon contained in the feedstock is carbon that is captured from the atmosphere as plants grow.

Carbon-based chemicals cannot be decarbonised, but they can be defossilised through a transition to renewable carbon sources, such as recycled material (e.g., plastic), carbon dioxide, and biomass [8, 14, 57]. Currently, renewable carbon sources account for 13% of carbon embedded in chemicals and materials each year and over half of this is biomass, which is the focus of this report [15]. The total amount of renewable carbon needed for defossilisation of organic chemicals in the future depends on whether the production of organic chemicals and materials increases in line with current trajectories, and it is important to recognise that all renewable carbon feedstocks come with limitations as well as benefits [15, 58, 59]. Even with improvements to infrastructure and technology, there is a limit to how much of the feedstock

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[12] Low carbon hydrogen refers to hydrogen produced through methods that incur low GHG emissions. It may include what is often referred to as "green hydrogen" but is not limited to this.

demand can be met through recycling, and there are ongoing questions around the safety of some technologies and products [45, 60-62]. Carbon dioxide utilisation technologies are mostly at very low technology readiness levels and require huge amounts of renewable energy [63, 64]. Sustainable biomass is a limited resource, and issues such as resource availability and technology development are discussed in detail later in this report. The evidence suggests that the transition to a defossilised chemicals sector would be best achieved through a circular bioeconomy that uses a variety of renewable carbon sources and implements circular economy principles, coupled with measures that limit levels of production and demand (Figure 4) [1, 2, 4, 10, 45, 50, 56, 63].

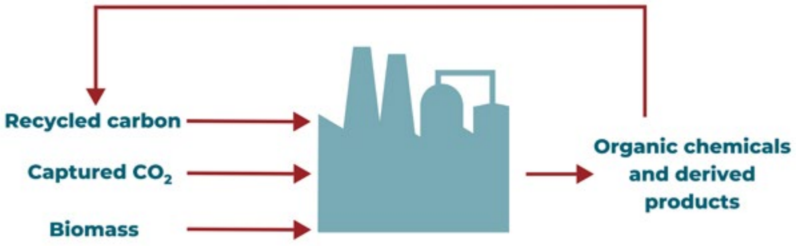

Figure 4. Renewable carbon feedstocks for organic chemicals and materials their use within a circular bioeconomy

Transitioning away from fossil feedstocks for chemicals will not be quick or easy: the petrochemical sector is large and complex with optimised and integrated processes and interconnected supply chains that have all been developed around fossil feedstocks; upstream production units used for fossil feedstock conversion are capital-intensive and have long lifetimes; and fossil feedstocks are cheap and still benefit from significant subsidies [1, 17, 65, 66]. So, without intervention from governments and policymakers fossil feedstocks will remain at the heart of the global chemical system. Another significant challenge that was raised by many of our stakeholders is that most people are not aware of the climate impact of the fossil carbon used in chemicals, and so the societal push to move away from fossil feedstocks is less than is seen for energy applications.

1.4 Sustainability beyond greenhouse gases

Alongside the climate impacts, it is important to acknowledge the other impacts of some organic chemicals and materials and the industry that produces them [9, 10]. Due to the ubiquitous nature of organic chemicals, people are regularly and variously exposed to them (e.g., in products, in homes, and at work). Loss to the environment (e.g., through dispersive use, mismanagement of waste, or leaks or emissions from manufacturing) also means many organic chemicals are found as pollutants worldwide [8, 9, 42]. Unfortunately, some organic chemicals and materials are hazardous, and if they are not appropriately managed, they can adversely affect human health and wellbeing, ecosystems, and the environment [9]. For example, plastic pollution is recognised as a significant global issue, but there is also increasing concern around the hazardous nature of many of the additives plastics contain and the significant health risks to many vulnerable communities living near plastic facilities around the world [9, 38, 50, 67, 68]. Approaches to mitigating the GHG emissions of the chemical system must therefore be considered in the context of their broader sustainability impacts to create a safe and sustainable chemical system as well as a net-zero one [45]. This means looking not just at the technologies and feedstocks used for chemical production, but at what kinds of chemicals and materials we need and what level of production and consumption is sustainable.

PART 2: MAKING CHEMICALS FROM BIOMASS

Biomass can be used to make a vast array of organic chemicals and materials including plastics and polymers, fine and speciality chemicals, and other products such as bitumen and functional materials (Figure 5). These bio-based chemicals and materials can replace fossil-based chemicals in a range of applications, such as home and personal care products, packaging, and construction. The molecules comprising biomass feedstocks are carbon-based, but they have different structures and chemical compositions than those in fossil feedstocks. As a result, new processes are often required to convert biomass feedstocks into valuable organic chemicals and materials. When successfully translated to industrial scale, these conversion technologies are used in dedicated biorefineries [69, 70]. In some cases, processes used in the petrochemical industry can be used to transform bio-based feedstocks into platform chemicals or intermediates [71, 72]. Biomass can be used to make drop-in bio-based chemicals, which are chemically identical to existing fossil-based chemicals, but the unique chemical structures found in biomass also enable novel bio-based chemicals with new structures and properties [66, 73].

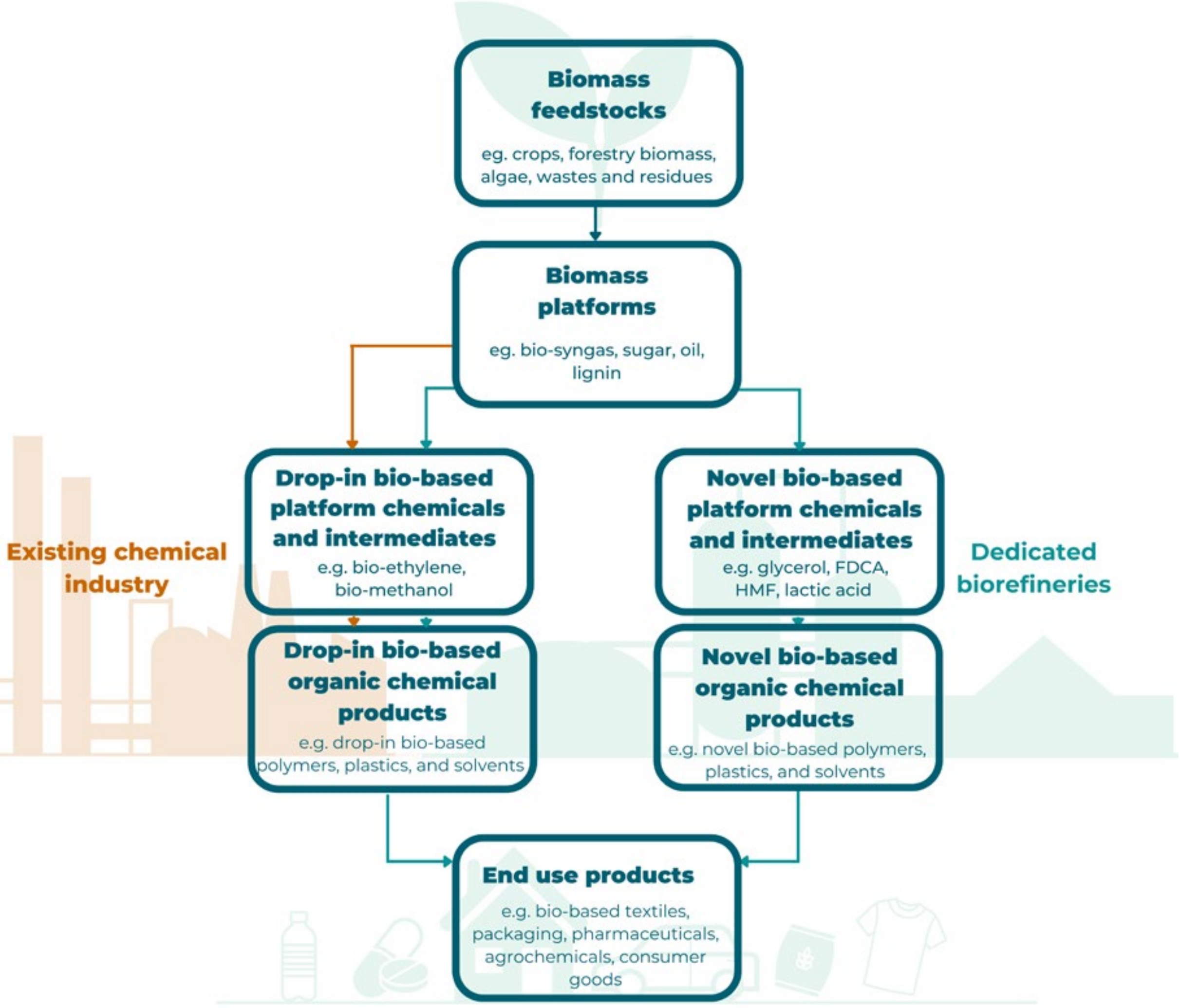

Figure 5. Biomass feedstocks to bio-based chemicals

2.1 Biomass feedstocks to bio-based chemicals

Biomass feedstocks include crops (e.g. annual crops such as wheat or sugar beet, perennials such as miscanthus and willow, and novel crops such as hemp), algae (e.g., macroalgae (i.e. seaweed) and microalgae), agricultural residues (e.g., straw and manure), forestry biomass, and other biogenic wastes and residues (e.g., food waste) [57, 74]. Feedstocks can be classified according to their major chemical components such as sugar, starch, or oil. Perennial crops, wood, and some wastes and residues are types of lignocellulosic biomass.

Biomass feedstocks contain a vast array of organic molecules, many of which have complex structures and contain elements (e.g., oxygen) that are not found in fossil feedstocks. Biomass sometimes contains valuable molecules that can be directly extracted and used. More often, conversion technologies are used to transform the molecules found in biomass into valuable bio-based chemicals [69]. Biomass feedstocks tend first to be fractionated (i.e. separating the different components of the biomass) or processed (i.e. breaking down the components in the biomass) into biomass platforms (e.g., sugar, oil, lignin, carbon dioxide, syngas, biomethane, and pyrolysis oil) from which a range of bio-based chemicals, materials, and fuels can be produced (Table 4) [57, 75].

Currently, sugar from annual crops such as maize and wheat is the most common bio-based chemical production platform [57, 76]. Alternative feedstocks such as wastes, residues, and lignocellulosic biomass can improve sustainability performance and avoid competition with food applications, but they are often heterogeneous and more challenging to process [77]. Lignocellulosic biomass is recalcitrant, and pre-treatment steps are usually required to access the polymers and sugars it contains before they can be processed using other technologies [57, 76, 78–80]. Pre-treatment can be achieved by chemical, physical, or biological means, but current technologies tend to add significantly to the cost and energy demand [77, 78].

Table 4. Common biomass platforms from which bio-based chemicals can be produced

BIOMASS PLATFORM	DETAILS
Sugar	Sugar extracted from sugar crops or yielded by the breakdown of polysaccharides (e.g., biological polymers composed of sugar monomers) from starch crops, algae, or lignocellulosic biomass [57]. Sugars are converted to products via chemical catalysis or fermentation [57]. Sugar from annual crops such as maize and wheat is a common platform for commercial scale bio-based chemicals production [57, 76].
Oil	Oils extracted from oily crops like palm, coconut, or rape seed, or from algae, animal material, or some waste streams (e.g., crude-tail oil from paper processing industries) [69, 81]. The components of bio-oils are converted into fatty acids and alkyl esters (including for bio-diesel applications), with glycerol as a by-product [57, 82]. Oleochemicals (i.e. chemicals derived from bio-oils) are already major industry, with derivatives used in products such as plastics and surfactants [57]. Bio-oils can also be used to produce bio-naphtha, a substance like the fossil-based naphtha often used as a feedstock in the petrochemical industry. Naphtha is currently a by-product of the HVO (hydrogenated vegetable oil) processes that convert bio-oils into biofuels [61, 87].
Lignin	Lignin is a naturally occurring polymer that can be directly extracted from lignocellulosic biomass [41, 61]. It is an extremely abundant material. Large amounts are already produced as a by-product of the paper and pulp industry but this is often burned for energy generation. However, lignin shows potential for use in the production of other valuable products in the future, for example aromatic chemicals and adhesives [61, 80].
Biogenic carbon dioxide	Biogenic carbon dioxide is that which is released via biomass combustion or as a by-product of other conversion processes such as fermentation and anaerobic digestion. Carbon dioxide can be converted into valuable products via catalytic processes or gas fermentation, though this usually requires the addition of hydrogen.
Syngas	Syngas is a gaseous mixture of carbon monoxide, carbon dioxide, hydrogen and water produced by biomass gasification or reforming of bio-methane. Catalytic conversion or gas fermentation can be used to make a variety of useful chemical products from syngas [57, 76].
Pyrolysis oil	Pyrolysis oil which is produced via pyrolysis (see Table 5) of biomass. Pyrolysis oil is a mixture of many different organic molecules and its composition varies according to the feedstocks used and how pyrolysis is caried out [85]. Some substances commonly found in pyrolysis oil can be purified and converted into valuable chemical products [57, 76, 86, 87].
Biomethane	Biomethane is a component of the biogas produced during anaerobic digestion [57, 88]. Biomethane is already produced commercially, and although this is mostly for energy applications, it has potential as a chemical feedstock to replace the fossil-derived methane currently used as a feedstock in the chemical industry. Researchers are also developing novel technologies for direct bio-conversion of methane to chemicals [89].

Conversion technologies based on chemical, thermochemical, or biological processes are used to transform biomass into bio-based chemicals (Table 5) [57, 76, 87, 90, 91]. There are also exciting new conversion technologies at the very early stages of development, such as photocatalysis (conversion using light) and electrocatalysis (conversion using electricity) [92, 93]. Each of the technologies described in Table 5 has its own strengths and limitations. For example, industrial biotechnology tends to use lower temperatures and pressures and fewer hazardous chemicals than other conversion technologies [9, 94, 95]. Not only can this lead to lower energy consumption and safer manufacturing, but it often means that the chemical structures found in biomass are maintained in the products, [9, 94, 95]. In contrast, many other conversion technologies, particularly thermochemical processes such as gasification, completely deconstruct the molecules found in biomass into simple building blocks. The nature of biological systems also enables industrial biotechnology to provide simple routes to complex chemical products that would not be possible via other processes [95]. However, industrial biotechnology also has limitations. It tends to use large volumes of water and require significant downstream processing to recover products, which increases costs and energy consumption [94-96]. Biological processes also tend to result in low yields, are often slower than chemical or catalytic processes, and there are inherent limitations on the scale of bioreactor that can be operated, all of which can be problematic for industrial systems [94-96]. A bio-based chemical system will likely require a variety of different conversion technologies, with the best approach varying according to the feedstock, product, and wider context.

Table 5. Technologies for making bio-based chemicals

CONVERSION TECHNOLOGY	DETAILS
Chemical synthesis	Chemical or catalytic conversion of biomass-derived components. Examples include transesterification of lipids from oil crops, catalytic conversion of sugars, and catalytic routes for syngas conversion [76, 87].
Thermochemical conversion	Conversion of biomass feedstocks through the application of heat, sometimes in the presence of a catalyst. Examples include pyrolysis, hydrothermal liquefaction, and gasification [57, 76, 86, 87, 99].
Biological conversion	Biological processes are often discussed under the banner of 'industrial biotechnology', which is defined as the use of biological systems, including enzymes, micro-organisms, cells, or whole organisms, to make valuable products such as chemicals or materials [94]. The scope and potential of industrial biotechnology is greatly increased by the growing field of engineering biology, which is the application of engineering principles to the design of biological systems[13]. Engineering biology encompasses the academic discipline synthetic biology, which is the design and construction of new biological systems, for example bacterial strains that produce interesting new compounds, or modified enzymes. Examples of biological conversion include: • Fermentation: Conversion of bio-based molecules such as sugars by microbes (e.g. yeast or bacteria) [57, 95]. Fermentation is commonly used to make alcohols, often driven by their use as fuels, but there are also examples of commercial-scale production of other chemicals such as high-value or speciality products [57, 95]. • Anaerobic digestion: Microbial conversion of biomass into biogas, a mixture of biomethane and biogenic carbon dioxide [57]. Anaerobic digestion is a versatile technology which is already widely deployed at commercial scale to produce biomethane from crops or low-value, mixed waste streams including food and agricultural waste [56, 57]. • Gas fermentation: Microbial conversion of single carbon (C1) gases such as biomethane, biogenic carbon dioxide (a by-product of anaerobic digestion and some fermentation processes), and bio-derived syngas [100, 101]. Gas fermentation is a less mature technology than sugar fermentation, but some examples are starting to reach commercial scale [100, 102]. • Biocatalysis: Biocatalysis involves the use of enzymes (biological catalysts) outside of the cellular environment [94].
Extraction	Some useful organic chemicals can be extracted directly from biomass feedstocks. For example, there are natural products in some plants that have pharmaceutical activity and pigments in algae that can be used to make inks and dyes [91, 103-105]. Engineering biology approaches mean it is increasingly possible to increase the amount of these valuable chemicals produced in plants or make new products [91, 104, 106]. Further examples can be found in a recent briefing from the High Value Biorenewables Network [107].

When biomass is converted into bio-based chemicals, not all the material ends up in the final product as some may become by-products, be lost as process carbon dioxide emissions, or end up as waste [111]. The biomass utilisation (or conversion) efficiency is affected by the feedstock, the technology, and the nature of the product [2, 111, 112]. High biomass utilisation efficiency usually stems from processes with fewer reaction steps, higher yields, and fewer waste or by-products, and this often correlates to bio-based products that retain a chemical structure that

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[13] There appears to be some discrepancy in the definitions used for engineering biology. The UK government definition appears to be broader than that used by UKRI, and in fact many of the systems discussed in this report under the umbrella of industrial biotechnology may fall under the definition of engineering biology used in the UK's National Vision for Engineering Biology [97,98].

is similar to that seen in the biomass [2, 111, 112]. The more efficient the biomass utilisation, the greater the amount of product that can be made from a specific volume of feedstock, and this can have benefits in terms of land use, environmental impact, and economics.

2.2 Drop-in bio-based products

Table 6 contains examples of how biomass is or could be used to make various important chemical products such as platform chemicals, plastics and other polymers, solvents, and fine and speciality chemicals. More detail can be found in Tables A1 – A6 in the appendix.

Biomass feedstocks can be converted into drop-in bio-based chemicals, which are structurally identical to existing fossil-based chemicals. Researchers have developed many drop-in bio-based chemicals at lab scale and some are already produced at commercial scale.

Some drop-in bio-based chemicals can be produced via entirely new manufacturing routes, but there are also opportunities for transforming drop-in bio-based raw materials, platform chemicals, or intermediates using existing chemical industry processes and infrastructure (Figure 5) [74, 75]. The same manufacturing processes used to convert fossil-based primary and platform chemicals into thousands of valuable chemical products could also transform drop-in bio-based equivalents into a vast array of bio-based derivatives (Table A1). The ethylene value chain, depicted in Figure 6, is an excellent example of this approach. Bioethylene is produced from bioethanol and converted into a range of derivatives such as biopolyethylene, bioethylene oxide, and surfactants at industrial scale [61, 113-118]. Bioethanol is produced in large volumes globally, mostly via fermentation of sugars from arable sugar crops and primarily for fuel applications. The maturity of bioethanol production technologies and the fact that it offers a route to the primary chemical ethylene means that ethanol is considered by many to be a crucial bio-based platform chemical for the future.

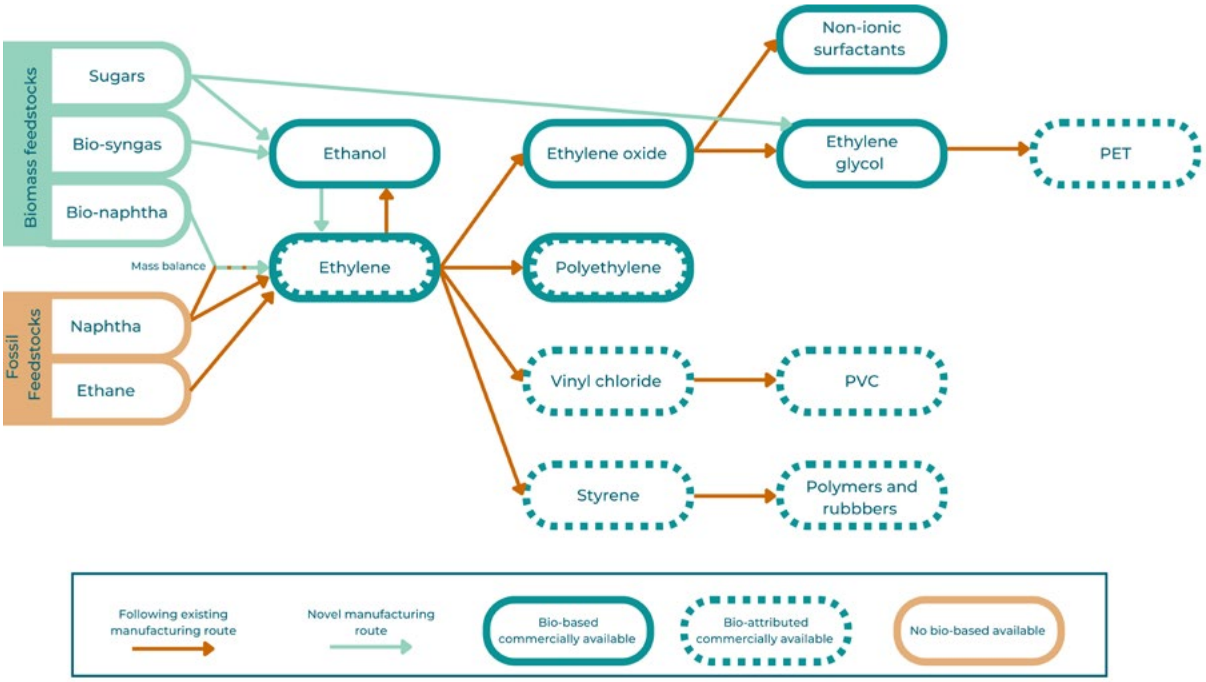

Figure 6. The ethylene value chain and options for utilising biomass to create drop-in bio-based products

Theoretically, most organic chemicals could be produced from biomass via drop-in bio-based primary and platform chemicals. However, in some cases it is possible to create a drop-in product without using the platforms and processes used in fossil-based production [71, 73]. Smart drop-ins are drop-in bio-based chemicals produced by an alternative pathway offering some advantage over the traditional route, such as more efficient use of the biomass feedstock, fewer synthetic steps, less complex synthesis, less energy intensive manufacturing, or reduced environmental impact (e.g., see Table A1 and A2) [73]. For example, bioethylene glycol can be produced from bioethylene, mirroring the production of ethylene glycol (a pre-cursor of PET) from ethylene in the petrochemical industry. However, producing bioethylene glycol directly from sugar avoids bioethylene altogether, resulting in fewer synthetic steps and a more efficient process [57, 127, 128]. Another example is a method developed by researchers for direct production of bio-adipic acid via fermentation [57, 130, 131]. Fossil-based adipic acid is derived from benzene, and the processes involved are a significant source of GHG emissions due to the release of NOx (nitrogen oxides). NOx production is avoided in the direct fermentation route [109, 194].

An alternative route to drop-in chemicals is an approach known as biomass balance, where a portion of the fossil feedstock used early in the manufacturing process is replaced by a similar bio-based material (Figure 7) [57, 72, 195]. For example, a mixture of naphtha and bio-naphtha may be fed into a cracker to make ethylene and propylene, or syngas and bio-syngas could be used for methanol production. The mixture of feedstocks used in the biomass balance process means that not every molecule of products will necessarily contain biogenic carbon. However, under the biomass balance approach manufacturers attribute all the biogenic carbon to one product stream and treat this as bio-based (Figure 7) [72]. Here we will refer to chemicals made via biomass balance as bio-attributed to differentiate them from those which are truly bio-based[16]. Bio-attributed methanol, ethylene, propylene, and BTX aromatics, are already produced commercially. A variety of bio-attributed products derived from these primary chemicals are also already available, and this includes many products that are not available in bio-based form (Table 6 and Table A1) [61, 122, 126-138]. Discussion with our stakeholders highlighted the differing opinions around the validity and sustainability of the biomass balance approach. Some have concerns about selling biomass balance products under the guise of bio-based products since they do not necessarily contain biogenic carbon. Others dispute this, likening it to consumers purchasing renewable electricity[17]. There are still questions about what proportion of the feedstock comes from biomass makes up in industrial biomass balance processes, and about how much this could be increased without significant changes to the processes or the resulting products. There is also some concern that over reliance on approaches such as mass balance may stifle innovation that could develop new technologies for more or improved biomass utilisation in the long run.

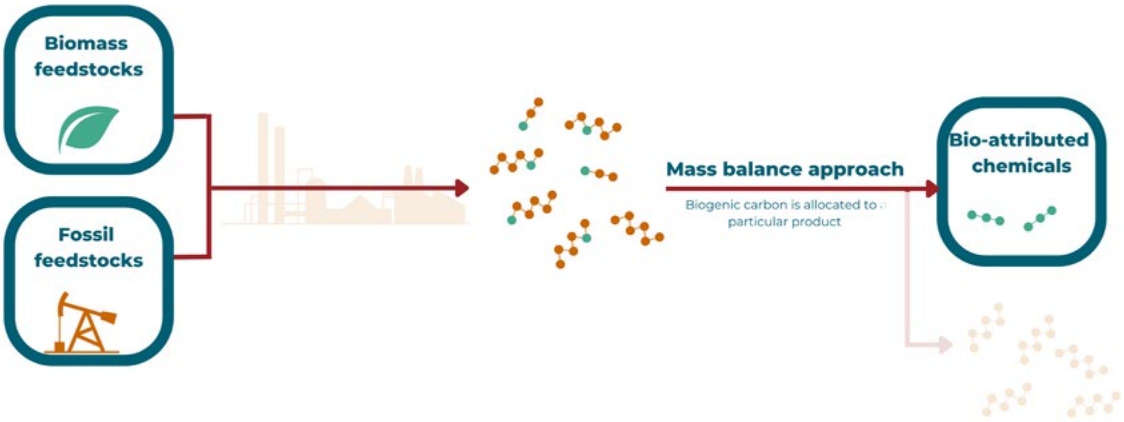

Figure 7. The biomass balance approach

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[16] The distinction between bio-based and bio-attributed is not always clear when looking at information from manufacturers and this may result in some errors in our discussion of certain products.

[17] When consumers buy renewable electricity, it relates to the portion of renewable electricity in the grid but doesn't necessarily mean that every individual receives renewably generated power.

Table 6. Examples of how biomass can be used to make important chemical products

CHEMICAL PRODUCT	EXAMPLES OF FOSSIL-BASED	KEY APPLICATIONS	APPROXIMATE GLOBAL DEMAND[14]
Platform chemicals	Primary chemicals (ethylene, propylene, methanol, and BTX aromatics)	Converted into vast array downstream chemicals and products.	Primary chemicals[15] alone total almost 500 Mt [20-23].
Plastics	Polyethylene, polypropylene, and polyvinyl chloride (PVC)	Packaging, textiles, automotives, household appliances, toys, sports equipment, and construction.	391 Mt
PLFs	Polyacrylics, polyesters, polyurethanes, vinyl polymers, and a variety of water-soluble polymers [19, 27].	Paints, coatings, inks, adhesives, home and personal care products, agrochemicals, water treatments, and lubricants [19].	36 Mt [19]
Synthetic fibres	Polyester (polyethylene terephthalate), polyamides (e.g., nylon 6,6 and nylon 6) ([30, 141].	Mainly textiles in clothing and home furnishings [142].	75 Mt [30]
Synthetic rubbers	Styrene butadiene rubber and polybutadiene rubber [28, 146].	Automotives (e.g. tyres), industrial and consumer goods (e.g. gloves, footwear), and construction [146, 147].	15 Mt [29]
Polymer composites	Polyesters, polyamides polyamides, and polyurethanes (polymer matrix) and polymer fibres, carbon nanotubes or carbon fibre (embedded fillers) [31, 32].	Automotives and other vehicles, wind energy (structural components of wind turbines) and other energy applications, aerospace, defence, and construction [32, 154].	12 Mt [33]
Solvents	Oxygenated solvents (e.g.e.g., ethanol, acetone), hydrocarbon solvents (e.g.e.g., cyclohexane), and halogenated solvents (e.g., dichloromethane).	Industry, home and personal care products, and paints [34-36].	28 Mt [37]
Plasticizer	Phthalates.	Plastic products, such as packaging, textiles, and construction.	11 Mt [167]
Surfactant	Linear alkylbenzene sulfonates (LAS), sodium lauryl ether sulphate (SLES), cationic surfactants, and non-ionic surfactants [39, 174, 175].	Home and personal care products, industrial applications, agrichemicals, pharmaceuticals (as drug delivery agents), and paints [39, 40].	19 Mt [176]
Bitumen	Often combined with aggregates such as sand to form asphalt.	Road and pavement surfacing, construction (e.g., roofing and waterproofing) [188].	Over 100 Mt [189]

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[14] Again, figures for annual global demand are annual figures, and the most recent year for which data is readily available varies across the dif
figures for approximate global demand without specifying a year. All data relates to a year no earlier than 2019, and more information can be

[15] Excluding ammonia.

DROP-IN BIO-BASED	NOVEL BIO-BASED
There are examples of primary chemcials and other platform chemicals or improtant intermediates produced commercially in bio-attributed (e.g., bio-attributed ethylene, propylene, methanol, and formaldehyde) and to a lesser extent bio-based (e.g., bio-based ethylene and ethylene oxide) forms [57, 110-126]. Smart drop-in routes to many intermediates or and platforms (e.g., bio-based ethylene glycol and adipic acid) are also being developed [57, 127-131].	A number of novel bio-based platform chemicals have emerged, some of which has achieved commercial production (e.g., succinic acid and glycerol), and some of which are still being developed (e.g., levoglucosan, hydroxymethylfurfural (HMF), and 2,5-Furandicarboxylic acid (FDCA)) [57, 82, 85, 111, 132-135].
Some drop-in bio-based plastics commercially available (e.g., polyethylene and partly bio-based PET) but more are commercially available in bio-attributed forms (e.g., bio-attributed polyethylene, polypropylene, and PVC) [115, 116, 119, 122, 123, 125, 126, 136].	A number of bio-based biodegradable plastics are available commercially (e.g., PLA and PHAs) [57, 65, 137-139]. There are also novel bio-based plastics that are made from monomers that are more readily derived from biomass than those used in fossil plastics (e.g., a variety of novel polyurethanes from plant oils, and the novel PET replacement PEF) [140].
Relatively few drop-in bio-based PLFs are commercially available, but there some examples of bio-attributed (e.g., polyacrylics and vinyl polymers) and bio-based (e.g., bio-based polyethylene glycol) products.	Novel bio-based PLFs have been developed, often with beneficially properties such as biodegradability or improved safety, but most remain in the research stage. There are some examples of commercially available bio-based PLFs (e.g., novel biobased polyacrylics, polyesters, and polyurethanes, and PLFs based on natural polymers).
Some bio-attributed (e.g., bio-attributed Nylon 6,6) partly bio-based (e.g., partly bio-based polyester) are available [143].	A range of novel polyesters and polyamides/ nylons have been developed at lab scale, and some are commercially available (e.g., bio-based polyamides/ nylons or biodegradable fibres such as PLA) [30, 141, 144, 145].
Some synthetic rubber is available in bio-attributed form (e.g., styrene butadiene and polybutadiene) or partly bio-based form (e.g., partially bio-based ethylene propylene diene monomer) and bio-based rotues are under development [121, 148-152].	Several novel bio-based synthetic rubbers that have been developed by researchers, and there is an interest in developing novel rubbers with properties such as biodegradability [28, 153].
Composites formed from drop-in bio-based polymer matrix materials (e.g. bio-based polyesters, polyamides and polyurethanes) and/ or drop-in bio-based fillers are being developed [154-158].	Composites formed from novel bio-based polymer matrix materials (e.g. PLA) and/ or novel bio-based fillers (e.g., biochar) are being developed, and in some cases these will allow new functionalities such as biodegradable composites [32, 159-161].
Drop-in replacements for several important oxygenated organic solvents are commercially available (e.g., bioethanol, bio-acetone, bio-butanol, and bio-ethyl acetate) [35, 57, 71, 111, 112, 162-164]. Less activity focused on drop-in replacements for hydrocarbon solvents and solvents that are particularly hazardous or toxic.	Research has focused on novel solvents that can be safer replacements for commonly used hazardous solvents or have performance benefits [112]. Some of these are already commercially available (e.g., cyrene, 2-Methyl-THF, and ethyl lactate) [35, 57, 112, 165, 166].
Some bio-attributed plasticizers are available, but most research seems to have focused on novel bio-based plasticizers [168].	There has been a lot of research activity related to safer bio-based plasticisers and there are already some commercially available bio-based plasticizers [111, 169-173].
Many surfactants are already partly dervied from bio-oils but creating fully bio-based surfactants is more challenging [39, 175]. Bio-attributed versions of some common surfactants are available and some fully bio-based surfactants have been launched in recent years (e.g., surfactants based on bioethylene oxide) [113, 177-179].	Many novel surfactants have been developed, often with an aim to make them non-toxic and biodegradable. There are already commercial examples (e.g., alkyl polyglucosides) [39, 180-187].
None	A range of bio-binders for use in bitumen have been developed [190, 191]. These tend to be mixed with fossil bitumen rather than replacing it totally [190, 191]. Most are still being scaled and tested, but there seems to one example commercially available [192, 193].

ferent products discussed. Here, we intend this number only to give an idea of the relative scales of the different markets, so we have presented
e found in the references.

Drop-in bio-based chemicals are often considered to be attractive because they can be used in products without a change in performance or function. The downside of this is that they don't address any of the environmental and health impacts of the equivalent fossil-based chemical beyond the GHG emissions. Drop-in bio-based plastics such as bio-based polyethylene can still end up as microplastics and plastic pollution and drop-in bio-based equivalents of toxic or harmful chemicals such as formaldehyde will still pose the same risk as their fossil counterparts. Furthermore, when it comes to deploying drop-in bio-based chemicals at scale they often struggle to compete with existing fossil-based products. This is perhaps unsurprising, because the organic chemicals that we use today were developed by an industry driven by fossil feedstocks, which has evolved and optimised over a long period of time [17, 66]. Many fossil-based organic chemicals have structures that are more difficult to produce from biomass feedstocks. This negatively impacts the economic and environmental performance of bio-based products and often means conversion of biomass to products is inefficient [66, 108, 109]. Drop-in bio-based chemicals are often more expensive than their fossil equivalents despite having the same performance [1, 57, 65, 204]. For example, bio-butanol accounted for roughly two thirds of the market until the 1950s when falling prices for fossil feedstocks meant the bio-based product was no longer cost competitive [35].

2.3 Novel bio-based chemicals

The fact that biomass feedstocks contain molecules that are markedly different from those found in fossil feedstocks makes a bio-based chemicals industry well suited to the production of novel organic chemicals [70]. Some novel chemicals have properties that are very similar to existing chemicals, meaning they can be used as direct replacements despite the new chemistries. It is also possible to create many novel bio-based chemicals with more unique properties and functions. Using the chemical structures found in biomass rather than attempting to replicate compounds derived from fossil feedstocks also tends to result in higher biomass utilisation efficiencies, which can positively impact process economics and environmental performance [77].

Novel bio-based plastics are an example that is worth attention (see Table A4). Plastics are ubiquitous in modern society but despite their useful properties they have significant negative consequences for the environment, ecosystems, and people's health [6, 205]. Some novel-biobased plastics have similar properties to common fossil-based plastics. For example, the novel bio-based plastic polyethylene furanoate (PEF) can directly replace polyethylene terephthalate (PET, a commonly used plastic) in many applications and can be recycled like PET [57, 65, 206]. Biomass also lends itself to the production of novel biodegradable plastics[18], which are gaining attention as a tool to help tackle plastic pollution [69]. For example, polylactic acid (PLA) is a bio-based and biodegradable plastic that is already commercially available [57, 65, 67, 137-139, 207]. Like many biodegradable plastics PLA products tend to require industrial facilities for rapid biodegradation and improper handling of these materials at end of life can mean they end up in conditions under which they do not quickly biodegrade [65, 67, 208]. Biodegradable plastics are not a silver bullet to address plastic pollution, but they are particularly useful for applications where recycling is challenging. This includes applications that result in contamination with organic material or lead to plastic entering composting facilities (e.g. food packaging that is hard to clean such as coffee pods or bags for food waste) or applications where it is hard to fully recover the plastic from the environment after use (e.g. tree shelters, agricultural mulching films, or fishing gear) [17, 65, 67, 205, 209-212].

Novel bio-based biodegradable polymers are also of interest for other applications such as synthetic rubbers, textiles, and polymers in liquid formulations (PLFs) (Table 6 and Table A5) [19, 27, 28, 153, 213-216]. There is particular interest in novel bio-based, biodegradable and non-toxic PLFs because many PLF applications, such as personal care and cleaning products, paints, and adhesives, make them hard to recycle or result in PLFs entering the environment or wastewater treatment systems where they tend to break down very slowly [19, 26, 27].

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[18] It is important to note that biodegradable is not synonymous with biobased: not all bio-based plastics are bio-degradable and not all bio-degradable plastics are bio-based.

Another potential benefit of novel bio-based chemicals is that some can be used to replace particularly toxic or hazardous organic chemicals, such as plastic additives, formaldehyde resins, and some solvents (Table 6 and Table A6) [9, 38, 111, 112, 168–173, 217–219]. For example, promising bio-based solvents include cyrene and ethyl lactate, both of which can potentially replace solvents such as dimethylformamide (DMF), a known liver toxin, in some applications. Production of cyrene has been demonstrated at pilot scale and a commercial plant is under construction [112, 166]. Ethyl lactate is already used in paints and coatings, gums, food additives, and cosmetics, and industrial cleaning [35, 57, 165].

There are many other examples of novel bio-based chemicals, such as novel bio-based surfactants, fine and speciality chemicals such as new dyes and pharmaceuticals, and functional materials with applications in electronics and heat storage [220, 221] (Table 6 and Table A6). Another interesting example is bio-bitumen, which is already undergoing trials for use in road and pavement surfacing [15, 188, 222]. Rather than trying to recreate the mixture of hydrocarbons in bitumen, bio-bitumen is based on novel bio-binders made from lignin or from bio-oils [190, 191, 223]. On top of the vast array of novel bio-based chemicals that have been developed, there are a number of promising novel platform chemicals which offer routes to many useful bio-based products, mirroring the approach taken in the existing chemicals industry (Table A2) [24, 82, 206, 224].

Despite the opportunities associated with novel bio-based chemicals, many still face significant barriers to commercialisation and widespread uptake. Like drop-in bio-based chemicals, many novel bio-based chemicals come with a high price tag, and unlike drop-in products they always rely on new markets developing and new technologies being deployed [24, 75, 114]. Additionally, the new chemistries in novel bio-based products can in some cases be a disadvantage, restricting use in certain applications, reducing the likelihood of uptake by industry, or impacting environmental or economic performance. For example: biodegradable plastics often have poor mechanical properties compared to conventional plastics (e.g. more brittle) [69]; some novel bio-based solvents are more viscous or less stable than conventional solvents [75]; and some forms of bio-bitumen appear to age or fracture more rapidly than fossil bitumen [173].

2.4 Biorefineries

A biorefinery is a dedicated facility for producing chemicals or fuels from biomass, using the kinds of technologies described in Table 5, but the term is often used specifically to refer to a system that makes a range of products and/or energy carriers (e.g. power, fuels) rather than a single product [56, 57, 70, 225]. Though in some ways this kind of integrated biorefinery approach is analogous with an oil refinery, it is in fact more complex: rather than just separating the feedstock components as an oil refinery does, a biorefinery converts a single feedstock into multiple products. An integrated biorefinery allows multiple valuable products to be obtained from a biomass feedstock which can improve the environmental and economic performance [104]. There are already hundreds of biorefineries operating around the world (e.g., the Bazancourt–Pomacle Biorefinery described below) [69, 70, 226].

The economics of a biorefinery is influenced by factors such as the technology pathway, operational decisions, location, products choice, energy requirements, yields, and the feedstock [57, 77, 94, 104]. Significant upfront investment is also required to scale up technologies and build biorefineries and infrastructure [57, 65, 71, 77, 204]. Biorefineries face inherent difficulties in feedstock acquisition and logistics, because biomass is more expensive to transport than petroleum and biomass resources are often widely distributed and, in some cases, seasonal [77, 227]. These place more limits on size in biorefineries than their petroleum refinery analogues, resulting in a higher capital expenditure requirement per tonne of product and therefore increasing cost [77]. The restrictions on achieving economies of scale, coupled with the need to build new infrastructure and the uncertainty around future demand for bio-based products, mean that biorefineries are a high-risk investment.

Moving toward a higher intensity processing environment, like that of the existing chemical industry, could help to overcome some of these limitations. This can be supported through the development of integrated biorefineries and co-location of facilities, mimicking the approach taken by the existing chemical industry, and often through deployment of thermochemical or chemical technologies instead of biological ones. Some of the logistical and economic challenges faced by biorefineries could also be addressed by creating feedstock flexible biorefineries and enabling the use of a greater variety of feedstocks such as lignocellulosic material, wastes, and residues [77]. To this end, significant effort is going into developing new cost-effective pre-treatment processes for lignocellulosic biomass [78, 79, 228, 229]. Some lignocellulosic biorefineries are now operating at commercial scale (e.g., lignocellulosic ethanol production) and there are more in the pipeline, but economic viability remains a challenge [57, 69, 128, 228, 230-233].

BAZANCOURT–POMACLE BIOREFINERY

The Bazancourt–Pomacle Biorefinery in France begun as a sugar refinery [234]. It is now a truly integrated biorefinery, converting 4 Mt biomass a year into chemicals, fuels, and food and feed ingredients [235, 236]. It utilises biomass from the surrounding region, benefiting the local agricultural economy, and was developed with the support of local farming cooperatives [73, 112, 235]. Multiple companies now operate at the site reaping the benefits of co-location such as sharing of intermediates, reduced waste, and lower energy consumption, as is commonly seen in the petrochemical industry [235]. There is also a multidisciplinary research centre on the site to support innovation and translation of new biomass utilisation approaches. The biorefinery has attracted large amounts of investment into the region, and directly employs 1,200 people and supports a further 800 jobs indirectly.

2.5 Transitioning to a bio-based chemical industry

There is growing interest in the use of biomass for chemicals because of the desire for more sustainable products. The transition to a more bio-based chemicals sector may also offer several social and economic benefits, through new industry, green jobs, and novel products that address societal need. Despite this, bio-based chemicals account for just a small portion the chemical products we use today [15, 69, 111]. The scientific literature reveals a vast array of bio-based chemicals that have been produced in labs, and Table 6 demonstrates there are already numerous examples of products that have been successfully scaled up and commercialised. However, most bio-based chemicals remain at the research and development stage and there are several challenges that must be overcome if the use of biomass in the chemical industry is to increase.

As mentioned in Part 1, the need to compete with products of the established petrochemical sector – with its established supply chains and markets, cheap feedstocks, and optimised and efficient systems which have developed over the course of more than a 100 years is a challenge for all renewable chemicals including those derived from biomass [1, 17, 65, 66]. In most places around the world, the policy landscape does nothing to incentivise the production of bio-based chemicals or enable sustainable chemicals to compete with fossil-based products. In fact, the use of fossil fuels is still heavily subsidised. Bio-based chemicals also face ongoing uncertainty around their climate and environmental impacts (see Part 3) and whether there is enough feedstock available for the chemical sector to use (see Part 4). Some bio-based systems face technical challenges which must be overcome through further research and innovation to create systems that are feasible and economically viable at scale, and there are common challenges associated with the scale up and deployment of new technologies. Highlighted below are some key barriers to a bio-based chemicals industry, based on those reported in the literature and our engagement with stakeholders [1, 8, 17, 57, 65, 69, 95, 111, 204, 237].

BARRIERS TO INCREASED USE OF BIOMASS FOR CHEMICALS PRODUCTION

- Higher cost than fossil-based alternative
- New infrastructure and large, high-risk capital investments
- Uncertain sustainability impacts
- Concerns around feedstock availability and sustainability
- Feedstock heterogeneity, seasonality, and distribution
- Low TRL technologies
- Challenges scaling up and deploying new technologies
- Lack of appropriately skilled workforce
- Lack of awareness of the GHG impact of fossil-based chemicals
- Lack of policy support in many regions of the world

The discussion earlier in this chapter highlighted the different ways that biomass might be used in the chemical sector moving forwards, and these come with their own benefits and challenges. Biomass may increasingly be used in products and processes that replicate those found in the current petrochemical industry. This would limit the need for new infrastructure and yield the same products consumers use now, but the reality is that this industry has evolved and optimised around the use of fossil feedstocks, meaning bio-based chemicals will struggle to compete. Alternatively, a more disruptive approach may be taken, based around novel bio-based products and biorefineries. This approach could result in a chemical system that is better suited to using biomass feedstocks, that allows for more efficient biomass use and expands the variety of valuable organic chemicals and materials beyond those we are familiar with today. However, it also demands the scale up and deployment of new technologies and the development of new markets, so will likely be slower and more difficult than a drop-in approach.

The extent to which the chemicals sector moves from fossil to biomass feedstocks in coming years will depend on the action that is taken to address the barriers described overleaf. Widespread replacement of fossil feedstocks with sources of renewable carbon such as biomass is unlikely unless policies are put in place that encourage this transition, for example by placing value on sustainability for bio-based products, or encouraging investment and innovation [1, 2]. The policy and regulatory landscape will influence which of the many different bio-based products and technologies are feasible, desirable, and successful in the future, but this will also depend on factors such as the economics, energy consumption, and environmental impacts of different systems, as well as feedstock availability, location, and consumer demand.

PART 3: EXAMINING THE SUSTAINABILITY OF BIO-BASED CHEMICALS

3.1 Greenhouse gas emissions

Replacing fossil feedstocks with biomass feedstocks in chemicals manufacturing can reduce emissions because the embedded carbon released during production and at end of life is biogenic, meaning it is the carbon captured from the atmosphere during biomass growth (Figure 8). Although this biogenic carbon cancels out when calculating emissions, the net life cycle emissions of bio-based chemicals are not necessarily zero because there are emissions related to biomass feedstock production, transport (of feedstocks, intermediates, and products), auxiliary inputs (e.g., other chemical reagents added during conversion), and energy requirements of processes (Figure 8). To determine if a bio-based chemical results in GHG emission savings compared to the equivalent fossil-based chemical (i.e., the product that is being replaced, sometimes referred to as the counterfactual), life cycle assessment (LCA, see page 30) is used to calculate and compare the life cycle GHG emissions of the two products.

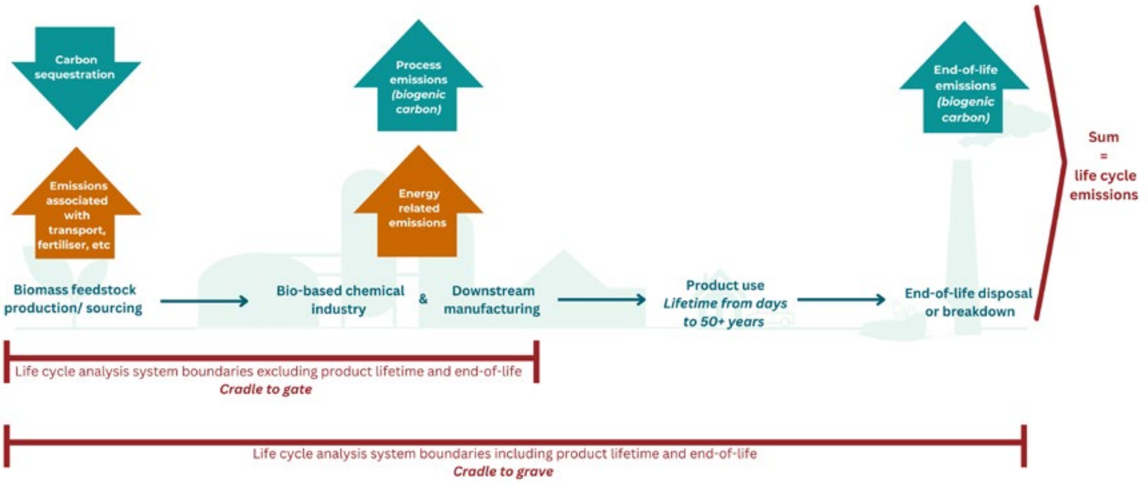

Figure 8. GHG emissions associated with the bio-based chemicals and materials, with red showing life cycle analysis considerations

In order to assess the GHG performance of bio-based chemicals compared to conventional fossil-based chemicals we reviewed the literature to collate GHG data for several bio-based platform chemicals, intermediates and plastics, and their fossil-based counterfactuals. A description of the literature review approach and full lists of the data collated are included in the appendix. Figure 9 shows ‘cradle to gate’ GHG emissions intensity data for bio-based and fossil-based chemicals [19]. The data in Figure 9 demonstrates that some bio-based chemicals and materials reduce GHG emissions compared to fossil-based products, and these reductions can be significant, but decreased emissions are not universal. This reflects the findings of other studies [65, 69, 238-250]. Figure 9 also demonstrates a problem that has been repeatedly highlighted in the literature: different studies often report strikingly different GHG values for the same bio-based product [57, 65, 238, 239, 251, 252].

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[19] Cradle to gate assessment includes GHG emissions generated up to the point where chemical products exit the factory, meaning downstream emissions such as those associated with end-of-life, are not included (see Figure 8). Cradle to gate data is used here because in many cases LCA data that includes the emissions across the whole lifecycle (i.e., cradle to grave) is not available.

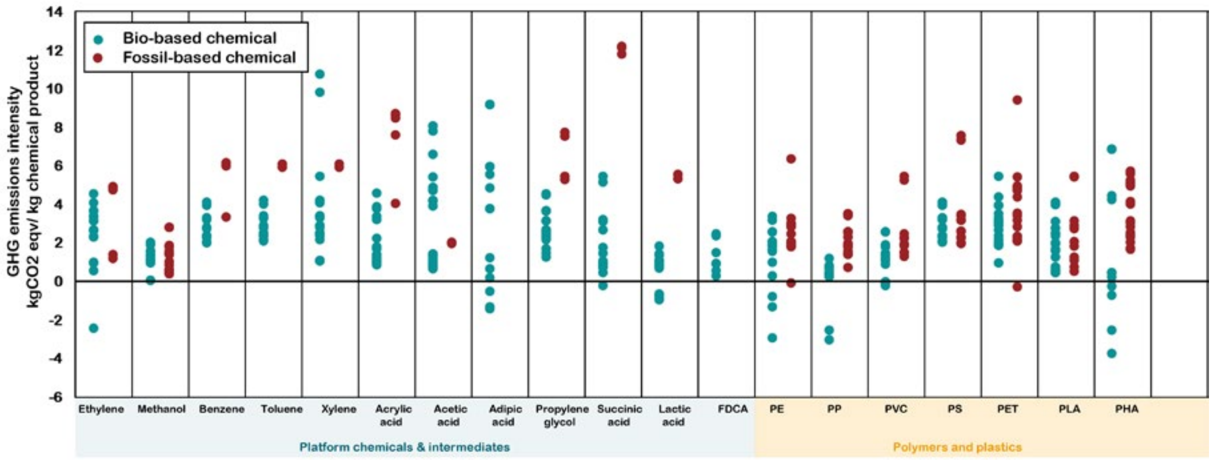

Figure 9. Climate change performance values ($kgCO_2\,^{eqv}/kg$) of bio-based (green) and fossil-based (red) platform chemicals and polymers gathered from the literature (see supplementary document). Each point reflects cradle to gate LCA data from an individual study. Acronyms represent: 2,5-Furandicarboxylic acid (FDCA), Polyethylene (PE), Polypropylene (PP), Polyvinyl Chloride (PVC), Polystyrene (PS), Polyethylene terephthalate (PET), Polylactic acid (PLA), Polyhydroxyalkanoates (PHA). Xylene is the para-xylene isomer.

The differences in GHG emissions reported can be due to differences in the LCA methodology or the details of the system being assessed (e.g., the feedstock or technology). Differences in LCA methodology and assumptions can make it impossible to accurately compare different LCA studies (see page 30), but even when consistent LCA approaches are applied the reality is that some variation in the potential GHG savings will always exist. Variation is also seen in products derived from fossil feedstocks (e.g., PET in Figure 9) carbon dioxide or recycled material, and biofuels and hydrogen [52, 58, 59, 63]. Although the variation in the climate impacts of bio-based chemicals is the cause of some hesitancy when it comes to implementing bio-based products, it would be more beneficial to focus on how technology developers and policymakers can develop or incentivise those products that deliver GHG savings over those that do not.

The array of LCA data that exists in the literature already provides some general rules that tend to maximise GHG savings associated with bio-based chemicals:

- **Use low-emission feedstocks**
  Emissions associated with feedstock production can significantly impact on life cycle GHG emissions of a bio-based product [109, 112, 216, 238, 243, 244, 246, 247, 249, 253]. Feedstocks produced through intensive agronomy (e.g., high fertiliser inputs), often arable crops, tend to have higher associated emissions than lignocellulosic biomass and wastes (though current pre-treatment processes can add significantly to the emissions of some lignocellulosic feedstocks). If land use change is considered, it can significantly increase the emissions associated with some feedstocks [109, 238, 240, 254]. The worst-case scenarios, where the production of a feedstock results in the large-scale release of previously stored carbon (e.g., clearing land or degrading soils), mean that any benefits gained through replacing a fossil-based product may be negated. Therefore, to improve life cycle GHGs priority should be given to resources that have not resulted in land use change, and ideally where excessive energy and resources have not been expended in the feedstock's growth, production, collection, and pre-treatment.
- **Replace fossil-based products that have high lifecycle emissions**
  Greater GHG savings tend to be possible for bio-based products replacing fossil-based product with high life cycle GHG emissions [109, 242].
- **Maximise energy efficiency**
  Energy generation results in GHG emissions and so the more energy used to make a bio-

based chemical, the greater the life cycle emissions. This is particularly important given that we still rely on fossil fuels for much of our electricity and heat. Higher GHG emissions are associated with processes requiring high heat or pressure, and products that require many synthetic steps. The pre-treatment processes that are necessary for lignocellulosic feedstocks can also significantly increase energy consumption, as can the extensive downstream processing required to extract and purify some bio-based products [104, 174, 238]. Thus, the energy demand and efficiency of conversion processes can have a significant impact on overall GHG performance. Value chains with lower active energy demands will almost always have achieve better overall GHG impacts compared to those needs significant energy (e.g., for processing, heat, or transportation).

- **Maximise biomass utilisation efficiency**
  Efficiency of biomass utilisation can have large influence on the GHG performance of a bio-based product. Systems designed and optimised for resource efficiency will achieve GHG performances exceeding that of less efficient systems. For example integrated biorefineries that have been designed to reduce waste and produce multiple products tend to outperform less well integrated systems, and bio-based products retaining chemical structures found in biomass tend to have greater biomass utilisation efficiency and thus lower emissions [2, 108, 109, 111, 216, 238, 241, 253].

The performance of a novel bio-based chemical compared to the fossil-based equivalent can also significantly affect the GHG savings achieved. For example, if the properties of a new bio-based material mean more of it is required to achieve the same function compared to the fossil version, this will decrease the overall GHG benefit. End-of-life fate can also significantly impact the GHG emissions, as it does for fossil-based chemicals [243, 253, 255]. This is particularly important if the bio-based product is dealt with differently at end-of-life or breaks down differently from the alternative fossil-based chemical. For example, the GHG performance of many biodegradable plastics is reliant on proper end-of-life management because if biodegradable items enter landfill sites they can break down into methane, which is a more potent GHG than carbon dioxide [249, 256].

LIFE CYCLE ASSESSMENT OF BIO-BASED CHEMICALS

Life cycle assessment (LCA) is a tool that can be applied to determine and compare the environmental impacts of bio-based and fossil-based chemicals [112, 257, 258]. LCA involves consideration of the energy and mass inputs and outputs of processes within the system boundaries that have been set. It is commonly used to assess the life cycle GHG emissions but can also be applied to other environmental impacts such as water consumption.

LCA can be used to validate the impacts of products and support decision making and if applied throughout the technology development process it can identify hotspots and enable improved GHG performance of the resulting bio-based chemicals. However, there are some issues to be considered for it to be robustly applied and accurately interpreted [243, 248, 252, 259, 260]:

- LCA can be performed with different system boundaries, either covering the whole life cycle of the product from feedstock extraction or production to end-of-life treatment (referred to as cradle to grave), or focusing on just a portion of this life cycle (e.g., from feedstock extraction or production to when the product leaves the factory, which is referred to as cradle to gate) (see Figure 8) [65, 112, 258].
- The approach to dealing with counterfactuals in LCA can have a large impact on the GHG performance of biomass systems [254, 261]. Counterfactuals is a term used to describe products or activities that have been mitigated or replaced by the bio-based product. Examples may include the fossil-based chemical that is replaced, or what would otherwise

have happened to the land or resource if it was not used to produce feedstock (e.g., would the land have reverted to a natural system, storing high levels of carbon in the process, or have been used for arable crops and released stored carbon). In certain circumstances where the production of a bio-based chemicals mitigates high counterfactual emissions (e.g., using biogenic wastes that would have biodegraded and released methane) based on the assumption applied, these avoided emissions may result in LCA results with negative emissions values, which in this case does not necessarily indicate net removal of carbon from the atmosphere.

- There is no standard method for considering temporal aspects of carbon, such as temporary storage in materials LCA, or for accounting for biogenic carbon across the life cycle [238, 259, 260, 262-264].
- True understanding of the GHG performance of a system requires realistic, industrial-scale data [57, 65, 112, 238]. Many bio-based chemicals are at low TRL, meaning this can be challenging. Assessment of industrial processes is also hampered by the confidential nature of the data required.
- LCA does not necessarily reflect the performance under optimised conditions or consider the impacts of wider system changes that are likely to occur in coming years, such as increased decarbonisation of the electricity grid which may reduce the emissions of some products more than others [238, 265].
- Most LCA that is carried out is attributional LCA, which considers the life cycle and supply chain of an individual product. However, if we want to truly understand the global impacts of a new technology or product, we need to look at the bigger picture using a consequential LCA approach, which is much more difficult [258].
- Differences in LCA methodology often make it impossible to directly compare different studies [57, 109, 240]. Harmonisation in LCA methodologies of similar products made via similar production pathways would be hugely helpful for those trying to compare products and make decisions. However, LCA is a tool and depending on the goal or the question you are trying to answer different methodologies may be most applicable [266]. We need to be particularly careful when comparing products with different functionality and products made in different ways because there may be product or technology specific reasons why certain methodological choices are made. The issue of different methodologies is compounded by a lack of transparency, as details of assumptions, data, and methodology are often not readily available (e.g., from suppliers or in publications). This problem is not limited to bio-based chemicals.

3.2 Negative emissions

Negative emission technologies such as bioenergy with carbon capture and storage (BECCS) are critical for many of the climate mitigation pathways that limit global warming to 1.5°C or even 2°C [74, 267]. The negative emissions these scenarios rely on come from permanent removal of GHGs from the atmosphere; for example, BECCS results in permanent geological storage of the biogenic carbon dioxide emitted during bioenergy processes [267, 268]. Climate mitigation scenarios do not yet consider negative emissions associated with bio-based chemicals and materials [74, 262, 263, 269, 270].

Permanent storage of biogenic carbon could be achieved through integration of bio-based chemicals with carbon capture and storage (CCS) in an approach like that seen for BECCS (Figure 10). Process emissions from bio-based chemical manufacturing or emissions from end-of-life incineration of bio-based products could be captured and then stored in underground reservoirs (Figure 10). Bioethanol production is an excellent example of how CCS can be applied to bio-based chemicals. During ethanolic fermentation, 30% of the carbon from the sugars is released as carbon dioxide, which is well suited to integration with CCS because it is very pure. There are already examples of bioethanol production with carbon capture in the USA but deployment of CCS at scale is still limited [267, 271].

Making chemicals from biomass embeds biogenic carbon in the chemical products. The lifetime of products and how they are dealt with at end-of-life determines how long the biogenic carbon is stored for [6, 17]. Many chemical products have short lifetimes, meaning embedded carbon will be released as GHG emissions within a year of manufacture if they break down or are incinerated. On the other hand, some chemical products, such as those used in construction, can have lifetimes or several decades. The storage of biogenic carbon in bio-based chemicals and materials is considered by some to be a potentially important form of negative emissions, but there is not yet a consensus on how this kind of temporary storage should be accounted for in LCA and modelling, with different studies treating it very differently [3, 6, 10, 45, 262, 269, 270]. Although temporary storage in long lifetime products is not the same as permanent negative emissions, it can delay the climate impacts by decades and thus help to prevent global temperatures from passing irreversible tipping points while other sectors decarbonise [260, 262].

Some studies have discussed the potential for negative life cycle emissions through landfilling of bio-based but non-biodegradable plastics, essentially extending the temporary storage of carbon in materials [3, 6, 10]. There still appears to be debate amongst researchers we talked to about the validity of this approach, and the wider challenges of landfill must also be acknowledged. For example, landfill capacity is limited and improper management of landfills can result in leakage into the environment and methane from biodegradation of biogenic waste [17, 25].

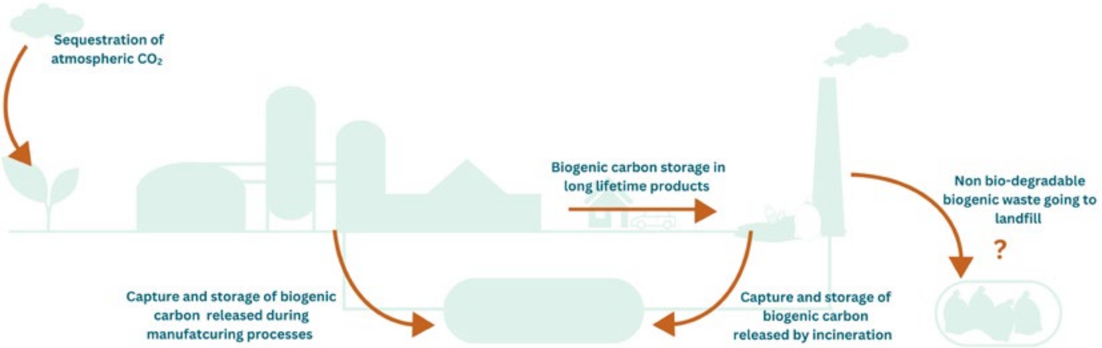

Figure 10. Potential routes to negative emissions from bio-based chemicals and materials

The data in Figure 9 includes several net negative GHG emissions values, but careful interrogation of the LCA methodology and data is required to determine if these reflect systems that truly deliver permanent removal of carbon from the atmosphere. The amount of carbon permanently stored must exceed that emitted across the whole product life cycle, and it is essential to understand the system boundaries used and how temporal aspects and counterfactuals are accounted for [254, 267]. The data in Figure 9 is cradle to gate LCA, and this excludes emissions associated with use and end-of-life and so does not consider the release of the embedded carbon. This means a negative GHG emission value might simply reflect the storage of carbon over the short lifetime of a product. Unfortunately, lack of transparency around the methods and assumptions used often mean it is not clear if these methodological factors explain negative emissions values from LCA, and this is the case for several of the studies represented in Figure 9. Certain LCA methods and assumptions can also yield negative emissions for studies of fossil-based chemicals (see Figure 9). However, it is important to be clear that the use of fossil carbon can never result in net transfer of carbon from the atmosphere to storage and negative emissions values from fossil-based chemicals can only be down to the LCA method applied.

3.3 Greenhouse gas impacts of a bio-based chemicals sector

Models that describe the energy system have supported policymakers in developing pathways for climate mitigation through its decarbonisation, but to date there has been less success doing this at a whole system level for chemicals. The nature and complexity of the chemicals sector and the issues around data availability can make this kind of assessment challenging. Such models also require evidence of the GHG emissions reduction potential of bio-based chemicals, and in many cases, there is insufficient LCA data available (see appendix). Additionally, standard climate mitigation models are designed to assess energy systems, and so tend not to account for the temporary storage of carbon in chemicals and materials and the temporal aspect this brings to the life cycle emissions of both fossil-based and bio-based products [17, 41, 260, 262].

The emissions related to chemicals and materials occur outside the bounds of the chemical industry, and the same will be true for the GHG benefits of bio-based chemicals. The international trade of feedstocks, intermediates, products, and wastes also means that across the life cycle of a chemical product, GHG emissions might occur in different regions of the world [272]. This poses an additional challenge if you want to understand the impacts of scaling up production of bio-based chemicals in a particular country or region. What matters from a climate change perspective is the overall change to GHG emissions, but the overall reductions may not necessarily be reflected in the territorial emission accounting of a particular country. For example, if new bio-based chemical manufacturing in the UK displaces manufacturing of fossil-based chemicals that occurred elsewhere in the world, it could result in a decrease in GHG emissions from the global chemical system at the same time as an increase in the UK's territorial emissions since the decrease in emissions from the fossil-based production happened elsewhere.

There are some interesting examples in the literature of models that have been used to assess the transition to a more sustainable global chemical system, which show that bio-based chemicals can help reduce emissions and that using biomass could even contribute towards the chemical system becoming a net carbon sink [3, 6, 10, 45]. These models also show that greater negative emissions across the system can be delivered by increasing the amount of biomass used and prioritising the storage of carbon at end-of-life (e.g., through CCS or landfill), indicating that to maximise GHG benefits of bio-based chemicals there is a need for an approach to carbon management that considers the whole life cycle of products, including how they are dealt with at end of life [6, 45]. However, we will always need carbon to make chemicals, and though sequestering biogenic carbon underground can result in negative emissions, it also means the biogenic carbon cannot be used again. This creates greater demand for virgin feedstocks for the chemical industry. If more virgin fossil feedstock is being used, the negative emissions from the biomass would be offset by the emissions stemming from the use of fossil carbon. Increased demand for biomass feedstocks may result in increased negative emissions, but there may also be negative sustainability impacts associated with very high demand for biomass feedstocks [6, 45]. Recycling bio-based products at end-of-life instead of capturing the carbon reduces the demand for virgin feedstocks of any kind, but it also does not deliver negative emissions if the carbon ends up being released back into the atmosphere at some point [6, 45]. All of this demonstrates the need to go beyond individual attributional LCA of single products and take a systems approach to carbon management for chemicals that also considers wider environmental impacts. The systems modelling that has been reported in the literature indicates that the optimum approach will be a circular bioeconomy that combines steps to manage levels of production and demand, increased circularity (recycling, reuse, etc.), biomass and carbon dioxide use, and carbon sequestration (i.e., negative emissions) [3, 6, 45].

3.4 Sustainability beyond greenhouse gases

Discussions around sustainability of bio-based chemicals often focus on the climate impacts, but it is important to also consider the broader environmental, economic, and social consequences of bio-based chemicals. The nature of the industry, products, and feedstocks means these impacts can be wide ranging, relating to issues such as land, nature, health, development, jobs, and equality [273, 274]. As with all biomass systems, there is potential for both sustainability risks and benefits from activities at each life cycle stage from feedstock production through to the eventual use and disposal of products.

As outlined in Part 1, the organic chemicals play many important roles in society, but their production and consumption can also have negative consequences, for example due to hazardous chemicals in products, pollution, and health impacts in fence line communities. Part 2 demonstrated that some novel bio-based products and new associated technologies might avoid these environmental and health risks. It is important to be clear that not all new products and technologies will deliver such benefits, and some come with their own risks. Evidence on the performance and impacts of any new products and technologies is important to avoid regrettable substitutions.

Consideration of feedstock sustainability is also critical for bio-based products. Different biomass feedstocks come with different sustainability risks and benefits. Concerns are often raised about the impacts of land use change, such as biodiversity loss, habitat destruction, deforestation, competition with other land uses, negative impacts on vulnerable, marginalised, and indigenous communities, and even land use related conflict [238, 240, 273, 275]. Palm oil, which is a major feedstock for the oleochemical industry, is a well-known example, where increased demand has led to deforestation and biodiversity loss [276]. When it comes to cultivation of arable crops, which make up a significant proportion of the biomass used for chemicals, there are risks associated with water availability, eutrophication, acidification, and the use of toxic pesticides, and concerns about competition with food production [45, 65, 109, 238, 239]. On the other hand, some biomass feedstocks deliver benefits beyond the potential GHG emission savings, such as jobs and economic growth in rural areas due to feedstock cultivation, reduced risk of forest fires due to sustainable forest management, or mitigation of negative impacts from poor waste management [273]. Depending on scale, location, and agronomy, perennial biomass crops can also offer opportunities for ecosystem services, such as improving biodiversity and soil carbon or reducing flood risks [277, 278].

What all of this tells us is that although biomass can support the transition to a more sustainable global chemical system, there are risks that must be addressed. Some products and technologies may come with lower GHG emissions and offer opportunities to help address other issues such as toxicity or pollution, but in other cases there may be trade-off to navigate between GHG emissions and other impacts. Care must be taken to deliver maximum benefits whilst also ensuring that they do not come at the cost of significant harm to people or the environment; it is here where policy and regulation will have an important role to play [45, 238, 273, 274].

PART 4: PRIORITY USES OF BIOMASS

Estimates suggest that 550 Mt carbon is embedded in chemicals and materials every year, 480 Mt of which is currently fossil carbon [15]. If business as usual continues, demand for chemicals and materials will increase significantly in the coming decades, meaning more carbon will be needed to make chemicals in the future [3, 6, 8, 10, 15]. The International Energy Agency (IEA) estimated that if all primary chemicals were to be produced from biomass in 2050, it would require roughly half of the world's sustainable biomass [8]. Sustainable biomass is a limited resource, but biomass is unlikely to be the only renewable carbon source used by the chemical industry in the future, and the total amount of carbon required for chemicals could be reduced if measures to limit production of chemical products are introduced [2, 3, 6, 10, 15, 45]. The real challenge in terms of sustainable biomass availability for chemicals is actually the fact that the chemical industry will not be the only sector looking to use biomass feedstocks in the future. As well as being a feedstock for chemicals, biomass is expected to play an important role in decarbonising energy systems and transport, as well as providing negative emissions through BECCS. There will be insufficient sustainably sourced biomass to fulfil all these applications in the future, and so it will be necessary to make decisions about which applications are the highest priority.

4.1 Priority uses of biomass

The best use of biomass depends on what the main objective is. The major driver for uptake of biomass and bioenergy systems is the potential to support climate change mitigation. To maximise the contribution to climate mitigation efforts, biomass use should be prioritised in [74]:

- **Applications that deliver the greatest reduction in emissions compared to the counterfactual**
  This will tend to be those where the counterfactual product or scenario has particularly high emissions, and systems that are more efficient in terms of energy use and biomass conversion.
- **Applications and sectors that cannot be decarbonised in other ways**
  This will include energy applications where alternatives such as electrification or hydrogen fuels are not suitable or not yet available. This will be dynamic: as new technologies develop the demand for biomass in different sectors will change, and the priority uses of biomass will likely change. For example, biofuels can reduce emissions from road transport in the near term, but as the road fleet is increasingly electrified this will become less important.
- **Applications that provide opportunities for negative emissions**
  Negative emission technologies are likely critical to meeting climate targets moving forwards, meaning applications of biomass that offer the potential for negative emissions are likely going to be high priority for governments moving forward.

The use of biomass as a carbon source for the chemicals sector is sometimes excluded from conversations around biomass use prioritisation or seen as secondary to energy applications. However, according to the principles described here, the chemical industry should be a priority sector for biomass use: there are limited alternatives for addressing the emissions stemming from carbon in chemicals because carbon-based chemicals and materials cannot be decarbonised; bio-based chemicals can deliver significant GHG emission reductions; and there are opportunities for negative emissions.

4.2 Priority uses of biomass within the chemical industry

Using the same principles applied to the discussion on prioritisation across different sectors, it also makes sense to prioritise the development of certain bio-based chemicals and materials to maximise the benefits delivered.

For maximum climate benefit, biomass use should be prioritised for chemicals and materials that deliver the greatest GHG savings. It is important to consider both the extent of the GHG savings compared to the counterfactual, and the total GHG emission reductions that might be achieved based on the global demand for a particular product. As described in Part 3, maximum emissions savings can be achieved by using low emission feedstocks and efficient products and processes, and replacing high emission products. Novel chemicals that retain the kinds of chemical structures found in biomass, tend to have higher utilisation efficiency and therefore greater GHG savings than many drop-in products. However, many of these novel products service relatively small markets and this limits the total GHG emission reductions that can be achieved. The greatest contribution to climate mitigation overall would likely be achieved through some combination of the two types of product [109].

Prioritising biomass for negative emission chemicals is more complex. Part 3 showed that negative emissions can be temporarily achieved through carbon storage in long lifetime bio-based chemicals. It may, therefore, seem sensible to prioritise biomass use in long lifetime products. However, consideration of the carbon flows at a system level seems to suggest that the potential for carbon storage across the chemical industry is determined by the proportion of biomass feedstock used and the proportion of long lifetime products, regardless of whether the biogenic carbon is actually used in the long lifetime products (see Figure 11). As far as we can tell, this is not at odds with the systems modelling that has demonstrated the potential for the chemical industry to become a carbon sink [3, 6, 10]. It seems that rather than prioritising bio-based chemicals with long lifetimes, the greatest benefit may be achieved by focusing on those which deliver the greatest emissions reductions compared to the fossil-based product and displacing the greatest volume of fossil feedstock overall. A similar argument could be made for negative emissions achieved by integration with CCS, and even for BECCS in the energy system. However, it is easier to incentivise and account for negative emissions if they can be tracked across one supply chain, where you can demonstrate that carbon has been removed from the atmosphere and then put underground. This is incredibly important when it comes to building trust in negative emission technologies, but also in ensuring that systems are designed and deployed in a way that delivers net carbon storage. This might also be true for carbon storage in products, but there is no consensus on this within the research community yet, and it seems that the question of whether biomass use would be best prioritised in long lifetime products demands further investigation.

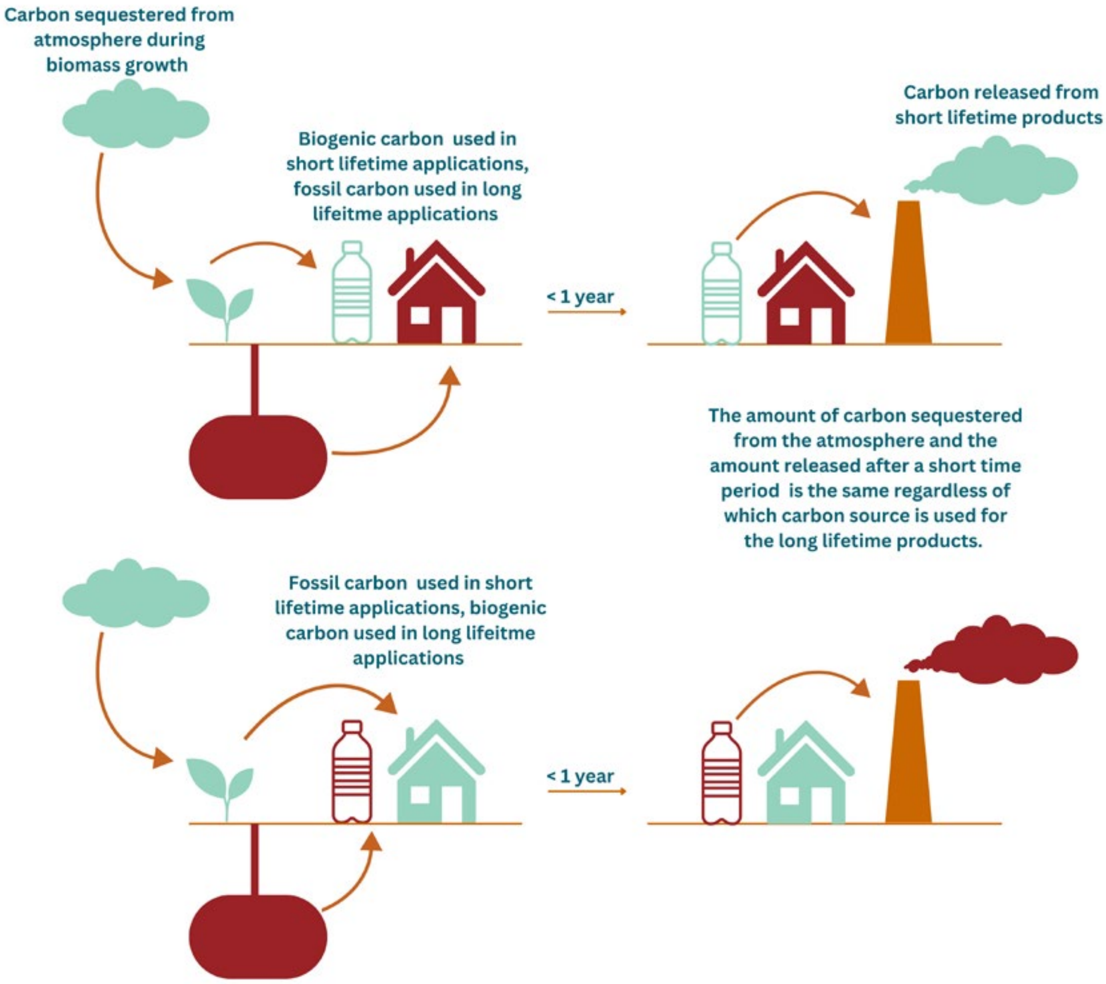

Figure 11. Systems view of the impacts of using biogenic carbon in long lifetime products

Although much of the interest in bio-based chemicals is driven by the potential climate benefits, prioritisation may also be influenced by factors such as market demand, economic viability, local context, and decisions around the kind of chemical products that are desirable in terms of wider environmental and social impacts (see Table 7). Again, the best use of biomass will depend on what the main objective is. There will likely be trade-offs to navigate because the bio-based products that deliver greatest benefit for the climate are not necessarily those that would be best for other objectives such as jobs, economy, or environment.

Furthermore, biomass use should be considered in the context of a chemical system based on a circular bioeconomy. Rather than simply thinking about how to gain the most benefit from using biomass, we need to think about carbon management and how different feedstocks and technologies can be optimally deployed to create a sustainable chemical system. For example, biomass use could be prioritised where it offers a particular benefit over recycled material, such as in the production of complex molecules that make use of the existing structures in biomass feedstocks that are not present in other forms of renewable carbon. The best source of renewable carbon will vary by location, technology, and product, and will change over time as new technologies, both for biomass and the wider circular bioeconomy, come online [1].

Prioritising biomass use in certain chemical applications could enable greater benefits, but different stakeholders in the chemicals space will have different drivers and objectives. So, if governments do not intervene to encourage biomass use in priority applications that deliver the greatest benefit for climate, society, or the environment, industry and the markets will decide and the outcomes may be different.

Table 7. Examples of approaches to prioritisation of different bio-based chemicals and materials according to the main objective of biomass use.

Climate change mitigation	• Products that deliver maximum GHG savings (e.g., those with high biomass utilisation efficiency or that displace high emission fossil-based products, such as adipic acid). • Products with large potential markets (e.g., drop-in replacements for the major global plastics or primary chemicals). • Products that can be integrated with CCS during manufacturing (e.g., bioethanol or biomethane (and their derivatives))[20]. • Products that offer greater GHG savings than alternative routes based on recycled material or carbon dioxide. • Long lifetime bio-based products (e.g., bio-based polymer composites, bio-based plastics for construction, and bio-based bitumen for road surfaces) (subject to the questions discussed in the main text).
Non-carbon benefits	• Novel products that can replace toxic or hazardous organic chemicals (e.g., safer plastic additives and solvents, and alternatives to formaldehyde resins). • Biodegradable products and plastics (e.g., PLA for use in hard-to-recycle packaging applications, or biodegradable PLFs). • Novel products that have other societal benefits (e.g., novel bio-based pharmaceuticals, nutraceuticals, or agrochemicals, • or insulating materials that can improve energy efficiency in homes). • Recyclable materials that can support the circular economy (e.g., bio-based PET or PEF).
Use of available feedstocks	• Products that are readily made from the feedstocks that are underutilised or most readily available in a particular region. • Regions which have less feedstock available may prioritise efficient conversion of feedstocks (e.g., novel products that retain chemical complexity from biomass) and low-volume, high-value products to create benefits from smaller pools of resource. • Products that utilise co-products and waste streams from other important biomass applications (e.g., bio-naphtha or bio-glycerol co-products from some bio-fuel production).
Near-term benefits	• Mature or high TRL products or technologies (e.g., bioethanol/ bioethylene derivatives). • Biomass balance products. • Products where there is clear consumer pull and interest from industry (e.g., ingredients that will be used in home care products and cosmetics, such as fragrances, surfactants, and PLFs).
Economics	• Bio-based chemicals that demand less capital investment or deliver the greatest profit.
Resource security and resilient supply chains	• Bio-based products that utilise a country's domestic resource or allow domestic production to replace vulnerable international supply chains of a fossil-based chemical.
Growth and jobs	• Products that would help maintain existing chemical industry and jobs, based on the manufacturing and supply chains already in place. • Products that best utilise a region's knowledge, skills, and technology development expertise. • Products that can support the sustainability targets of other important manufacturing sectors, such as automotive production.

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20 Both ethanolic fermentation and anaerobic digestion produce carbon dioxide as a by-product and systems with CCS integrated are relatively well developed.

PART 5: BIO-BASED CHEMICALS IN THE UK

5.1 The UK chemical system

Figure 12. Major UK chemical industry clusters

The UK chemical sector is well-established and diverse. It comprises thousands of companies which support hundreds of thousands of jobs, and it adds significant value to the economy [16, 279, 280]. UK chemical production is mainly concentrated within four industrial clusters: Hull, Teesside, Runcorn, and Grangemouth (Figure 12) [279]. However, in recent decades, a number of critical manufacturing sites have closed, and the UK's share of the global chemicals market has decreased significantly [279, 281].

Ethylene is the highest volume product of the UK chemical industry and a significant export [12, 282]. The UK chemical industry also produces many other organic chemicals and materials, from large volumes of plastics and a variety of lower volume, higher value speciality products such as fragrances and pharmaceuticals [5, 279, 280, 283]. The sector is a major exporter, but there is also a significant reliance on imports and many supply chains are complex, global, and interconnected [5, 12, 205, 279, 280, 284]. Examination of the UK chemical sector reveals a complex landscape, but the lack of publicly available data makes it challenging to map and quantify. There is a clearer picture of plastics than other parts of the system, thanks to studies such as that recently published by Drewniok et al (Figure 13) [5].

Each year the UK produces 1.5 - 1.7 Mt plastic, processes over 3 Mt plastic, and consumes 5 Mt plastic, meaning it is heavily reliant on imports.

The 5 Mt of plastic consumed in the UK each year would release 13.5 Mt CO_2 if it were all incinerated.

The UK chemical industry makes a variety of plastics, with polyethylene, polypropylene, PVC and PET produced in the largest volumes.

UK plastic consumption is mainly associated with packaging, consumer products, automotives, and construction materials.

26 Mt CO_2 eq is emitted across the life cycle of the plastics consumed in the UK each year. A large portion of these emissions occur outside the UK.

Figure 13. UK plastics: facts and figures. Based on data from references [5, 140, 221, 223, 224]. Emissions related to plastic incineration were calculated according to the assumption that incinerating 1 kg plastic leads to an average of 2.7kg carbon dioxide [2]

The chemical sector is the UK's second-largest direct industrial GHG emitter after steel, accounting for 19% of UK industrial emissions [16]. Scope 3 emissions would add significantly to this figure. Beyond this, UK consumption also results in significant emissions outside the UK. For example, a lot of emissions associated with plastics consumed in the UK occur elsewhere because of the import of plastics and plastic goods and the export of plastic waste [5, 286]. The closure of parts of the UK chemical industry has resulted in a higher proportion of GHG emissions associated with UK consumption occurring internationally, and this has contributed to the fall in direct emissions from the UK chemical sector in recent decades [12, 16].

The UK has a legally binding target of net zero GHG emissions by 2050. For the chemical system to be consistent with net zero, the emissions stemming from the whole life cycle of organic chemicals and materials must be addressed. However, thus far efforts to address UK chemical industry emissions have focused mainly on areas such as renewable energy and CCS [12].

5.2 Bio-based chemicals in the UK

Bio-based chemicals make up only a very small portion of the chemicals and materials used in the UK and examples of bio-based chemicals production are limited. Most of the UK's activity around bio-based chemicals seems to be focused on early stage technology development and innovation, with few companies producing bio-based chemicals at commercial or approaching commercial scales [224][21]. We are not aware of any UK production of bio-based or bio-attributed primary chemicals. There are a small number of biorefineries operational in the UK, producing both drop-in and novel bio-based chemical products, with more under construction [164, 185, 226, 287, 288]. There are several large facilities producing bioethanol, which is currently used for fuel purposes.

Despite the low levels of commercial activity, the UK is home to significant research expertise and enabling technologies in many disciplines that will underpin the development of bio-based products and there is a wealth of research occurring in this space in both academic and industrial environments [76, 224, 289, 290]). This includes research activity in several major chemical companies as well as a range of SMEs, and there are many partnerships between industry and UK universities [112, 161, 164, 166, 185, 186, 210, 224, 287, 291-297]. So far, little of this R&D has manifested as UK-based scale-up and manufacturing, and there are numerous examples of research that is carried out in the UK being scaled up elsewhere [224, 290].

Part 2 of this report highlighted some of the challenges faced by the bio-based chemicals sector, all of which are relevant to the UK. In particular, difficulty accessing finance and appropriate pilot and demonstration scale testing facilities are often stated as particular barriers to those trying to develop bio-based chemicals in the UK [289, 290]. There are also questions around feedstock availability, especially because of the UK's restricted capacity for domestic feedstock production compared to some other regions of the world and its significant ambitions for biomass use for energy and negative emissions (e.g., for BECCS and sustainable aviation fuel (SAF)) [13]. A number of resource modelling studies have assessed UK biomass feedstock availability and, in some cases, attempted to forecast the levels biomass feedstock that the UK may be able to access in the future [13, 298-306]. Models indicate the UK could have access to greater amounts of sustainable biomass in the future, but estimates vary greatly and modelling future biomass availability is notoriously challenging, especially since the availability of feedstocks such as wastes, residues, and crops will be significantly affected by the policy landscape.

Bio-based chemicals could help to reduce the GHG emissions associated with the UK chemical system and the products we consume, but the impact of increased domestic production of bio-based chemicals on the UK's carbon budget is less clear because of the large reliance on imports. Mapping and modelling of the UK's chemical system and its impacts is hampered by a lack of publicly available data and the complexity of the system due to large levels of international trade along the supply chain. There is also limited evidence to date of the impacts of large-scale deployment of bio-based chemicals in the UK in terms of things such as

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[21] This is based on a 2017 report. The perspective of our stakeholders is that this does not seem to have changed significantly in the subsequent years.

economics and jobs.

Another major challenge is a lack of ambition or steer from UK government. To date, the issue of emissions stemming from the carbon in chemicals seems to have received little attention from UK Government. The 2023 Biomass Strategy only briefly touched on the use of biomass in the chemical industry, but it did acknowledge the need for replacements for fossil-feedstocks in the chemical industry and the potential role for biomass [13]. The UK has no policy or regulatory mechanisms that are designed to encourage the production of bio-based chemicals. The absence of policy interventions that would encourage the use of biomass (or renewable carbon in general) in chemicals and materials, discourages the activity and investment that is needed to develop the sector and means that biomass tends to be diverted into certain energy applications where there are policy incentives in place, such as transport fuels [2, 12, 289]. In contrast, ambitious policies relating to renewable or bio-based chemicals are being implemented in other regions of the world, and some chemical companies are beginning to set their own targets for renewable carbon [4, 46, 307-311].

5.3 Opportunities for the UK

This report demonstrates that the UK could build on its successful research and innovation on bio-based chemicals, and unlock potential benefits to the economy, environment, and people. Figure 14 outlines the roles the UK could play in a future global bio-based chemicals system and the potential opportunities and benefits each type of activity could deliver.

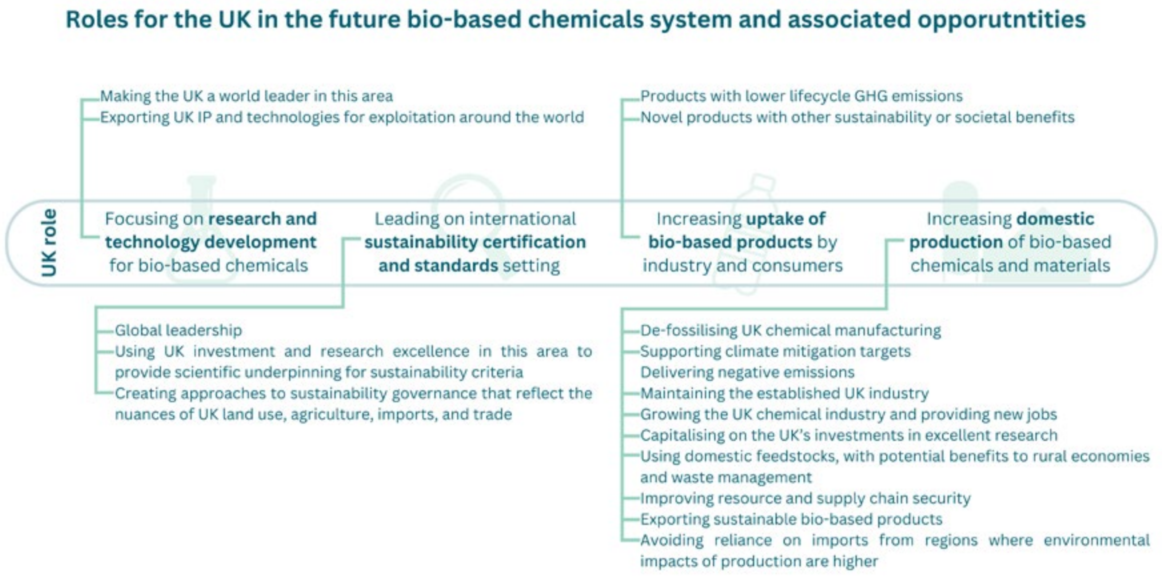

Figure 14. Possible roles for the UK in the future bio-based chemical system and associated opportunities

If UK production of bio-based chemicals and materials is to be increased, it is worth considering if the UK might prioritise certain bio-based chemicals to support particular policy objectives. For example:

- **Prioritise negative emissions**
  In the 2023 Biomass Strategy from UK government, the long-term priority for biomass use is overwhelmingly for the delivery of negative emissions [13]. The strategy focuses on negative emission energy systems (e.g., BECCS for power production, or linked to SAF, AD or other fuel applications), but negative emissions could also be delivered by appropriate production of bio-based chemicals. Biomass use could be prioritised in technologies that can be integrated

with CCS during production and/or at end of life, or possibly in long lifetime products [22], where LCA confirms negative life cycle emissions can be achieved.

- **Prioritise existing products and industries**
  The UK already has an established chemical industry and so opportunities might be sought to use biomass within existing manufacturing processes, for example by creating drop-in intermediates or following a mass balance approach. This would make use of the UK's existing infrastructure and know-how and could help to maintain UK chemical manufacturing and perhaps prevent more from moving abroad, whilst also increasing sustainability. An example of a product that might be prioritised under this approach is ethylene, which is produced in large volumes within the UK chemical industry using fossil feedstocks and is already being produced at scale from biomass in a number of places around the world from bioethanol or the use of bio-naphtha in a mass balance approach (Table A1) [12]. Ethylene is produced in very large quantities, meaning that as biomass displaces fossil feedstocks, the total emissions savings could be significant, though this would also require significant volumes of feedstock. Products such as ethylene also tend to be manufactured in the major industrial clusters, so could potentially be well placed to allow integration of bio-based chemicals production with the UK's planned CCS infrastructure.
- **Prioritise low-volume, high-value products**
  The UK is a small country with restricted capacity for domestic feedstock production compared to some other regions of the world, and so it may be better placed to deliver lower volume, higher value chemicals, such as novel bio-based products that service relatively small markets. Though this scale of manufacturing may not be able to offer the same scale of GHG emissions as large-scale displacement of fossil products like ethylene, it also requires less feedstock and could offer opportunities to turn local resources into economic opportunities. A previous publication, UKBioChem10, identified ten bio-based chemicals of this type that offered particular opportunities for the UK [206].
- **Prioritise chemicals made from underutilised feedstocks**
  It may be beneficial to prioritise bio-based chemicals that can be made from feedstocks that are currently underutilised, may be available in greater quantities in the future, or themselves come with environmental benefits. Feedstocks such as waste, and lignocellulosic material such as wheat straw and forestry residues are currently underutilised in the UK [13]. Ambitions for increased production of perennial biomass crops such as miscanthus and short rotation coppice (SRC) willow may also lead to increased availability of these types of lignocellulosic biomass being available in the UK in the future, and there are also novel feedstocks such as hemp and seaweed that are gaining attention [13, 91, 312]. This will also demand new technologies, particularly when it comes to lignocellulosic biomass where commercial scale pre-treatment for extraction of sugars has not yet been achieved in the UK.

5.4 Next steps for bio-based chemicals in the UK

Unlocking the potential benefits of bio-based chemicals for the UK will demand action across society, from policymakers, industry, and academics, as well as cross-sectoral collaboration. Progress should be underpinned by continued research and innovation to address evidence gaps, support decision-making, and develop new technologies and products that meet the needs of society, whilst also being scalable, and economically, socially, and environmentally sustainable. This will demand research across many disciplines, from chemical engineering and biosciences to economics, systems modelling, and social science. Outlined below are some areas we have identified as priorities for future research based on the information presented in this report. Lessons can be learned from those with expertise in the wider biomass and bioenergy space, where there are many decades of work on feedstocks and technologies that have been scaled. There is also a need for collaboration and communication between those working on bio-based chemicals, and those working on circular economy, other forms of renewable carbon,

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[22] Subject to the ongoing questions highlighted in Part 4.

and renewable energy, to support a joined-up approach to carbon management and the development of a sustainable chemical system.

BIO-BASED CHEMICALS R&D PRIORITIES

- Development and optimisation of technologies that will allow the use of a wider range of low-carbon feedstocks, including cost-effective and scalable conversion of lignocellulosic feedstocks.
- Development of integrated biorefineries and systems that couple the production of bio-based chemicals with other priority applications such as transport fuels.
- New routes to drop-in and novel bio-based chemicals, including platform chemicals, novel products with useful properties (e.g., biodegradable polymers, safer solvents), and products that are important for other manufacturing sectors (e.g., sustainable materials for renewable energy).
- Applications based on industrial biotechnology, and (where necessary) implementation of engineering biology approaches to improve the production of bio-based chemicals using biological systems (e.g., engineering bacteria to be more suitable for use under industrial conditions, or engineering plants that produce high-value compounds as they grow).
- Optimisation of biomass-to-chemicals process efficiency, to enhance resource utilisation throughout the value chain.
- Evaluation of the economic viability and scalability of biomass-based production processes, considering factors such as feedstock availability, production costs, and market demand.
- Evaluation and optimisation of the climate, environment, and wider sustainability impacts of bio-based chemicals and materials.
- Further examination of the opportunities for carbon storage and negative emissions through integration with CCS, carbon management, and long lifetime products.
- Studies on potential large-scale economic, social, and environmental impacts of increased deployment of bio-based chemicals in the UK, and how this varies according to the approach taken within the industry.
- Improved mapping of the UK and global chemical industries and better quantification of their carbon impacts.

Our recommendations for policy makers, which are presented on the next page, are the actions which we believe are essential if the benefits and opportunities described above are to be delivered for the UK.

RECOMMENDATIONS FOR UK POLICY MAKERS

Now...

- **Articulate the opportunity and secure cross-government consensus**
  The UK needs a plan to address the climate impacts of organic, carbon-based chemicals. The issue of carbon in chemicals and the potential for bio-based products cuts across numerous sectors and the interests of several government departments. There is a need for departmental leadership and a shared vision for a future sustainable chemical system, considering the feedstocks the UK will produce and use, what the UK will manufacture and at what scale, and what kinds of chemicals and materials should be used in the UK. This should be linked to departmental policy objectives such as net zero, agriculture, environment, industry, jobs, trade, and just transition.

Next...

- **Develop a roadmap for the transition**
  A detailed plan is required for how the government's vision for renewable and bio-based chemicals will be delivered. It is essential that the strategy takes account of the UK's carbon budgets and the global impacts of UK production and consumption and show how capacity in the sector can be developed while managing resource and life cycle impacts to people and the environment. The plan should also address the need for regulatory and support frameworks, sustainability governance, mechanisms for end-of-life/waste management, skills, research, business models, and support and infrastructure for scale-up and innovation.
- **Improve sustainability governance and regulation**
  It is essential that any future use of biomass in the chemicals sector is underpinned by rigorous, trusted, and enforceable sustainability governance to build confidence, deliver sustainability benefits, and minimise negative impacts. This requires a harmonised approach to sustainability criteria, so that biomass is valued in the same way no matter what the end use is, and which considers factors beyond just GHG emissions. In the 2023 Biomass Strategy, the UK Government committed to improving existing sustainability criteria through the development of a new cross-sectoral sustainability framework, which has the potential to deliver this kind of harmonised approach. It is imperative that this framework, and improvements to relevant application-specific regulation of chemicals and products (e.g., updates to UK REACH), is progressed in parallel with bio-based chemical deployment to ensure feedstocks and products are safe and sustainable.

Future...

- **Implement policy to accelerate sustainable chemicals**
  Bio-based chemicals, and chemicals derived from other renewable carbon sources, are not being expanded in the UK because there are no explicit incentives that prioritise them over fossil-based production. If the bio-based chemicals industry and markets are to grow, new policy incentives (e.g., renewable carbon mandates or sustainable public procurement policies) will be needed[23]. These should be designed to encourage bio-based chemicals that deliver environmental, economic, and social benefits that are superior to fossil production and to other uses of the biomass over life cycle. Although it would be possible to implement policies that generally incentivise the use of biomass feedstocks for chemicals production, the variation in the climate and environmental impacts of bio-based chemicals means that it is essential that we specifically encourage bio-based chemicals with positive carbon, environmental and other desired impacts. If the goal is to increase domestic manufacturing, policy interventions will need to go beyond those focused on products, to create an enabling environment for the scale-up and deployment of sustainable chemical production in the UK.

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[23] Further discussion of policy mechanisms that could support the transition to chemicals derived from biomass or other renewable carbon sources can be found in the following references: [1, 2, 6, 10, 12, 62, 243, 244, 246–248].

APPENDICES

APPENDIX 1: GLOSSARY

ANNUAL CROPS	Annual crops are grown on a yearly cycle, and in the context of biomass examples include wheat, maize, and sugar beet.
AROMATICS	Aromatic molecules are chemically stable organic chemicals based on ring structures. Examples include benzene, toluene, and xylene.
BIO-BASED CHEMICALS AND MATERIALS	Bio-based chemicals and materials (sometimes collectively referred to as bio-based products) are products made from biomass. This does not include food products, and for this report, we have chosen to exclude traditional bio-based products such as paper, wood, or cotton, and natural fibres.
BIODEGRADABLE	Bio-based chemicals and materials (sometimes collectively referred to as bio-based products) are products made from biomass. This does not include food products, and for this report, we have chosen to exclude traditional bio-based products such as paper, wood, or cotton and natural fibres.
BIOECONOMY	The bioeconomy can be broadly defined as all economic sectors that use biomass to make products, (such as agriculture, food, drink and wood-based products, biofuels, and bio-based chemicals and materials such as plastics) [74]. This report is focused on the aspects of the bioeconomy related to the production of chemicals and synthetic materials, rather than the use of paper, wood, and natural fibres. The circular bioeconomy is the integration of bioeconomy principles with the principles of circular economy [56, 90].
BIOGENIC CARBON	Biogenic carbon refers to the carbon that plants sequester from the atmosphere as they grow, which they use to create biomass. It is used to refer to this carbon as it is used in products and travels along the value chain.
BIOMASS	Biomass is a term that can be used to describe all organic carbon-based materials, including living and dead matter in the environment or material that has been harvested [74]. In this report we follow the lead of the CCC in using a narrower definition of biomass [74]; here, we use the term to refer to organic bio-derived material that is intended for use as an industrial feedstock, including purpose-grown crops, forest biomass, and wastes and residues.
CATALYSTS	A catalyst is a substance that can be used to speed up a chemical reaction, without being consumed by the reaction.
CHEMICAL INDUSTRY	The manufacturing industry that produces chemicals and materials derived from them. This includes both organic chemicals and inorganic chemicals.
CHEMICAL SYSTEM	Here we use chemical system to refer to the system that includes the chemical industry but also the related upstream and downstream activities, such as the use and disposal of chemicals and materials that are made from them.

CIRCULAR ECONOMY	Circular economy principles guide minimal extraction of raw materials and production of waste, through material efficiency, product reuse and durability, recycling, and waste valorisation, in contrast to the linear economy that we currently rely on which is built around a "take, make, dispose" model [9, 56].
COUNTERFACTUAL	Counterfactuals is a term used in LCA to describe products or activities that have been mitigated or replaced. In the context of this report, examples may include the fossil-based chemical that is replaced, or what would otherwise have happened to the land or resource if it was not used to produce feedstock.
DEFOSSILISATION	Defossilisation is a transition away from fossil feedstocks such as oil, gas, and coal.
DROP-IN BIO-BASED CHEMICALS	Drop-in bio-based chemicals are chemically identical to existing fossil-based chemicals [70, 77]. For example, biopolyethylene is a drop-in alternative to ethylene derived from fossil feedstocks.
ECONOMIES OF SCALE	Economic advantage that is gained by increasing scale of industrial production, due to lower capital expenditure requirement per tonne of product at larger scales and therefore lower cost.
ENGINEERING BIOLOGY	Engineering biology is the application of engineering principles to the design of biological systems [249]. It encompasses the academic discipline synthetic biology, which is the design and construction of new biological systems, for example bacterial strains that produce interesting new compounds, or modified enzymes.
ENZYME	Enzymes are proteins that are biological catalysts.
GREEN CHEMISTRY	Green chemistry is an area of chemistry focused on developing more sustainable chemical processes and products. For example it includes principles such as waste prevention, efficient conversion of feedstock to products, less hazardous chemical processes, designing safer chemicals, and use of renewable carbon feedstocks [9, 45]. The principles of green chemistry are widely used, but there is no agreed definition of what qualifies a chemical or process as green [9].
HYDROCARBON	Hydrocarbons are molecules made only of the chemical elements carbon and hydrogen.
INDIRECT LAND USE CHANGE	Indirect land use change refers to the land use change that may occur as an unintended consequence of biomass production, and the emissions that this can cause. For example, if a biomass crop is grown on land that was previously used for cattle, this may result in deforestation elsewhere to house the cattle and this leads to emissions.
INDUSTRIAL BIOTECHNOLOGY	Industrial biotechnology is the use of biological systems, including enzymes, micro-organisms, cells, or whole organisms, to make valuable products such as chemicals or materials [97].
INTERMEDIATE	A chemical intermediate is a substance formed in between a starting material and the desired end product. For example, in the production of ethylene glycol, ethylene is first converted to ethylene oxide, and then another reaction turns ethylene oxide into ethylene glycol. In this example ethylene oxide is an intermediate.

LIFE CYCLE ASSESSMENT	Life cycle assessment (LCA) is a tool that can be applied to determine and compare the environmental impacts of different products, technologies, and activities [115, 196, 197]. LCA involves consideration of the energy and mass inputs and outputs of processes within the system boundaries that have been set. It is commonly used to assess the life cycle GHG emissions but can also be applied to other environmental impacts such as water consumption and acidification.
MONOMER	A molecule used as a chemical building block in the production of polymers.
NEGATIVE EMISSIONS	Negative emissions occur when GHGs are removed from the atmosphere. Usually, the term is used to refer to systems where the removal is permanent.
NET ZERO	The term net zero is used to refer to a system with no net GHG emissions. This is not necessarily the same as no GHG emissions and can be achieved if the amount of sequestration is equal to any emissions that occur.
NOVEL BIO-BASED CHEMICALS	Novel bio-based chemicals contain unique structures that mean they are not chemically identical to any existing fossil-based chemicals [70, 77]. They are sometimes referred to as dedicated bio-based chemicals.
OLEFINS	Olefins are hydrocarbons which contain two carbon atoms joined by a double bond. Olefins are important chemical building blocks, with key examples being ethylene and propylene [8, 193].
ORGANIC CHEMICAL	Organic chemicals are carbon-based chemicals. They tend to have structures of carbon atoms joined in chains or rings, with other elements such as hydrogen, oxygen, or nitrogen attached.
PERENNIAL CROP	Perennial crops are crops that regrow after harvesting and do not have to be replanted every year. In the context of biomass, examples include miscanthus and willow.
PETROCHEMICAL	Petrochemicals are chemicals derived from fossil feedstocks such as oil and gas. This includes organic chemicals, but also chemicals such as ammonia. Here we also use the term fossil-based chemical to refer to chemicals produced from fossil feedstocks as opposed to renewable carbon sources.
PLATFORM CHEMICAL	A platform chemical is a chemical intermediate which, due to its structure, can be converted into many different useful chemical derivatives [24].
POLYMER	Polymers are long chain molecules made from many smaller chemical building blocks (known as monomers) joined together via polymerisation reactions. Polymers can be categorised by the types of monomers used and the chemical bonds that join them together. For example, categories of synthetic polymer discussed in this report are: • Polyolefins – made by polymerisation of olefins such as ethylene and propylene. Examples include polyethylene and polypropylene. • Vinyl polymers – made by polymerisation of vinyl monomers, for example polyvinyl chloride. • Polyesters – polymerisation of alcohols and carboxylic acids. Examples include polyethylene terephthalate (PET) which is often simply referred to as polyester, and polylactic acid (PLA, formed by polymerisation of lactic acid). • Polyurethanes – made through polymerisation of isocyanates and polyols. • Polyacrylics or polyacrylates – made by polymerisation of acrylate monomers. Examples include polymethylmethacrylate (PMMA) which is often referred to as acrylic.

RENEWABLE CARBON FEEDSTOCKS	Renewable carbon feedstocks are sources of carbon that can displace fossil-carbon sources [1]. These include carbon dioxide, recycled material, and biomass.
TECHNO-ECONOMIC ANALYSIS	Techno-economic analysis is a method for assessing the economic performance of a technology or process.
TECHNOLOGY READINESS LEVEL	Technology readiness levels (TRL) are an approach to communicating the maturity of a technology, from TRL 1 which corresponds to principles being investigated in a lab, to TRL 9 which corresponds to industrial operation.

Units

Gt	100 million tonnes
Mt	1 million tonnes
Gt CO_2	100 million tonnes of carbon dioxide
Gt CO_2^{eqv}	100 million tonnes of carbon dioxide equivalent. This is a measure of total greenhouse gas emissions including greenhouse gases other than carbon dioxide in terms of the amount of carbon dioxide that would have the same global warming potential.
$kgCO_2^{eqv}$ / kg	Kilograms of carbon dioxide equivalent emitted per kilogram of chemical product.

APPENDIX 2: BIO-BASED PRODUCTS REVIEW

These tables outline how biomass can be used, or is being used, to make important categories of chemical product. It is based on a more detailed review provided in a supplementary document. This review is not designed to be exhaustive but to act as an introduction and to highlight opportunities. It does not attempt to cover the entire array of products found in the scientific literature. The complexity and lack of publicly available data make it hard to get a full and detailed picture of the bio-based chemicals sector. We have used academic publications as well as a variety of online information sources to carry out this review. We have interpreted the information available to the best of our ability, but it should be noted that in some cases it is not clear from the information available online whether a product is bio-based or bio-attributed.

Table A1. Key primary chemicals and routes for bio-based production.

PRIMARY CHEMICAL	APPROXIMATE GLOBAL DEMAND[24]	FOSSIL-BASED PRODUCTION	KEY DERIVATIVES AND THEIR USES
Ethylene	161 Mt [20]	Predominantly by cracking of naphtha or other feedstocks like ethane, with some made via methanol-to-olefins processes [8].	Most common derivative is polyethylene, which is mainly used for plastic packaging [8]. Other major derivatives include ethylene oxide, ethylene glycol, vinyl chloride, and styrene, which is produced via reaction with benzene. Common downstream products include surfactants (e.g., for home and personal care products), and a variety of plastics, fibres, and rubbers, such as PVC, polystyrene, and polyester [8, 57, 317-321].
Propylene	114 Mt [21]	Predominantly by cracking of naphtha or other feedstocks like ethane, with some made via methanol-to-olefins processes [8].	Most common derivative is polypropylene [8]. Other common derivatives include propylene oxide, propylene glycol, acrylonitrile, acrylamide, and acrylic acid [8, 19, 57, 322-325]. Common downstream products include solvents, coolants, and many polymers such as polyurethanes, polyesters, polyacrylics, and polyacrylamides. These polymers have applications in a variety of plastic products, rubbers, textiles, and PLFs [8, 19, 323-325]. Polyacrylamide is also used to make carbon fibre.
Methanol	98 Mt (including fuel applications) [22]	Catalytic conversion of syngas [8, 11, 57].	Most common derivative is formaldehyde. Other important derivatives include acetic acid, acetic anhydride, and methyl methacrylate (MMA). Downstream products include solvents, pharmaceuticals, dyes, preservatives, adhesives, a variety of PLFs (e.g. for personal care products, paints and coatings, and agrochemicals) and plastics (e.g., for construction, automotives, and consumer goods) [8, 19, 111, 330-336]. Methanol is also converted into ethylene and propylene via the methanol-to-olefins process, and conversion of methanol-to-aromatics is under development [8, 331].
BTX aromatics	121 Mt [23]	Cracking or reforming of naphtha. Methanol-to-aromatics in development [8, 10].	The major derivatives of BTX aromatics are used to make important polymers such as polystyrene, nylon, polyurethanes, and PET, with applications as plastics, PLFs, rubbers, and textiles [10, 341-344]. Other important derivative applications include solvents, plastic additives, and intermediates for pharmaceutical production [343].

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[24] Again, figures for annual global demand are annual figures, and the most recent year for which data is readily available varies across the dif
figures for approximate global demand without specifying a year. All data relates to a year no earlier than 2019, and more information can be

BIO-BASED PRODUCTION	BIO-BASED DERIVATIVES
Bio-attributed ethylene from bio-naphtha is commercially available [116]. Bio-based ethylene is produced at commercial scale via dehydration of bioethanol [57, 115, 117]. Bioethanol is mostly produced via sugar fermentation and currently most production is for fuel applications [10, 228, 230].	Bio-based forms of a number of the key ethylene derivatives, including bioethylene oxide and biopolyethylene, are now available and more are available in bio-attributed forms via bio-attributed ethylene [57, 110-115, 119-123]. Smart drop-in rotues to some derivatives are under development, for example commercial production of bioethylene glycol directly from sugar rather than via bioethylene is on the horizon [127, 128].
Bio-attributed propylene dervied from bio-naphtha is commercially available [57]. Some bio-propylene production is produced from bio propane [326]. Several other approaches to the production of propylene from biomass have been developed but are not yet at commercial scale, including conversion of bio ethanol or bio methanol [57, 327, 328].	A number of propylene derivatives are now available in bio-attributed forms, but for most bio-based versions are not commercially available [57, 196-198]. Polypropylene is available in bio-attributed form, and some bio-based production is reported [326]. Smart drop-ins produced via alternative routes are being developed for some [57, 129, 197, 329]. For example, bio-propylene glycol dervied from glycerol is commercially available [129].
Biomethanol can be produced from bio-derived syngas from biomass gasification or biomethane reforming [334]. Bio-attributed methanol is commercially available [118]. Some biomethanol is commercially available and more plants in the pipeline [334, 337, 338]. A lot of the biomethanol production to date appears to be driven by interest in fuel applications.	Bio-attributed versions of formaldehyde and other methanol derivatives are available [118, 124]. Bio-based versions of acetic acid and its derivatives are available commercially, but these tend to be produced from ethanol rather than methanol [57, 71, 111, 233, 339, 340]. Novel bio-based alternatives to formaldehyde have received significant attention [218].
Bio-attributed aromatics are commercially available. Rotues to bio-based BTX via biomass gasification or pyrolysis are under development, with some reaching demonstration scale production, but none are yet at commercial scale [57, 345, 346]. Alternative routes to some aromatics from novel bio-based platform chemicals are also being investigated [140, 347, 348].	Some derivatives, including a variety of polymers, are available in bio-attributed forms [121, 131, 196, 199, 200]. Bio-based production of some derivatives has been demonstrated but commercial production will be reliant on bio-based BTX production at scale. Smart routes to some derivatives, such as adipic acid (a benzene derivative used to make nylon) are being investigated [57, 130, 131]. Researchers are also investigating deconstruction of lignin as a route to a range of drop-in and novel aromatic compounds [57, 341, 348, 349].

ferent products discussed. Here, we intend this number only to give an idea of the relative scales of the different markets, so we have presented
e found in the references.

Table A2. Examples of promising bio-based platform chemicals

PLATFORM CHEMICAL	APPROXIMATE GLOBAL DEMAND	BIO-BASED PRODUCTION
Succinic acid	70 kt (~50% bio-based and 50% fossil-based) [350]	Commercial scale production via sugar fermentation [57, 111, 135].
Glycerol	100 kt (bio-based dominates) [353]	Large amounts made as a by-product of the processing of bio-oils into fatty acids and biofuels [57, 82].
Levoglucosan	Not yet commercial	Pyrolysis of lignocellulosic biomass, though not yet at commercial scale [85].
Hydroxymethylfurfural (HMF)	Not yet commercial	Catalytic or thermochemical conversion of sugars [206, 355]. Full scale commercial production is yet to be achieved [132-134].

KEY DERIVATIVES
Bio-succinic acid could be used as a replacement for fossil based adipic acid (a benzene derivative) in some applications (e.g., nylon production). Succinic acid can also be converted into numerous valuable derivatives such as biodegradable polymers like polybutylene succinate (PBS) and novel plasticizers [57, 82, 169]. The major use of bio-succinic acid is expected to be the production of 1,4-Butanediol (BDO) which is currently produced from fossil feedstocks [82]. BDO is used in the production of plastics (e.g. polyesters and polyurethanes), fibres (e.g. polyurethane fibres in the form of Lycra), tetrahydrofuran (THF, an improtant solvent), and a range of other products such as plasticizers and pharmaceuticals [57, 351]. Bio-BDO is commercially available and bio-based Lycra based on bio-BDO is in the pipeline [57, 352].
Bio-glycerol is directly used in personal care products, pharmaceuticals, and foods, and can also be a solvent. It also has numerous valuable derivatives including surfactants, pharmaceuticals, and polymers such as polyesters and polyurethanes with applications in plastics, PLFs and synthetic fibres [35, 57, 82, 129, 224]. Some glycerol derivatives are drop-in products, where production from glycerol is a smart route, for example glycerol can be used to make bio-based propylene glycol and epichlorohydrin, which are usually dervied from propylene [57, 73, 224].
Levoglucosan can be converted directly into various high added-value platform chemicals including HMF, levoglucosenone, and styrene, or into glucose [85]. Levoglucosenone is a derivative of levoglucosan that can also be made directly by pyrolysis [354]. Pilot scale production of levoglucosenone has been achieved using forestry waste, and a commercial plant is under construction [166]. Levoglucosenone has applications in the production of fine chemicals and pharmaceutical as well as a range of chemicals for use in polymers and molecules such as HMF [224, 354]. There is particular interest in conversion of levoglucosenone into cyrene, a novel bio-based solvent that can replace some hazardous petrochemical solvents in a number of applications [112, 166].
Research has demonstrated the conversion of HMF into drop in replacements for a number of chemicals currently produced from fossil feedstocks, such as caprolactam (a monomer used for nylon-6 production) and a number of other intermediates used for plastic, pharmaceutical, and agrichemical production [224, 355]. HMF also has potential in the production of novel solvents and alternatives to formaldehyde resins [175, 217, 218]. Other potentially valuable derivatives, include 2,5-Furandicarboxylic acid (FDCA) and levullinic acid [57, 82, 206, 224, 355]. FDCA production is in the pipeline with the first commercial plant under construction [57, 356]. The main use for FDCA will be production of the novel plastic PEF [57, 206]. Levullinic acid has only been produced at small scales to date but it has a number of potentially interesting derivatives including 2-methyl-THF, a novel bio-based solvent, polymers, plasticizers and fine chemicals for production of agrichemicals [82, 112, 171, 224, 357].

Table A3. Commonly used plastics and routes for bio-based production

PLASTIC	APPROXIMATE GLOBAL DEMAND	KEY APPLICATIONS	TYPICAL LIFETIME
Polyethylene (PE)	105 Mt (27% global plastics demand) [25]	Main use (over 50% of demand) is in packaging. Some use in construction and a variety of other applications such as consumer goods [25, 358].	Mostly short
Polypropylene (PP)	75 Mt (19.3% global plastics demand) [25]	Main use is packaging, but also significant application in consumer goods (e.g. toys, sanitary products, buckets), automotives, and construction [25, 359, 360].	Mostly short
Polyvinyl chloride (PVC)	50 Mt (13% global plastics demand) [25]	Majority used in construction (e.g. pipes, window frames, flooring, roofing) [25, 361].	Mostly long
Polyethylene terephthalate (PET)	24 Mt (6% global plastics demand) [25]	The majority of PET is used in packaging, particularly in the food and drinks industry and for bottles [25, 140, 319].	Short
Polyurethane (PU)	22 Mt (5.5% global plastics demand) [25]	Many different applications for example as rigid, insulating foams in construction (e.g. insulating foams), industrial applications (e.g. insulation), household goods (e.g. insulation in fridges, flexible foams in cushioned furniture), and automobiles (e.g. car seats, insulation panels) [25, 363-365].	Varied, many medium and long
Polystyrene (PS)	21 Mt (5% global plastics demand) [25]	Main uses are in packaging and construction [25, 372].	Short to long

Table A4. Examples of novel bio-based plastics[25]

PLASTIC	APPROXIMATE GLOBAL DEMAND	KEY APPLICATIONS
Polylactic acid (PLA)	Estimated production capacity of >250 kt [65].	Mainly used in packaging (e.g. as replacement for polyolefins [65]), though there are applications in textiles, consumer goods, agricultural materials, and parts in the automotive industry [207].
Polyhydroxyalkanaoates (PHAs)	Estimated production capacity of >30 kt [65].	Mainly packaging with other potential uses in biomedical applications (such as implanted medical devices and drug delivery systems), and agricultural uses (such as films) [137].
Polyethylene furanoate (PEF)	Commercial production of PEF is expected to begin in 2024 [356].	Direct replacement of PET. Dominant uses likely to be in packaging.

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25 There are also variety of natural polymers (e.g., starch, alginate, cellulose) that can be used to make plastics [65]. The focus of this report is sy

END OF LIFE	FOSSIL-BASED PRODUCTION	BIO-BASED PRODUCTION
Non-biodegradable. Recyclable. Often landfilled, incinerated, or leaked to environment.	Polymerisation of ethylene.	Bio-attributed and bio-based polyethylene are commercially available [115, 116].
Non-biodegradable. Recyclable. Often landfilled, incinerated, or leaked to environment.	Polymerisation of propylene.	Bio-attributed polypropylene produced from bio-attributed propylene is commercially available [122, 123]. Some bio-based polypropylene production has been reported [326] but is not as widespread as polyethylene due to limited bio-propylene production.
Non-biodegradable. Recyclable. Often landfilled, incinerated, or leaked to environment.	Polymerization of vinyl chloride, which is derived from ethylene.	Bio-attributed PVC derived from bio-attributed ethylene is commercially available [119, 136].
Non-biodegradable. Recyclable. Often landfilled, incinerated, or leaked to environment.	Polymerization of ethylene glycol (derived from ethylene) and terephthalic acid (derived from xylene) [140].	PET, made from bioethylene glycol and fossil PTA (resulting in a product that is about 30% bio-based), is commercially available [65, 362].
Non-biodegradable. Recyclable. Often landfilled, incinerated, or leaked to environment.	A group of plastics based on various polyurethane polymers [363]. Typically made through polymerisation of isocyanates (e.g., toluene diisocyanate (TDI, derived from toluene) or methylene diphenyl diisocyanate (MDI, made from derivatives of methanol and benzene)) and polyols (e.g., polyols derived from ethylene oxide or propylene oxide, which are derivatives of ethylene and propylene respectively) [363, 366].	A range of novel polyurethanes based on bio-based polyols, often from plant-oil fatty acid, and fossil-based isocyanates have been developed and some are now commercially available [363, 367-369]. Bio-based versions of the common isocyanates used for polyurethanes are not yet available. Bio-attributed forms of some polyurethanes are now available [199, 370, 371].
Non-biodegradable. Recyclable but not commonly recycled.	Produced by polymerization of styrene, produced from ethylene and benzene.	Bio-attributed polystyrene is commercially available, but bio-based polystyrene is not [121, 201, 203].

TYPICAL LIFETIME	END OF LIFE	BIO-BASED PRODUCTION
Mainly short	Compostable in industrial facilities and recyclable where there are appropriate facilities [65]. Where there are not appropriate compositing or recycling facilities in place it is still sent to landfill or incinerated.	Polymerisation of lactic acid, which is produced via fermentation [57, 65, 137-139].
Mainly short	Compostable in industrial facilities and recyclable where there are appropriate facilities, and some PHAs are biodegradable in soil and marine environments [65, 137, 208, 373].	Produced by fermentation (i.e., directly produced in bacteria rather than being synthesised) with some commercial production [137, 208, 224, 373][22]. There are different kinds of PHA with varying structures and properties [208, 373].
Mainly short	Non-biodegradable. Recyclable.	Polymerization of bio-based ethylene glycol and FDCA [140].

nthetic materials and chemicals produced from biomass so plastics from natural polymers are not discussed in detail here.

Table A5. Polymers in applications beyond plastics, and routes for bio-based production

CHEMICAL PRODUCT	APPROXIMATE GLOBAL DEMAND	KEY APPLICATIONS	TYPICAL LIFETIME	END OF LIFE
PLFs	36 Mt [19]	Curable formulations (majority demand by volume) are used in paints, coatings, adhesives and sealants (e.g., in furniture, consumer goods, automotives, and construction). Liquid formulations are used in home and personal care products, agrochemicals, water treatments, and as lubricants [19].	Curable mostly medium/ long Liquid mainly short [19]	Curable formulations tend to be incinerated or go to landfill, as do lubricants. Liquid formulations are often dispersed during use meaning they go to wastewater treatment systems and/or the environment [19, 27].
Synthetic rubber	15 Mt [29]	The main use of synthetic rubbers is in automotives (e.g. tyres), but they also have a variety of other uses in non-durable and durable industrial and consumer goods (e.g. gloves, tyres, footwear), and construction [146, 147].	Mainly medium	Incineration, landfill, or recycling. Recycling often involves crumbled rubber being incorporated into other products, including long lifetime applications such as road surfacing.
Synthetic fibres	75 Mt [30]	Mainly textiles in clothing and home furnishings [142].	Mainly medium	Recycling is possible for some, but rates are very low. Mostly landfilled or incinerated [379].
Polymers composites	12 Mt [33]	Automotives and other vehicles, wind energy (structural components of wind turbines) and other energy applications, aerospace, defence, and construction [32, 154].	Mostly medium and long	Incineration or landfill. Recycling technologies are being developed for more composites.

FOSSIL-BASED PRODUCTION	DROP-IN BIO-BASED	NOVEL BIO-BASED
Many different polymers are used as PLFs, usually derived from common platform chemicals such as those discussed in Table 3. Some of the most common types are polyacrylics, polyesters, polyurethanes, vinyl polymers, and a variety of water-soluble polymers [19, 27].	Relatively few drop-in bio-based PLFs are commercially available to date. Commercial products include examples of drop-in bio-attributed and partially bio-based polyacrylics and vinyl polymers, drop-in bio-based polyesters, such as bio-based polyethylene glycol dervied from bioethylene oxide [19, 27, 113, 124, 374-376].	A variety of novel bio-based PLFs have been developed, often with beneficially properties such as biodegradability or improved safety. Most remain in the research stage but there are some commercially available, such as examples of novel biobased polyacrylics, polyesters, and polyurethanes, as well as PLFs based on natural polymers [19, 27, 363, 377, 378].
The main types of synthetic rubber are styrene butadiene rubber and polybutadiene rubber, produced from the monomers styrene (a derivative of ethylene and benzene) and butadiene [28, 146]. Another common synthetic rubber is ethylene propylene diene monomer rubber (EPDM), made from ethylene and propylene, along with an additional monomer which can vary [28, 146].	Styrene butadiene rubber and polybutadiene rubber are available in bio-attributed forms though production of bio-based monomers is under development [121, 148] [149-151]. Partially bio-based EPDM made using bioethylene is available [152].	Several novel bio-based synthetic rubbers that have been developed by researchers, and there is an interest in developing novel rubbers with properties such as biodegradability [28, 153].
Over half of global fibre demand is polyester (polyethylene terephthalate), which is the same polymer as the plastic PET (see Table 5) [30]. Another important class of synthetic fibres is polyamides, the most common of which are nylon 6,6 and nylon 6 (based on derivatives of BTX aromatics) ([141].	Partially bio-based polyester fibre made using bioethylene glycol is commercially available, and routes to bio- terephthalic acid that will enable bio-polyester are under development [215, 345, 380]. Bio-attributed Nylon 6,6, is available, but bio-based nylon 6,6 and nylon 6 are not [143]. Smart routes to bio-based monomers for nylon 6 and nylon 6,6 are being developed [57, 130, 194, 381-384].	A range of novel polyesters and polyamides/ nylons have been developed at lab scale, and some are commercially available. Some of the novel fibres that have been developed are biodegradable, for example PLA [213-216, 385]. Commercially available bio-based polyamides/ nylons are dervied from fatty acids, though others been demonstrated at lab scale (e.g., based on the bio-based platform chemical succinic acid) [30, 141, 144, 145].
Composite materials are formed by embedding fillers (fibres or nanoparticles, e.g., natural fibres, synthetic polymer fibres, inorganic particles, carbon nanotubes or carbon fibre), in a polymer matrix [31, 32]. The polymer matrix can be formed using a whole range of organic polymers, including those already discussed in Table 5 [31]. For example, polyesters, polyamides and polyurethanes are often used as the matrix materials [32].	Drop-in bio-based plastics could be used for the matrix materials (e.g. bio-based polyesters, polyamides and polyurethanes (Table 5) [154, 155]. Some drop-in bio-based filler materials have also been developed [154, 155]. For example, carbon fibre produced from bio-based polyacrylonitrile is being scaled up for use in composites and direct routes to carbon fibre from lignin are also being developed [156].	Natural fibres are already used in some polymer composites [154, 155]. Novel bio-based plastics such as PLA can be used as matrix materials in composites [32, 159]. Researchers have also created polymer composites with using novel bio-based filler materials such as biochar, the solid product of biomass pyrolysis that is formed alongside pyrolysis oil [160].

Table A6. Other types of chemical product and opportunities for bio-based production

CHEMICAL PRODUCT	APPROXIMATE GLOBAL DEMAND	KEY APPLICATIONS	TYPICAL LIFETIME	END OF LIFE
Solvents	28 Mt [37]	Used in industry for extraction, separation, and purification, and to dissolve reagents for chemical reactions [35], and are an essential ingredient in many cleaning products, perfumes, varnishes, and paints [34-36].	Mostly short	Many solvents are incinerated after use but there is also leakage into the envrionment (e.g., through accidental release or evaporation).
Plasticizer	11 Mt [167]	Plastic products, from packaging to fibres and construction.	Varied	Plasticisers can reach the environment due to leaching from plastic products. They may be incinerated at end of life, but if a plastic containing plasticisers is recycled the plasticizer may be in the new product.
Surfactant	19 Mt [176]	Most common use is in home and personal care products. Other applications include industrial applications (e.g. food processing, industrial cleaning, mining, water treatment), agrichemicals, pharmaceuticals (as drug delivery agents), and paints [39, 40].	Mostly short and dispersive.	Often lost to water treatment system or envrionment during use [175].
Bitumen	Over 100 Mt [189]	Often combined with aggregates such as sand to form asphalt. Main application is in road and pavement surfacing. Other applications include construction, such as roofing and waterproofing [188].	Mostly long	Recycling, landfill, or incineration.

FOSSIL-BASED PRODUCTION	DROP-IN BIO-BASED	NOVEL BIO-BASED
Different types of organic solvents include oxygenated solvents (e.g., alcohols such as isobutanol or ethanol, or acetone), hydrocarbon solvents (e.g., cyclohexane or aromatics such as toluene), and halogenated solvents (e.g., solvents containing elements like chlorine, such as dichloromethane (DCM). Most are derived from primary chemicals, and in fact a number of key primary/ platform chemicals are also important solvents (e.g. ethanol, toluene, and acetone) [34].	Drop-in replacements for several important organic solvents including bioethanol, bio-acetone, and bio-butanol, which are produced via fermentation, and bio-ethyl acetate which is produced from bioethanol [35, 57, 71, 111, 112, 162, 163]. These are all oxygenated solvent that can be used as safer replacements for other more problematic solvents. Less activity focused on drop-in replacements for hydrocarbon solvents and solvents that are particularly hazardous or toxic.	Research has focused on novel solvents that can be safer replacements for commonly used hazardous solvents or have performance benefits [112]. Examples include Cyrene and 2-Methyl-THF (both easily derived from promising bio-based platform chemicals), and ethyl lactate (dervied from lactic acid produced via fermentation), all of which can replace hazardous solvents in some applications [35, 57, 112, 165, 166].
Derived from primary chemicals, often through multiple steps due to their complex structures. For example, the common class of plasticizers phthalates are complex derivatives of xylene.	Some bio-attributed alternatives to fossil-based plasticizers are available, but most research seems to have focused on novel bio-based plasticizers[168].	There has been a lot of research activity related to safer bio-based plasticisers [172, 173]. The nature of the structures favoured for plasticizers lends itself to the types of complex molecules that are commonly found in biomass [386]. Bio-based plasticizers are often dervied from succinic acid or bio-oils, and some are commercialised [111, 169-171].
Surfactants have structures based around a head group attached to a tail group. Common tail groups are olefin chains [39, 174, 175]. The head groups are more varied. Common surfactants include linear alkylbenzene sulfonates (LAS, which have a head group dervied from benzene), sodium lauryl ether sulphate (SLES, with a head group formed from ethylene oxide and sulphur trioxide), cationic surfactants with head groups derived from ammonia, and non-ionic surfactants with head groups dervied from ethylene oxide [39, 174, 175].	The tail group in many surfactants is dervied from fatty acids from bio-oils [39, 175]. Creating fully bio-based surfactants is more challenging. Bio-attributed versions of some common surfactants are available [178, 179]. Ethylene oxide is an important intermediate for many common surfactants and bio-based surfactants derived from bioethylene based head groups and bio-based tails (e.g. based on fatty acids) have been launched by a number of companies in recent years [113, 177].	Many novel surfactants have been developed, often with an aim to make them non-toxic and biodegradable. Research has developed bio-based surfactants dervied from sugar, glycerol, and HMF [39, 175, 387]. Some are already commercialised. For example, alkyl polyglucosides are bio-based, biodegradable surfactants that have been commercially available for many years [39, 180]. There are also microbial surfactants, produced directly via fermentation rather than synthetised industrially from bio-based building blocks [181-187].
Bitumen is a mixture of high molecular weight hydrocarbons obtained from heavy oil fractions (i.e. it is a by-product of oil refining, rather than being dervied from chemical industry feedstocks) [15, 222].	None	A range of bio-binders for use in bitumen have been developed, mostly based on biocrudes or bio-oils from thermochemical processing of biomass [190]. Another promising option is use of lignin as a binder [191]. At the moment bio-binders tend to be mixed with fossil bitumen rather than replacing it totally [190, 191]. Most of the work thus far has been at lab scale but bitumen containing some bio-based binder is now being used by a company in the UK [192, 193].

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